Skulls in the Stars

The intersection of physics, optics, history and pulp fiction

Mr. Faraday's (most excellent) experimental researches in electricity (1831)

Posted on December 25, 2008 by skullsinthestars

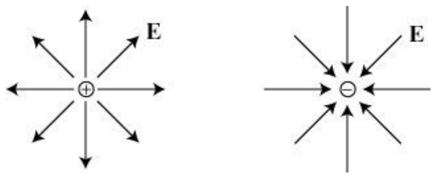
Michael Faraday (1791 – 1867) was a master of electricity. His researches established may important results in electromagnetic theory, including some which are now so taken for granted that Faraday's name is unfortunately not even thought of in connection with them.

I started to investigate Faraday's writings while working on a post about Edward Bulwer-Lytton's novel The Coming Race, which quotes Faraday to justify B-L's fictional source of energy, vril. This led me back through Faraday's monumental collection of researches on electricity, a collection of over 25 articles published in the Philosophical Transactions of the Royal Society under the blanket title, "Experimental researches in electricity."

Faraday, though apparently not very sophisticated theoretically, was an amazing experimentalist. Though I was originally looking for only a single quotation from his articles, I eventually downloaded a half-dozen of his works and I thought I'd discuss their details and their historical import.

We start with what is arguably his most important physical contribution, now known as Faraday's law. Faraday's work opened the door to the discovery of Maxwell's equations and the identification of light as an electromagnetic wave. I find it most satisfying to review the experimental work knowing the underlying physical law, so we begin with a qualitative discussion of the "need to know" information concerning electricity, magnetism, and Faraday's law.

First, we need to say a little bit about electric fields and magnetic fields! Electric charges are attracted to or repelled from one another, depending upon whether the sign of the charges are of opposite sign or the same sign, respectively. We can interpret this result as the interaction of one charge with the electric field emanated by the other, which is usually depicted as a 'flow' of field emanating from or entering into the charge. The field flows away from positive charge, and towards negative charge:



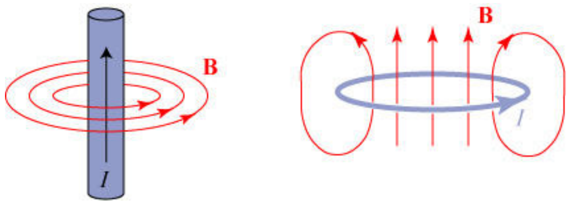
An electric charge q which is placed into the electric field will feel a force **F** equal to the product of the electric field (a vector quantity) and the value of the charge itself,

$$\mathbf{F} = q\mathbf{E}.$$

We won't go into the specific mathematical form of the electric field. Suffice to say, a positive charge placed into the field of another positive charge will be pushed away, while a positive charge placed into the field of a negative charge will be attracted. The study of the forces/fields of unmoving (static) electric charges is known as *electrostatics*.

Magnetic fields are a little more difficult to explain. Historically, magnetic forces were considered to be completely different than electric forces, as the only sources of magnetism at first were natural permanent magnets. This changed in 1820, when Hans Christian Ørsted accidentally discovered that an electric current, i.e.

moving electric charges, will deflect a magnetic compass needle. This was the first evidence that electricity and magnetism were actually related to one another. After hearing of these discoveries, André-Marie Ampère elaborated upon them and formulated the basic principles of *magnetostatics*: steady (static) electric currents result in magnetic fields which circulate around them:



A long, straight wire carrying current I will have a magnetic field which circulates around its axis, while (more important for our later discussion) a loop of current will have a magnetic field which passes through the middle. The direction of the field $\mathbf{B}$ can be determined using the so-called 'right-hand rule': if you point the thumb of your right hand in the direction of the current, your fingers curve in the direction that the magnetic field circulates around it.

