Skulls in the Stars
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Michael Faraday, grand unified theorist? (1851)

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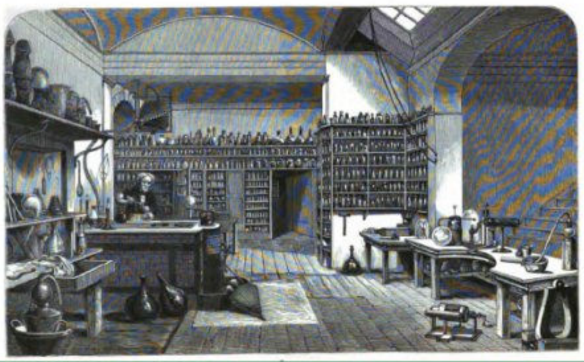
At long last, I get to blog about the paper that first piqued my interest about the research of Michael Faraday! If you haven't been following my Faraday posts, let me give a quick recap: Michael Faraday (1791-1867) was one of the greatest experimental physicists of all time, and the discoverer of some of the most important effects related to electricity and magnetism. I've blogged previously about his discovery of electromagnetic induction, his work in proving that all forms of electricity have the same common origin, and his demonstration of the relationship between light and magnetism (Faraday rotation). I haven't even had time to discuss Faraday's contributions in formulating the laws of electrolysis, understanding diamagnetism, and inventing the Faraday cage.

The common thread of many of these discoveries is their goal: demonstrating that all the physical forces of nature are but different manifestations of a single, 'universal' force. This idea was a surprisingly modern one for Faraday's time, and is known today as a unified field theory. Such research was likely on the minds of many researchers of that era, however: once Ørsted discovered that a magnetic compass needle could be deflected by an electric current, the notion that all forces might be related was a tantalizing dream. Faraday went further than any of his contemporaries in realizing that dream, and experimentally cemented the link between electricity and magnetism and light. Faraday was by no means done, however, and in 1851 he published the results of his attempts to demonstrate that electricity and *gravity* are related!

Though his results were negative, they are a fascinating piece of experimental work and provide some lessons for modern day theorists and experimentalists alike.



Faraday's laboratory at the Royal Institution, from *The Life and Letters of Faraday*, vol. 2.

Faraday's report on his experimental findings was presented to the Royal Society on August 1, 1850. Titled, "On the possible relation of gravity to electricity," it appeared in print in vol. 141 of the Philosophical Transactions (1851), pp. 1-6. He begins the paper by stating yet again his belief in a unifying principle:

> *The long and constant persuasion that all the forces of nature are mutually dependent, having one common origin, or rather being different manifestations of one fundamental power, has made me often think upon the possibility of establishing, by experiment, a connection between gravity and electricity, and so introducing the former into the group, the chain of which, including also magnetism, chemical force and heat, binds so many and such varied exhibitions of force together by common relations. Though the researches I have made with this object in view have produced*

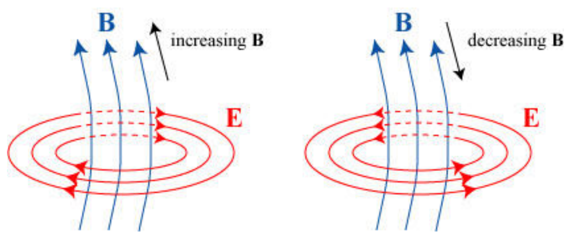
> *only negative results, yet I think a short statement of the matter, as it has presented itself to my mind, and of the result of the experiments, which offering at first much to encourage, were only reduced to their true value by most careful searchings after sources of error, may be useful, both as a general statement of the problem, and as awakening the minds of others to its consideration.*

It is one thing to believe in a link between two different physical phenomena; it is quite another thing entirely to implement a rigorous strategy for demonstrating that link! For instance, I have previously noted how a number of researchers had devised experiments suggesting a relationship between light and magnetism, but these early experiments were rough and inconclusive, and it was not until much later that Faraday found a way to systematically link them. Faraday muses in some detail about what a connection between gravity and electricity would look like:

