Skulls in the Stars
The intersection of physics, optics, history and pulp fiction

Faraday brings light and magnetism together (1845)

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The more I read of Michael Faraday's work, the more I am in awe of the scientist's insights and abilities. As evidence of the remarkable intuition he had regarding the forces of nature, consider the following passage:

> *I have long held an opinion, almost amounting to conviction, in common I believe with many others of natural knowledge, that the various forms under which the forces of matter are made manifest have one common origin; or, in other words, are so directly and mutually dependent, that they are convertible, as it were, one into another, and possess equivalents of power in their action. In modern times the proofs of their convertibility have been accumulated to a very considerable extent, and a commencement made of the determination of their equivalent forces.*

Faraday wrote this as the introduction to the nineteenth series of his "Experimental Researches in Electricity," published in the *Philosophical Transactions* (vol 136, pp. 1-20) in 1846! It is an eloquent and remarkably timeless statement which could very well have been written by any modern physicist working on the foundations of a grand unified theory of forces.

As he himself notes in the passage above, Faraday was not alone in envisioning a single theory encompassing all physical phenomena. Indeed, once Ørsted discovered that a magnetic compass needle could be deflected by an electric current, the relationship of electricity and magnetism, as well as other forces, was very much on the minds of physicists. Faraday, however, led the charge in actually demonstrating these relations. As I have noted in previous blog posts, Faraday demonstrated experimentally that magnets could induce electric currents (Faraday induction) around 1831, and also compiled evidence demonstrating that the diverse sources of electricity were different manifestations of the same electrical phenomena around 1833.

Because of these discoveries (and other hugely important ones that I haven't had time yet to discuss), by 1845 Faraday was one of the most prestigious and famous scientists in England. He was by no means done with his research, however, and in that year he presented a paper describing his observations that a magnetic field can indirectly influence the behavior of a light wave. This was the first definitive evidence that light and electromagnetism are related, and helped pave the way for Maxwell's brilliant theoretical demonstration of the existence of electromagnetic waves, and their identity with light.

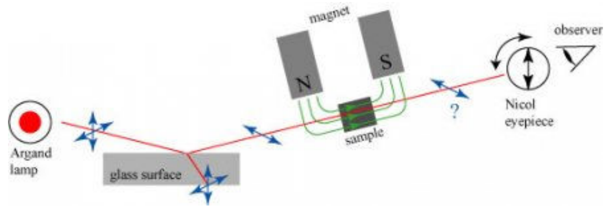
The effect that Faraday observed is now known as *Faraday rotation*, and we take a look at the experiments, and their reception, in this post.

Faraday rotation is actually a rather subtle effect, and quite tricky to explain; we'll start this post by looking at it through the experiments of Faraday, and then end the post with a physical explanation. Faraday describes his experimental setup as follows:

> *A ray of light issuing from an Argand lamp, was polarized in a horizontal plane by reflection from a surface of glass, and the polarized ray passed through a Nichol's eye-piece revolving on a horizontal axis, so as to be easily examined by the latter. Between the polarizing mirror and the eye-piece, two powerful electro-magnetic poles were arranged, being either the poles of a horse-shoe magnet, or the contrary poles of two cylinder magnets; they were separated from each other about two inches in the direction of the line of the ray, and so placed, that, if on the same side of the*

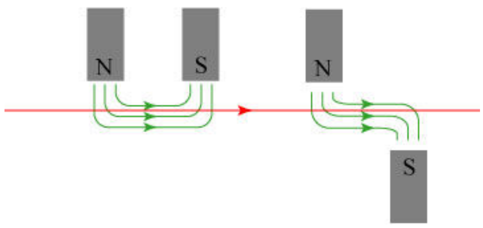
polarized ray, it might pass near them; or, if on contrary sides, it might go between them, its direction being always parallel, or nearly so, to the magnetic lines of force. After that, any transparent substance placed between the two poles, would have passing through it, both the polarized ray and the magnetic lines of force at the same time and in the same direction.