The force created by a magnetic field is a little more difficult to explain in simple terms; the formula for the force on an electric charge q moving at velocity $\mathbf{v}$ is given by:

$$\mathbf{F} = q\mathbf{v} \times \mathbf{B},$$

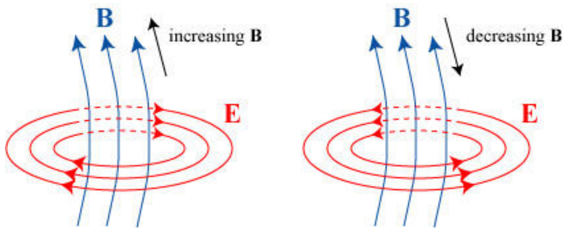
where $\times$ is a vector operation known as the cross product. For our purposes, it suffices to note that the effect of the cross product is that the magnetic force on a moving charge is perpendicular to both the direction the charge is moving and the direction of the magnetic field. If the magnetic field is pointing up and a positive charge is moving north, the charge will experience a force to the west (a negative charge will experience a force to the east).

The preceding discussion is essentially the state of understanding of electric and magnetic fields in Faraday's time: Charges produce electric fields, and charges in electric fields experience electric forces. Moving charges produce magnetic fields, and moving charges in magnetic fields experience magnetic forces. Ørsted and Ampère's discoveries had established a link between electricity and magnetism, in that moving *electric* charges produce *magnetic* fields. Faraday solidified the link between the two forces with the important discovery was that a *changing* magnetic field produces an electric field!

Without going into too much detail, this phenomenon can be demonstrated as follows: imagine a wire loop attached to an ammeter, a device for measuring electric current. As we bring a magnet towards the wire loop, we find that a current arises in the loop, but this current appears only while the magnet is moving. The electric field which creates this current is directly related to the rate of change of the magnetic field flowing through it. Formally, we may state Faraday's law as:

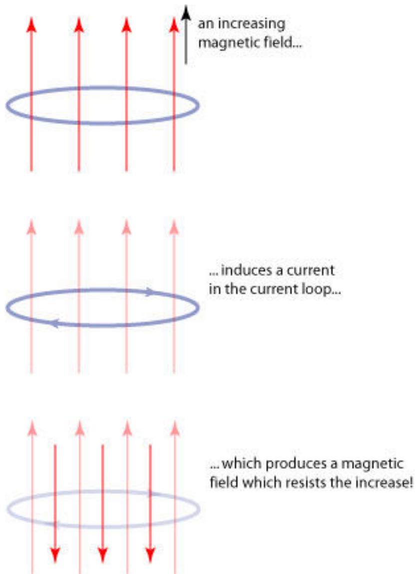
> *The induced electromotive force or EMF in any closed circuit is equal to the time rate of change of the magnetic flux through the circuit.*

Current appears only when the number of magnetic field lines (the 'magnetic flux') passing through the loop is *changing*. This is illustrated below:

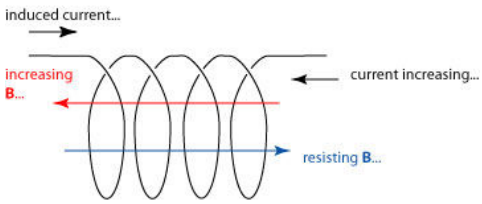


A circulating electric field is produced while the magnetic field is growing or shrinking. It is important to note that the electric field does not depend at all on the overall strength of the magnetic field, or its direction; it only depends on how fast, and in what way, the magnetic field is changing.

It is important to note the direction of the induced electric field. As we have seen from Ampère's discovery, a current loop produces a magnetic field. From the picture above, we can determine that the induced electric field produces a magnetic field which *resists* the original changing field:



Faraday's law is the basis for one of the fundamental electrical components, the [inductor](), which in its simplest form is a helical coil of wire. When the amount of current running through the wire is changed, this changes the magnetic field running through the center of the helix. In turn, a counter-current is produced by Faraday's law which resists the original change:



In essence, an inductor resists changes to the current flowing through it.

Now let us turn to Faraday's discovery of his eponymous effect, which was reported upon in the *Philosophical Transactions of the Royal Society of London*, vol. 122 (1832), 125-162. The entire paper is striking for its clarity and detail, and begins with the reasoning which led his investigations*:

> *The power which electricity of tension possesses of causing an opposite electrical state in its vicinity has been expressed by the general term Induction; which, as it has been received into*

scientific language, may also, with propriety, be used in the same general sense to express the power which electrical currents may possess of inducing any particular state upon matter in their immediate neighbourhood, otherwise indifferent. It is with this meaning that I purpose using it in the present paper.