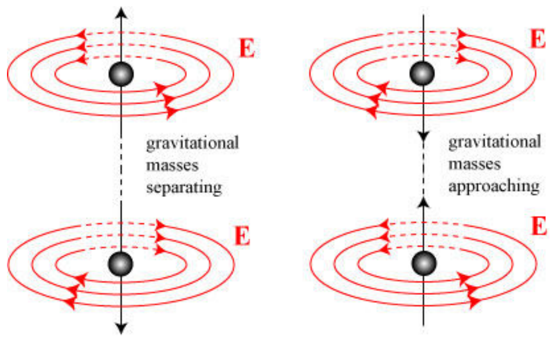
> *In searching for some principle on which an experimental inquiry after the identification or relation of the two forces could be founded, it seemed that if such a relation existed, there must be something in gravity which would correspond to the dual or antithetical nature of the forms of force in electricity and magnetism. To my mind it appeared possible that the ceding to the force or the approach of gravitating bodies on the one hand, and the effectual reversion of the force or separation of the bodies on the other, might present the points of correspondence; quiescence (as to motion) being the neutral condition. The final unchangeability of gravity did not seem affected by such an assumption; for the acting bodies when at rest would ever have the same relation to each other, and it would only be at the times of motion to and fro that any results related to electricity could be expected. Such results, if possible, could only be exceedingly small; but, if possible, i.e. if true, no terms could exaggerate the value of the relation they would establish.*

> *The thought on which the experiments were founded was, that, as two bodies moved towards each other by the force of gravity, currents of electricity might be developed either in them or in the surrounding matter in one direction; and that as they were by extra force moved from each other against the power of gravitation, the opposite currents might be produced. Also, that these currents would have relation to the line of approach and recession, and not to space generally, so that two bodies approaching would have currents in the opposite direction as to space generally, but the same as to the direction of their motion along the line joining them. It will be unnecessary to go further into the suppositions which arose concerning these points, or regarding the effect of forced motions either coinciding with, or across the direction of the earth's gravitation, and many other matters, than to say that, as the effect looked for was exceedingly small, so no hope was entertained of any result except by means of the gravitation of the earth. The earth was therefore made to be the one body, and the indicating mass of matter to be experimented with the other.*

Faraday seems to be drawing an analogy here to his monumental discovery of electromagnetic induction (which I discussed in detail here). In electromagnetic induction, a *changing* magnetic field **B** passing through a current loop induces a circulating electric field **E** in the current loop, as illustrated below:



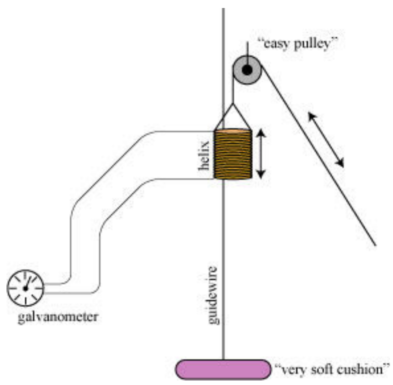
Faraday envisioned something similar for electric fields induced by gravitation:



I've drawn the hypothetical electrical field induced by gravity according to a 'right-hand rule': pointing the thumb in the direction of motion relative to the center of mass, the electric field would circulate in a direction following the curve of the fingers. Like electromagnetic induction, Faraday also naturally assumed that such an electric current would only persist while the objects were in motion towards/away from each other.

With this model of electrical-gravitational interaction, the next problem was to devise an experiment to detect the hypothetical gravitationally-induced currents. Faraday tried two different experiments, and we look at each of them in turn.

For the first experiment, Faraday twisted 350 feet of copper wire into a hollow cylindrical helix 4 inches long, with an internal diameter of 1 inch and an external diameter of 2 inches. This helix was attached to a line running along a pulley, allowing it to be raised 36 feet and dropped onto a "very soft cushion". Long wires connected the ends of the helix to a sensitive galvanometer, placed 50 feet away and level midway with the path of the helix. This is illustrated below:

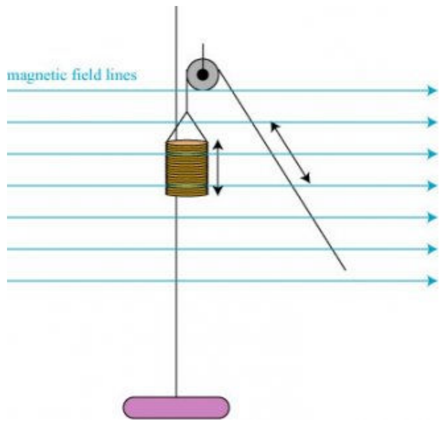


Faraday does not explicitly mention a guidewire, but it is reasonable to assume its presence is necessary to keep the helix falling with its axis vertical.