Unlike in many of his earlier papers, Faraday does not provide a detailed figure of this experimental setup. The description is clear enough, though, to roughly sketch out:



An Argand lamp, the standard oil lamp of the day, was used as a light source. The light produced by this lamp (and, indeed, all ordinary light sources) is unpolarized, i.e. a random mixture of light with electric field oscillating horizontally and vertically, drawn as the crossed blue lines. (For a basic explanation of polarization, see my 'optics basics' post on the subject.) The light is reflected from the glass surface at Brewster's angle, a special angle of incidence at which the vertically polarized light is perfectly transmitted into the glass. The light which is reflected is therefore now completely polarized in the horizontal plane. The polarized light passes through a material sample subject to a magnetic field produced by an electromagnet, and then enters a Nicol eyepiece (curiously misspelled 'Nichol' by Faraday). This eyepiece is based on the Nicol prism, which transmits light of only one polarization. When the eyepiece is aligned parallel to the direction of polarization, one observes a maximum brightness, and when the eyepiece is aligned perpendicular to the direction of polarization, one observes a minimum.

The real 'meat' of the experiment is the material sample subject to the magnetic field. Faraday determined that he could only observe an effect when the magnetic field lines were aligned parallel to the direction of the light ray. Being extremely thorough, Faraday considered two different arrangements for the magnets, which both satisfy this condition:

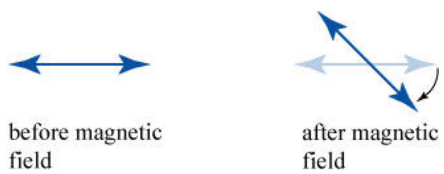


Faraday first used as a sample an optical glass, silicated borate of lead. We let him tell the story of his discovery from there:

A piece of this glass, about two inches square and 0.5 of an inch thick, having flat and polished edges, was placed as a diamagnetic between the poles (not as yet magnetized by the electric current), so that the polarized ray shouuld pass through its length; the glass acted as air, water, or any other indifferent substance would do; and if the eye-piece were previously turned into such a position that the polarized ray was extinguished, or rather the image produced by it rendered invisible, then the introduction of this glass made no alteration in that respect. In this state of circumstances the force of the electro-magnet was developed, by sending an electric current through its coils, and immediately the image of the lamp-flame became visible, and continued so

> *long as the arrangement continued magnetic. On stopping the electric current, and so causing the magnetic force to cease, the light instantly disappeared; these phenomena could be renewed at pleasure, at any instant of time, and upon any occasion, showing a perfect dependence of cause and effect.*
>
> …
>
> *The character of the force thus impressed upon the diamagnetic is that of rotation; for when the image of the lamp-flame has thus been rendered visible, revolution of the eye-piece to the right or left, more or less, will cause its extinction; and the further motion of the eye-piece to the one side or other of this position will produce the reappearance of the light, and that with complementary tints, according as this further motion is to the right- or left-hand.*
>
> *When the pole nearest to the observer was a marked pole, i.e. the same as the north end of a magnetic needle, and the further pole was unmarked, the rotation of the ray was right-handed; for the eye-piece had to be turned to the right-hand, or clock fashion, to overtake the ray and restore the image to its first condition. When the poles were reversed, which was instantly done by changing the direction of the electric current, the rotation was changed also and became left-handed, the alteration being to an equal degree in extent as before. The direction was always the same for the same line of magnetic force.*

In short, the eye-piece was turned so that no polarized light passed through it. When the magnet was turned on, suddenly light began to pass through the eye-piece again! The only explanation which matched the experimental results is that the action of the magnet/material rotated the direction of polarization! This is illustrated crudely below. Assuming the ray of light is coming towards you (out of the computer monitor), and that the magnetic field lines are pointing in the *opposite* direction, the 'before' and 'after' pictures of what you would see as the magnetic field is turned on are as follows:



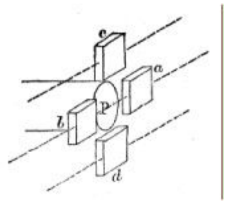
It is worth noting how thorough Faraday was in proving that he had not only a real, but near-universal, effect. Not only an electro-magnet was used, but an ordinary horseshoe magnet was also brought near the optical system, and