Certain effect of the induction of electrical currents have already been recognised and described: as those of magnetization; Ampere's experiments of bringing a copper disc near to a flat spiral; his repetition with electromagnets of Arago's extraordinary experiments, and perhaps a few others. Still it appeared unlikely that these could be all the effects induction by currents could produce; especially as, upon dispensing with iron, almost the whole of them disappear, whilst yet an infinity of bodies, exhibiting definite phenomena of induction with electricity of tension, still remain to be acted upon by the induction of of electricity in motion.

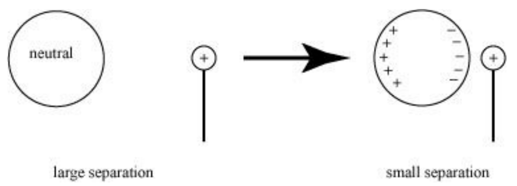
Further: Whether Ampere's beautiful theory were adopted, or any other, or whatever reservation were mentally made, still it appeared very extraordinary, that as every electric current was accompanied by a corresponding intensity of magnetic action at right angles to the current, good conductors of electricity, when placed within the sphere of this action, should not have any current induced through them, or some sensible effect produced equivalent in force to such a current.

These considerations, with their consequence, the hope of obtaining electricity from ordinary magnetism, have stimulated me at various times to investigate experimentally the inductive effect of electric currents. I lately arrived at positive results; and not only had my hopes fulfilled, but obtained a key which appeared to me to open out a full explanation of Arago's magnetic phenomena, and also to discover a new state, which may probably have great influence in some of the most important effects of electric currents.

These results I purpose describing, not as they were obtained, but in such a manner as to give the most concise view of the whole.

There's a lot of information in this introduction, and we will return to some of the details (such as Arago's magnetic phenomena) later. Several things are worth pointing out right away.

First, Faraday was motivated to perform his research by the phenomenon of electric induction. When a positively-charged object is brought close to an electrically neutral object, the positive charges in the neutral object are repelled, and the negative charges attracted. The details of this process depend on the material, but the net result is that the neutral object has had electrical charges 'induced' within it:

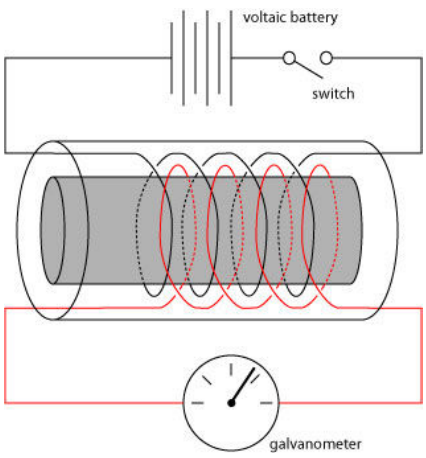


Faraday seems to have followed the following reasoning: 1. Electric charges can induce charge separation in other objects through their electric fields. 2. Magnetic fields are produced by moving electric charges. 3. By analogy, might not an electric current therefore induce an electric current in a nearby wire through its magnetic field? This is a wonderful bit of physical intuition; Faraday clearly saw a strong analogy between the behavior of electricity and magnetism, though the connection turns out to go farther than he initially imagined.

To maximize any possible effect, Faraday wanted to have two very long wires placed very close to one another. By what seems to be a happy coincidence, Faraday used overlapping helicoids:

> *Almost twenty-six feet of copper wire one twentieth of an inch in diameter were wound round a cylinder of wood as a helix, the different spires of which were prevented from touching by a thin interposed twine. This helix was covered with calico, and then a second wire applied in the same manner. In this way twelve helices were superposed, each containing an average length of wire of twenty-seven feet, and all in the same direction. The first, third, fifth, seventh, ninth, and eleventh of these helices were connected at their extremities end to end, so as to form one helix; the others were connected in a similar manner; and thus two principal helices were produced, closely interposed, having the same direction, not touching anywhere, and each containing one hundred and fifty-five feet in length of wire.*
>
> *One of these helices was connected with a galvanometer, the other with a voltaic battery of ten pairs of plates four inches square, with double coppers and well charged; yet not the slightest sensible deflection of the galvanometer needle could be observed.*