An immediate objection to this setup is a concern that ordinary electromagnetic induction could appear! Faraday considered this and addressed it in his experiment:

> *Such a helix, either in rising or falling, can produce no deviation at the galvanometer by any current due to the magnetism of the earth; for as it remains parallel to itself during the fall, so the lines of equal magnetic force, which being parallel to the dip, are intersected by the wire convolutions of the descending helix, are cut with an equal velocity on both sides of the helix, and consequently no effect of magneto-electric induction is produced.*

In other words, because the helix is falling perpendicular to the magnetic field lines, there is no net change in magnetic flux in the helix and no induced current:



Faraday showed his true mettle as an experimentalist in these experiments, not because they failed, but because at first they seemed to succeed:

> *A solid cylinder of copper, three-fourths of an inch in diameter and 7 inches in length, was now introduced into the helix and carefully fastened in it, being bound round with a cloth so as not to move, and this compound arrangement was allowed to fall as before. It gave very minute but remarkably regular indications of a current at the galvanometer; and the probability of these being related to gravity appeared the greater, when it was found that on raising the helix or core, similar indications of contrary currents appeared. It was some time before I was able to refer these currents to their true cause, but at last I traced them to the action of a part of the conducting wires proceeding from the helix to the galvanometer. The two wires had been regularly twisted together, but the effect of many falls had opened a part near the middle distance into a sort of loop, so that the wires, instead of being tightly twisted together like the strands of a rope, were separate for 3 feet, as if the strands were open. In falling, this loop opened out more or less, but always in the same manner; and the consequence was that the part of it representing the transverse opening, which was furthest from the galvanometer, travelled over a larger space than the corresponding part nearest the galvanometer. Now had they travelled through equal spaces, the effect of the magnetic lines of force of the earth upon them would have been equal, and no effect at the galvanometer would have been produced; as it was, currents in opposite directions , but of unequal amounts of force, tended to be produced, and a current equal to the difference actually appeared… Therefore no positive or favourable evidence was supplied in favour of the original assumption by this use of a copper core in the helix.*

Boiling down Faraday's prose into a brief summary: the wires stretching from the galvanometer to the helix, which had been twisted together, had separated. The two wires moved different distances as the helix fell, and therefore passed through different magnetic fields and had a net current induced.

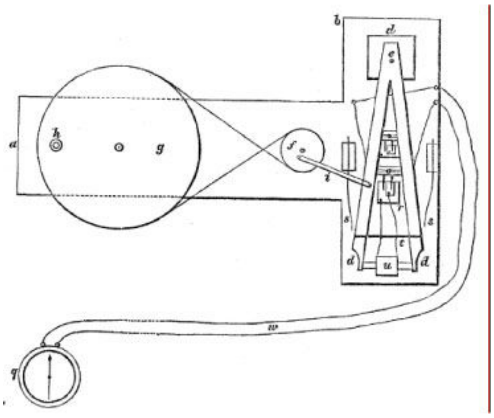
Faraday's response demonstrates the traits of a good experimentalist. He had determined experimental results that not only agreed exactly with his predictions, but fulfilled a life's dream of proving the identity of the physical forces! Psychologically, it would have been very easy, even tempting, to "go with it" and not doublecheck the experiment too closely.