> *The results were feeble, but still sufficient to show the perfect identity of action between electro-magnets and common magnets in their power over light.*

Different configurations of magnets were used:

> *Two magnetic poles were employed end-ways, i.e. the cores of the electro-magnets were hollow iron cylinders, and the ray of polarized light passed along their axes and through the diamagnetic placed between them: the effect was the same.*

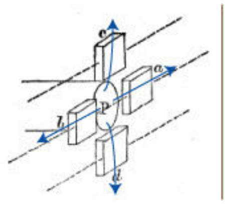
Furthermore, Faraday employed a single magnetic pole, and evaluated how the effect depended on the relative orientation of the pole and the glass. Faraday's illustration of this is shown below:



Faraday notes:

> *When the heavy glass was beyond the magnet, being close to it but between the magnet and the polarizing reflector, the rotation was in one direction, dependent on the nature of the pole; when the diamagnetic was on the near side, being close to it but between it and the eye, the rotation for the same pole was in the contrary direction to what it was before; and when the magnetic pole was changed, both these directions were changed with it. When the heavy glass was placed in a corresponding position to the pole, but above or below it, so that the magnetic curves were no longer passing through the glass parallel to the ray of polarized light, but rather perpendicular to it, then no effect was produced. These peculiarities may be understood by reference to Fig. 1, where* a *and* b *represent the first positions of the diamagnetic, and* c *and* d *the latter positions, the course of the ray being marked by the dotted line.*

This demonstration summarizes nicely the relationship between Faraday rotation and the orientation of the magnetic field. We add to Faraday's figure a sketch of the magnetic lines emanating from the pole in blue:



Assuming the rays are coming from the left, in *a* the ray and the magnetic field are parallel, in *b* the ray and the magnetic field are antiparallel, producing the opposite rotation as *a*, and in *c* and *d* the ray and the field are perpendicular, producing no effect.

Faraday summarized the entire effect as follows:

> *Magnetic lines, then, in passing through silicated borate of lead, and a great number of other substances, cause these bodies to act upon a polarized ray of light when the lines are parallel to the ray, or in proportion as they are parallel to it: if they are perpendicular to the ray, they have no action upon it. They give the diamagnetic the power of rotating the ray; and the law of this action on light is, that if a magnetic line of force be going from a north pole, or coming from a south pole, along the path of a polarized ray coming to the observer, it will rotate that ray to the right-hand; or, that if such a line of force be coming from a north pole, or going from a south pole, it will rotate such a ray to the left hand.*

Faraday wasn't kidding when he referred to a 'great number of other substances'; in addition to a variety of solids, he did numerous liquids:

> *Of aqueous solutions I tried* 150 or more*, including the soluble acids, alkalies and salts, with sugar, gum &c., the list of which would be too long to give here…*

Emphasis mine! That's a lot of liquids to test. If that's what is required to be a good experimentalist, I now understand why I was drawn to theory!

This observation of Faraday rotation had profound implications. Faraday himself stated:

> *Thus is established, I think for the first time, a true, direct relation and dependence between light and the magnetic and electric forces; and thus a great addition made to the facts and considerations which tend to prove that all natural forces are tied together, and have one common origin. It is, no doubt, difficult in the present state of our knowledge to express our expectation in exact terms; and, though I have said that another of the powers of nature is, in these experiments, directly related to the rest, I ought, perhaps, rather to say that another form of the great power is distinctly and directly related to the other forms; or, that the great power manifested by particular phenomena in particular forms, is here further identified and recognized, by the direct relation of its form of light to its forms of electricity and magnetism.*

As I noted in a previous post, and Faraday acknowledged in his paper, a number of researchers had previously developed curious experimental observations seemingly relating magnetism to light, but those early results were very non-rigorous and unreliably repeatable. Faraday demonstrated a definite effect which could be quantified and repeated consistently.