A galvanometer is a current measuring device which features a needle deflected by the magnetic field created by the current flowing through the device. A simplified version of Faraday's experiment is shown below (neglecting the multiple interconnected helices):



By sending a current through one helix (the black one), Faraday hoped to induce a detectable current through the other (the red one), which he could detect via the galvanometer. His results were not exactly what he expected, however:

> *When the contact was made, there was a sudden and very slight effect at the galvanometer, and there was also a similar slight effect when the contact with the battery was broken. But whilst the voltaic current was continuing to pass through the one helix, no galvanometrical appearances of any effect like induction upon the other helix could be perceived, although the active power of the battery was proved to be great, by its heating the whole of its own helix, and by the brilliancy of the discharge when made through charcoal.*
>
> *Repetition of the experiments with a battery of one hundred and twenty pairs of plates produced no other effects; but it was ascertained, both at this and at the former time, that the slight deflection of the needle occurring at the moment of completing the connexion, was always in one direction, and that the equally slight deflection produced when the contact was broken was in the other direction; and also, that these effects occurred when the first helices were used.*

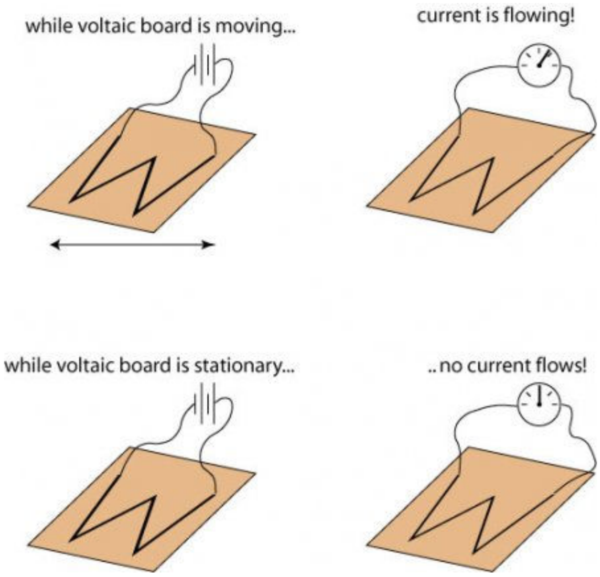
This is the first historical description of Faraday induction! The use of a helical configuration was convenient, because it maximized the amount of magnetic flux passing through the electrical circuit and hence the amount of current induced. His initial statements already encapsulate almost every statement of import about Faraday induction. Induction only occurs when the current is switched on or off (i.e. when the magnetic field produced by that current is changing). Also, induction goes one way for *increasing* current, and the opposite way for *decreasing* current.

Faraday further confirmed the presence of an induced current by replacing the galvanometer with another helix. If current was flowing through this helix, it would produce a magnetic field, which could in principle magnetize a steel needle placed within. He found that, if he placed the needle, turned on the system, and removed the needle before turning it off, the needle would be slightly magnetized. If he instead turned the system on and off before removing the needle, "it exhibited little or no magnetism; the first effect having been nearly neutralized by the second." This is also readily understandable: the magnetic fields produced when the system is turned on and off are in opposite directions, and their magnetizing influence will tend to cancel.