With a negative result in his first experiment, Faraday thought again about his model of the gravity/electricity interaction:

> *On further consideration of the original assumption, namely, a relation between the forces, and of the effects that might be looked for consequent upon a condition of tension in and around the*

particles of the body, which, as we know, are at the same moment the residence of both gravitating and electric forces, and are subject to the gravitation of the earth, it seemed probable that the stopping of the up and down motion in the line of gravity would produce contrary effects to the coming on of the motion, and that, whether the stopping was sudden or gradual; also that a motion downward quicker than that which gravity could communicate, would give more effect than the gravity result by itself, and that a corresponding increase in the velocity upwards would be proportionally effectual. In such case a machine which could give a rapid alternating up and down motion, might be very useful in producing many minute units of inductive action in a small space and moderate time; for then, by proper commutators, the accelerated and retarded parts of each half-vibration could be separated and recombined into one consistent current, and this current could be sent through the galvanometer during the time its needle was swinging in one direction, and afterwards reversed for the time of a swing in the other direction; and so on alternately until the effect had become sensible, if any were produced by the assumed cause.

In analogy with electromagnetic induction, Faraday reasoned that the greatest effects are due to rapid *changes*, or *accelerations*, in the system, and designed an experiment to maximize those changes. Faraday's illustration of the machine for his second experiment is shown below:



A short description of this device is as follows. A wheel *g* is turned via handle *h*, which rocks the wooden lever *d*,*d*,*d* in oscillatory motion constrained by springs *s*. This motion moves a metal cylinder through the fixed helix *u*, and any current produced is converted to a single-direction current by the commutator *r*. Finally, the current is registered at galvanometer *q*. In this system, currents could be produced by induction by the earth's magnetic field; Faraday canceled this effect by using magnets to negate the earth's field. In this configuration,

However rapidly the machine was worked, or whatever the position of the commutator, there was no result at the galvanometer. Cylinders of bismuth, glass, sulphur, gutta percha, &c., were also employed, but with the same negative conclusion.

Surprisingly, a slight change in the system again produced seemingly positive results.

Then the helix was taken from its fixed support and fastened on to the copper cylinder so as to move with it, and now very regular and comparatively large effects were produced. After a while, however, these were traced to causes other than gravity, and of the following kind. The helix was fixed at one end of a lever, at a point 22 inches from its axis, and being 2 inches in diameter its wires on one side were only 21 inches, and on the other side 23 inches from this axis. Hence, in vibrating these parts travelled with velocities and through spaces which are as 21:23. When therefore their paths were across the lines of magnetic force of the earth, electro-currents tended to

> *form in these different parts proportionate in amount or strength to these numbers…*

In short, the wires were connected to the different ends of the helix in an asymmetric way, which allowed electromagnetic induction to occur in the earth's magnetic field.

In spite of these results, Faraday remained a believer in a unified theory:

> *Here end my trials for the present. The results are negative. They do not shake my strong feeling of the existence of a relation between gravity and electricity, though they give no proof that such a relation exists.*

Faraday's was simply too far ahead of his time, both experimentally and theoretically. A proper unification of electricity and magnetism alone would not be accomplished until nearly a decade later when Maxwell formulated his electromagnetic wave theory of light. The next major scientist to attempt to develop a unified theory of forces would be Einstein in the 1950s, a hundred years later. However, he would also be limited by an incomplete picture of nature: the strong and weak nuclear forces were still poorly understood at the time of Einstein's research.

There's a bit of a lesson, and a cautionary tale, in this history for modern scientists looking for a 'theory of everything.' Though great strides have been made in understanding the fundamental forces of nature, researchers should always be open to the possibility that there may be pieces missing from the puzzle, such as extremely weak fundamental forces which have not yet been detected. Such hypothetical missing pieces could be a barrier to finding a grand unified theory, as they were for Faraday and Einstein. However, I should say that by no means am I implying that we shouldn't try!

Faraday first wrote about his suspicions concerning gravity in his laboratory notebook on March 19, 1849. He spelled out his thoughts on the experiments in a series of paragraphs, and then concluded with the lovely statement:

> *ALL THIS IS A DREAM. Still examine it by a few experiments. Nothing is too wonderful to be true, if it be consistent with the laws of nature; and in such things as these, experiment is the best test of such consistency.*

I suspect that Faraday would have been delighted to see how far scientists have come in making his dream a reality! Electromagnetism was unified by Maxwell in the 1860s, and in the 1960s, the electromagnetic and weak nuclear forces were unified in so-called electroweak theory. Numerous researchers are attempting to bring gravity and the strong nuclear force together as well. Success will be the culmination of theories and hopes that stretch back over at least 150 years, to an aging scientist alone in his lab, dropping helices from the ceiling.

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