On November 8th, 1845, a brief notice appeared in the magazine the 'Athenaeum',which effectively exposed Faraday's result to the world (from The Life and Letters of Faraday, vol. 2, 1870):

> *Mr. Faraday, on Monday (November 3), announced at a meeting of the council of the Royal Institution a very remarkable discovery, which appears to connect the imponderable agencies yet closer together, if it does not indeed prove that light, heat and electricity are merely modifications of one great universal principle.*

This tantalizingly brief announcement really captured the attention of friends and acquaintences of Faraday, who immediately began writing for more information! From Dr. Whewell to Faraday, November 20, 1845:

> *My dear Sir, — I am somewhat scrupulous about trying to take up your time with letter writing, but I cannot help wishing to know a little more than the "Athenaeum" tells us as to your recent discoveries of the relations of light and magnetism. I cannot help believing that it is another great stride up the ladder of generalisation, on which you have been climbing so high and standing so firm…*

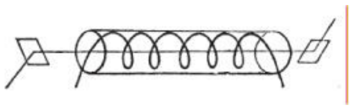
From Mrs. Marcet to Faraday, November 24, 1845:

> *Dear Mr. Faraday, — I have this morning read in the "Athenaeum," some account of a discovery you announce to the public respecting the identity of the imponderable agents, heat, light and electricity; and as I am at this moment correcting the sheets of my "Conversations on Chemistry" for a new edition, might I take the liberty of begging you would inform me where I could obtain a correct account of this discovery. It is, I fear, of too abstruse a nature to be adapted to my young pupils; yet I cannot make up my mind to publish a new edition without making mention of it; I have, therefore, kept back the proof sheets of the 'Conversation on Electricity,' which I was this morning revising, until I receive your answer, in hopes of being able to introduce it in that sheet.*

Most fascinating, and illustrative, is the letter of Sir John Herschel, a prominent astronomer of the time:

> *My dear Sir, — I have this morning read with great delight a notice in the "Athenaeum" of your experiments proving the connection of light with magnetism.*
>
> …
>
> *Therefore, induction led me to conclude that a similar connection exists, and must turn up somehow or other, between the electric current and polarised light, and that the plane of polarisation would be deflected by magneto-electricity.*
>
> *It is now a great many years ago that I tried to bring this to the test of experiment (I think it was between 1822 and 1825), when, on the occasion of a great magnetic display by Mr. Pepys, at the London Institution, I came prepared with a copper helix in an earthern tube (as a non-conductor), and a pair of black glass plates, so arranged as that the second reflection should extinguish a ray polarised by the first. After traversing the axis of the copper helix, I expected to see light take the place of darkness — perhaps coloured bands — when contact was made. The effect was nil. But the battery was exhausted, and the wire long and not thick, and it was doubtful whether the full charge remaining in the battery did pass, being only a single couple of large plates.*

Herschel's drawing of his experiment is shown below:



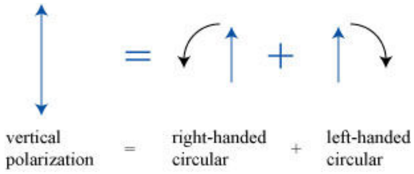
The coiled wire will produce a magnetic field running along the axis parallel to the ray of light, and the prisms act as polarizers. Herschel's experiment is very much a crude version of Faraday's, except that it is missing the crucial ingredient of a material for the light to pass through! Had Herschel developed his experimental apparatus further, it is reasonable to think we might be referring to 'Herschel rotation' instead of 'Faraday rotation'.

This is a good illustration that science is more of a process undertaken by a community, and not just the work of a few geniuses working in isolation. Though Faraday was undoubtedly a gifted genius, the time was right for *someone* to investigate and discover a relationship between light and magnetism, as the example of Herschel highlights.

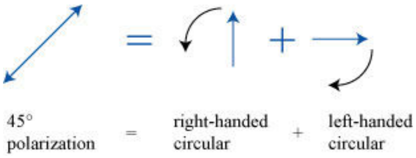
Faraday's discovery of Faraday rotation was an important stepping-stone to the discovery that light is an electromagnetic wave, as first proposed by James Clerk Maxwell in 1865. Maxwell was well aware of Faraday's results, as was the entire scientific community!