Faraday was extremely thorough; the small effect he was observing might still have been due to some quirk of the experimental setup, in particular some sort of discharge related to turning on the switch. He therefore produced the effect by a quite different technique, which allowed the current to continually flow:

> *In the preceding experiments the wires were placed near to each other, and the contact of the inducing one with the battery made when the inductive effect was required; but as some particular action might be supposed to be exerted at the moments of making and breaking contact, the induction was produced in another way. Several feet of copper wire were stretched in wide zigzag forms, representing the letter W, on one surface of a broad board; a second wire was stretched in precisely similar forms on a second board, so that when brought near the first, the wires should everywhere touch, except that a sheet of thick paper was interposed. One of these wires was connected with the galvanometer, and the other with a voltaic battery. The first wire was then moved towards the second, and as it approached, the needle was deflected. Being then removed, the needle was deflected in the opposite direction. By first making the wires approach and then recede, simultaneously with the vibrations of the needle, the latter soon became very extensive; but when the wires ceased to move from or towards each other, the galvanometer needle soon came to its usual position.*
>
> *As the wires approximated, the induced current was in the* contrary *direction to the inducing current. As the wires receded, the induced current was in the* same *direction as the inducing current. When the wires remained stationary, there was no induced current.*

The system was as shown schematically below:



There are two important observations to take from this new experiment. First, Faraday induction can be created by *moving* the inducing wire as well as by changing the current in the inducing wire. The strength of the magnetic field generated by the inducing wire varies with distance from the wire. Therefore, by moving the wire towards the 'induced' wire, the magnetic field flux at that wire is increased.

Second, Faraday notes that "the induced current was in the *contrary* direction to the inducing current." Though he has not yet formulated it as such, this is the first statement that suggests that the induced current is such that its magnetic field partially cancels any change in the magnetic field around it.

In Faraday's time, electricity and magnetism were still relatively unexplored topics. Faraday did not at first rule out that the galvanometer was being affected by means other than electricity, so he attempted to detect the presence of a current by alternative means, initially with little success:

> *I could obtain no evidence by the tongue, or spark, or by heating fine wire or charcoal, of the electricity passing through the wire under induction; neither could I obtain any chemical effects, though the contacts with metallic and other solutions were made and broken alternately with those of the battery, so that the second effect of induction should not oppose or neutralize the first.*

It was clearly a different era of science: most researchers these days would (I hope) hesitate to detect electrical discharges by sticking the wire to their tongue!

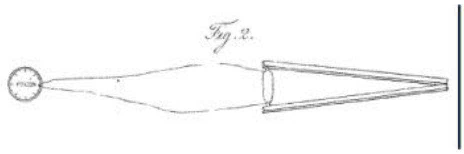
This monumental discovery covers only the first six pages of Faraday's 37 page report! The next section is just as important as the first, as it explicitly demonstrates the 'evolution of electricity from magnetism'. Though it was clear in Faraday's time that electrical current produced magnetism, it did not necessarily follow that the induction of electrical current already described was an effect arising from magnetism. Faraday produced another cylinder of helices such as described above, save for the fact that the inner core was constructed of hollow pasteboard, allowing objects to be slid within. First, Faraday demonstrated that the previously described effects held true for his new cylinder. Then he introduced a cylinder of soft iron into the middle of the helix. We let his own words speak for themselves on the next step:

> *Similar effects were then produced by ordinary magnets: thus the hollow helix just described had all its elementary helices connected with the galvanometer by two copper wires, each five feet in length; the soft iron cylinder was introduced into its axis; a couple of bar magnets, each twenty-*

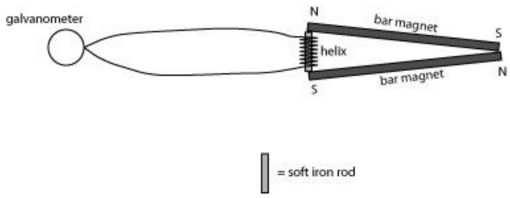
four inches long, were arranged with their opposite poles at one end in contact, so as to resemble a horse-shoe magnet, and then contact made between the other poles and the ends of the iron cylinder, so as to convert it for the time into a magnet: by breaking the magnetic contacts, or reversing them, the magnetism of the iron cylinder could be destroyed or reverse at pleasure.

Upon making magnetic contact, the needle was deflected; continuing the contact, the needle became indifferent, and resumed its first position; on breaking the contact, it was again deflected, but in the opposite direction to the first effect, and then it again became indifferent. When the magnetic contacts were reversed, the deflections were reversed.

Faraday's own figure depicting the setup is shown below:



This is a little hard to interpret, so let's reproduce it with labels:



When the bar magnets are touched to the iron rod, it is magnetized! This magnetization of the iron is an increase in magnetic flux, which results in a current appearing in the helix which partially counteracts this magnetization. When the bar magnets are removed, the magnetization was removed, and a current appears in the helix which partially counteracts this demagnetization.

The electrical induction in this case is done completely with magnets and no electrical currents. However, a 'circuit' must still be closed, in this case a magnetic circuit, and it is still possible that something unusual happens on closing the circuit. To this, Faraday tried the following variation:

But as it might be supposed that in all the preceding experiments of this section it was by some peculiar effect taking place during the formation of the magnet, and not by its mere virtual approximation, that the momentary induced current was excited, the following experiment was mlade. All the similar ends of the compound hollow helix were bound together by copper wire, forming two general terminations, and these were connected with the galvanometer. The soft iron cylinder was removed, and a cylindrical magnet, three quarters of an inch in diameter and eight inches and a half in length, used instead. One end of this magnet was introduced into the axis of the helix, and then, the galvanometer-needle being stationary, the magnet was suddenly thrust in; immediately the needle was deflected in the same direction as if the magnet had been formed by either of the two preceding processes. Being left in, the needle resumed its first position, and then the magnet being withdrawn the needle was deflected in the opposite direction. These effects were not great; but by introducing and withdrawing the magnet, so that the impulse each time should be added to those previously communicated to the needle, the latter could be made to vibrate through an arc of 180° or more.

In other words, a permanent magnet was shoved directly into the center of the helix. This also is effectively changing the amount of magnetic flux through the system, and resulted in an induced current while the magnet was in motion.

Various larger magnets were employed in place of the pair of bar magnets; it is interesting to note that powerful magnets were presumably hard to come by in that time:

> *The Royal Society are in possession of a large compound magnet formerly belonging to Dr. Gowin Knight, which, by permission of the President and Council, I was allowed to use in the prosecution of these experiments: it is at present in the charge of Mr. Christie, at his house at Woolwich, where, by Mr. Christie's kindness, I was at liberty to work; and I have to acknowledge my obligations to him for his assistance in all the experiments and observations made with it. This magnet is composed of about 450 bar magnets, each fifteen inches long, one inch wide, and half an inch thick, arranged in a box so as to present at one of its extremities two external poles. These poles projected horizontally six inches from the box, were each twelve inches high and three inches wide. They were nine inches apart; and when a soft iron cylinder, three quarters of an inch in diameter and twelve inches long, was put across from one to the other, it required a force of nearly one hundred pounds to break the contact.*

Initially, attempts to demonstrate electrical action other than with the galvanometer were not met with success; however,

> *But on repeating the experiments more at leisure at the Royal Institution, with an armed loadstone belonging to Professor Daniell and capable of lifting about thirty pounds, a frog was very powerfully convulsed each time magnetic contact was made. At first the convulsions could not be obtained on breaking magnetic contact; but conceiving the deficiency of effect was because of the comparative slowness of separation, the latter act was effected by a blow, and then the frog was convulsed strongly. The more instantaneous the union or disunion is effected, the more powerful the convulsion. I thought also I could perceive the sensation upon the tongue and the flash before the eyes; but I could obtain no evidence of chemical action.*

This use of frogs and chemicals was not solely for the purpose of 'doublechecking' the results. Researchers had not yet proven conclusively that static electricity, voltaic (chemical) electricity and 'animal electricity' were manifestations of the same phenomenon, as they seemed rather different in their details. Faraday himself would, in a later report, discuss his investigations of their identical origins.