So what is Faraday rotation? It is, in fact, a rather complicated interaction by which the magnetic field affects the motion of electrons in a material. The material in turn responds in an unusual way to polarized light, resulting in a net rotation of the polarization. Even a simple calculation riddled with approximations takes some work (another post, perhaps), so we'll try and give a hand-waving description.

First, we note that a linear state of polarization, where the electric field oscillates along a single line perpendicular to the plane of polarization, can always be written as the sum of two circularly polarized fields. For instance, a vertically polarized field can be written as two circularly polarized fields, where the electric fields both start at twelve o'clock and rotate in opposite directions around the clock:

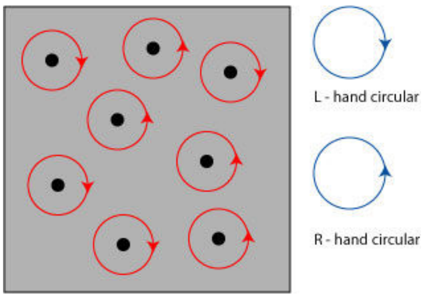


As long as the fields rotate at the same speed, their horizontal components, pointing in opposite directions, cancel and only the vertical component remains. What happens if the right-handed circular field starts at twelve while the left-handed circular starts at three o'clock? Then the field is polarized at 45 degrees to the vertical:



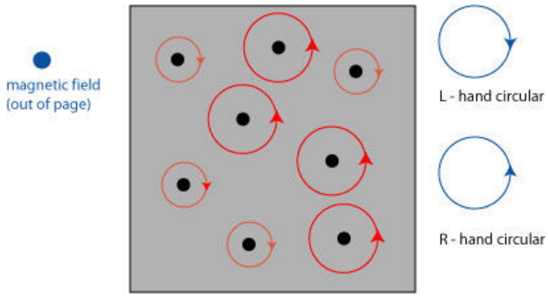
Supposing we start with vertical polarization, if one of the circular waves travels faster than the other, it will also rotate faster and the result is a rotation of the linear polarization.

What can cause one types of circular polarization to travel faster than another? Let's pretend our material (the glass Faraday used, for instance) consists of a collection of atoms with electrons orbiting in a plane transverse to the direction of a light ray. We would expect that half of the electrons are moving clockwise, i.e. in the same direction as left-handed circular light, while half of the electrons are moving counter-clockwise. Imagining that we are looking at the ray of light at the output of the experiment, we might draw a crude, crude picture as follows:



In this simple model, we can imagine that the circularly polarized waves interact mostly with those atoms spinning in the same direction as they are. Since there are the same number of atoms of both types, however, the net effect is that both circular polarizations have the same number of interactions and travel at the same speed.

Now we turn on a magnetic field along the direction of a light ray. The result of the magnetic field is to increase the speed of electrons orbiting one direction, and decrease the speed of electrons orbiting in the other direction. Now there is a fundamental asymmetry introduced into the system: left-handed polarization and right-handed polarization see electrons orbiting at different speeds, and in turn the different polarization states of light travel at different speeds in the medium. The net effect, as we have said, is that linearly polarized light is rotated as it travels in the medium:



This is a very crude picture, which oversimplifies the behavior of matter, ignores quantum effects, and is a cartoon depiction of the interaction of light and matter! Nevertheless, it is a crude way of understanding the origins of Faraday rotation without doing a lot of math.

The Faraday effect is of some significance in astronomy, as light and radio waves traveling over interstellar distances are subject to Faraday rotation on interaction with free electrons. It has also caused its share of controversy: over a decade ago, a statistical analysis suggested that an additional rotation of light occurred depending on the part of the galaxy from which radio waves traveled, which was suggested to be evidence of a fundamental anisotropy of the universe! The analysis, which took data from many astronomical measurements over numerous years, was widely criticized and is now generally considered to be inaccurate.

Faraday's discovery is used in several practical devices such as the optical isolator, which allows light propagation in only one direction, and the Faraday rotator, which rotates the polarization direction of light. From a physical point of view, Faraday's observation was a major step in the discovery of electromagnetic waves, and remarkable for "a labourer of many years' standing, made daily to feel my wearing out."

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Uncle Al *says:*
March 2, 2009 at 1:00 pm