It is worth noting that Faraday's work was not without some mistakes. In the third section of his paper, "New electrical state or condition of matter," he postulates that induction represents a new state of matter:

> *Whilst the wire is subject to either volta-electric or magneto-electric induction, it appears to be in a peculiar state; for it resists the formation of an electrical current in it, whereas, if in its common condition, such a current would be produced; and when left uninfluenced it has the power of originating a current, a power which the wire does not possess under common circumstances. This electrical condition of matter has not hitherto been recog- nised, but it probably exerts a very important influence in many if not most of the phenomena produced by currents of electricity. For reasons which will immediately appear, I have, after advising with several learned friends, ventured to designate it as the* electro-tonic *state.*

Faraday seems to have initially found the transient nature of the induced current as evidence of some sort of peculiar state of matter, and he spends many pages on it. However, his publication contains the following footnote at the beginning of the section:

> *This section having been read at the Royal Society and reported upon, and having also, in consequence of a letter from myself to M. Hachette, been noticed at the French Institute, I feel bound to let it stand as part of the paper; but later investigations of the laws governing these phenomena, induce me to think that the latter can be fully explained without admitting the electro-tonic state. My views on this point will appear in the second series of these researches.*

By the time of publication, he had already realized his ‘electro-tonic’ theory was wrong, but since it had been presented at conference, he included the discussion!

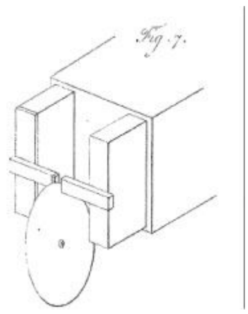
The last major portion of the paper concerns the application of Faraday’s discovery of induction to explain an unusual discovery that had previously been made by Arago:

> *If a plate of copper be revolved close to a magnetic needle, or magnet, suspended in such a way that the latter may rotate in a plane parallel to that of the former, the magnet tends to follow the motion of the plate; or if the magnet be revolved, the plate tends to follow its motion; and the effect is so powerful, that magnets or plates of many pounds weight may be thus carried round. If the magnet and plate be at rest relative to each other, not the slightest effect, attractive or repulsive, or of any kind, can be observed between them. This is the phenomenon discovered by M. Arago; and he states that the effect takes place not only with all metals, but with solids, liquids, and even gases, i.e. with all substances.*

In other words, if one hangs a magnetic needle above a copper disc, and both are unmoving, no force exists between them. If the plate is rotated, however, the needle tends to get ‘dragged’ along with it; conversely, if the needle is moved, the plate gets dragged along. Faraday notes,

> *Upon obtaining electricity from magnets by the means already described, I hoped to make the experiment of M. Arago a new source of electricity; and did not despair, by reference to terrestrial magneto-electric induction, of being able to construct a new electrical machine.*

Using the super-powerful permanent magnet of the Royal Society as before, Faraday prepared a copper disc so that its edge would spin between the magnetic poles:



A galvanometer was attached to the disc, and its response studied:

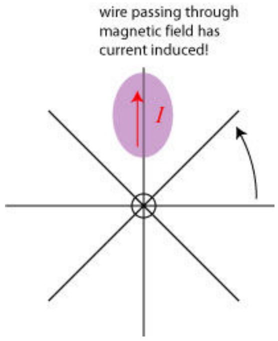
> *One of the galvanometer wires was passed twice or thrice loosely round the brass axis of the plate, and the other attached to a conductor, which itself was retained by the hand in contact with the amalgamated edge of the disc at the part immediately between the magnetic poles. Under these circumstances all was quiescent, and the galvanometer exhibited no effect. But the instant the plate moved, the galvanometer was influenced, and by revolving the plate quickly the needle could*

be deflected 90° or more.

In other words, when the disc is spun, an electrical current flows from the axis of the disc to the rim of the disc! This again is a current induced by a changing magnetic field:

> *The experiments described combine to prove that when a piece of metal (and the same may be true of all conducting matter) is passed either before a single pole, or between the opposite poles of a magnet, or near electromagnetic poles, whether ferruginous or not, electrical currents are produced across the metal transverse to the direction of motion; and which therefore, in Arago's experiments, will approximate towards the direction of radii. If a single wire be moved like the spoke of a wheel near a magnetic pole, a current of electricity is determined through it from one end towards the other. If a wheel be imagined, constructed of a great number of these radii, and this revolved near the pole, in the manner of the copper disc , each radius will have a current produced in it as it passes by the pole. If the radii be supposed to be in contact laterally, a copper disc results, in which the directions of the currents will be generally the same, being modified only by the coaction which can take place between the particles, now that they are in metallic contact.*

Basically, a copper disc can be considered a collection of wires, like the spokes of a wheel:



Each wire is passing through a changing magnetic field when it passes the poles of the magnet, and an electric field is therefore induced in the wire! A quantitative assessment of such problems are now regularly assigned in undergraduate electromagnetism courses.

This paper did not mark the complete body of Faraday's work on electrical induction. The experiments are described, and the generality of the effect (its presence in any situation where changing magnetic fields arise) is demonstrated, but the modern formulation of Faraday's law is not given. As noted, Faraday was apparently not much of a theorist, though his physical intuition was stunning, as can be seen from the work discussed here.

Before we conclude, we should note a couple of Faraday's footnotes which fall into the category of "The more things change, the more they stay the same." In particular, Faraday has to argue against misrepresentation of his work and argue for the primacy of his work! In the former case, he notes

> *The Lycée, No. 36, for January 1st, has a long and rather premature article, in which it endeavours to show anticipations by French philosophers of my researches. It however mistakes the erroneous results of Mr. Fresnel and Ampere for true ones, and then imagines my true results are like those erroneous ones. I notice it here, however, for the purpose of doing honour to Fresnel in a much higher degree than would have been merited by a feeble anticipation of the present investigations. That great philosopher, at the same time with myself and fifty other persons, made experiments which the present paper proves could give no expected result. He was deceived for the*

> *moment, and published his imaginary success; but on more carefully repeating his trials, he could find no proof of their accuracy; and, in the high and pure philosophic desire to remove error as well as discover truth, he recanted his first statement. The example of Berzelius regarding the first Thorina is another instance of this fine feeling; and as occasions are not rare, it would be to the dignity of science if such examples were more frequently followed.*

Apparently the French scientists attempted to show that Faraday's work had already been done by Fresnel and Ampere! Furthermore, Faraday notes at the end of his paper,

> *In consequence of the long period which has intervened between the reading and printing of the foregoing paper, accounts of the experiments have been dispersed, and, through a letter of my own to M. Hachette, have reached France and Italy. That letter was translated (with some errors), and read to the Academy of Sciences at Paris, 26th December, 1831. A copy of it in Le Temps of the 28th December quickly reached Signor Nobili, who, with Signor Antinori, immediately experimented upon the subject, and obtained many of the results mentioned in my letter; others they could not obtain or understand, because of the brevity of my account. These results by Signori Nobili and Antinori have been embodied in a paper dated 31st January 1832, and printed and published in the number of the Antologia dated November 1831, (according at least to the copy of the paper kindly sent me by Signor Nobili). It is evident the work could not have been then printed; and though Signor Nobili, in his paper, has inserted my letter as the text of his experiments, yet the circumstance of back date has caused many here, who have heard of Nobili's experiments by report only, to imagine his results were anterior to, instead of being dependent upon, mine.*

Here we see the familiar problem of reporting before publication: Faraday had discussed his experiments before publication, and others had (honestly) reproduced his work. However, many apparently thought that the later work by Nobili and Antinori was in fact the first! The history books have managed to get it straight and give Faraday the credit he deserves.

Faraday's discovery was one of the final breakthroughs that led Maxwell to formulate his famous system of equations, and be led from those equations to the interpretation of light as an electromagnetic wave! In fact, one can interpret Faraday's induced currents as the transmission of extremely low frequency electromagnetic waves. Faraday's law is also fundamental in the operation of many electrical generators, electric motors, and transformers.

This was a hard paper to discuss, because it is 37 pages and so filled with useful information that almost every page is worth quoting! Suffice to say that I've left out a lot of interesting experimental detail in the interest of sanity: Faraday was a *very* thorough fellow.

We'll come back and discuss a number of Faraday's other discoveries, which range from the practical to fundamental to the visionary!

Update: In a happy coincidence, I only now see that yesterday Jennifer at *Cocktail Party Physics* wrote a post about Faraday and his work! Check it out here.

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* Note: The original article has numbered paragraphs and numerous references to these paragraph numbers and also to figures. I have left out these numberings from the original text.