Chapter 11

Faraday's Lines of Force

Modern Physics Begins

Michael Faraday, by Thomas Phillips, *circa*1841.

Michael Faraday, 1791-1867

““The [natural] philosopher should be a man willing to listen to every suggestion, but determined to judge for himself. He should not be biased by appearances; have no favourite hypothesis; be of no school; and in doctrine have no master. He should not be a respecter of persons, but of things. Truth should be his primary object. If to these qualities be added industry, he may indeed hope to walk within the veil of the temple of nature. “” *Fifth Lecture to the City Philosophical Society, 1816.*

His story is almost out of Charles Dickens ...with whom he became friendly as an adult. While he was not exactly like Pip, Michael Faraday's story is a warm, threadbare-to-success tale. There will never be another Faraday. Single-handedly he linked electricity with magnetism, and back again. He essentially invented the field of electro-chemistry, the motor, the generator, and created the basis of numerous industrial processes. All because he was inquisitive.

11.0.1 Goals of this chapter:

- Understand:
  - Faraday's Law of Induction
  - Lines of Force (see the Diagrammatica chapter following)
  - Importance of the Ether
- Appreciate:
  - The general idea of a motor
  - The general idea of a generator
- Be familiar with:
  - Faraday's life


Figure 11.1: Young Michael Faraday

11.1 A Little Bit of Faraday

Faraday grew up in an exceedingly poor family in suburban London at the beginning of the Industrial Revolution. His blacksmith father moved the Faraday family to the city to try to find work and as a result, Michael and his three siblings had little formal education. But his luck was stunning and his enterprise was impressive. He was apprenticed at the age of 14 to a generous bookbinder and encouraged to read many of the books that he worked on. He found himself infatuated with chemistry texts, which were all the rage and was even permitted a little chemical lab in the book shop. By the time he was in his late teens, he was beginning to attend public educational events in the city and in 1812 a customer who was a member of the Royal Institution presented him with tickets to the farewell public lectures of the preeminent scientist in Britain. And so electric (pun intended!) with excitement, with notebook in hand, young Faraday set off to attend the series on chemistry by Sir Humphrey Davy of the Royal Institution. Davy was a flamboyant pioneer in many aspects of chemistry, but most notably electrolysis in which electrical currents are used to dissociate chemical compounds into their separate constituents. A one-man industry of chemical analysis, he gave regular public talks and demonstrations, often using his own body as a part of the show dangerously inhaling noxious elements of one kind or another.

With pencil in hand, young Michael faithfully attended the lectures in the gallery, wrote out and bound them, and presumptively sent them to Davy. So imagine Faraday's astonishment when one day a summons arrived for him to visit the Great Man who had fired one of his laboratory assistants for fighting and out of the blue, offered the job to Michael. His apprenticeship had ended, he was at loose ends, and so the timing was remarkably fortuitous. He accepted and after a short introduction in the Laboratory to his amazement he was bundled up with Davy's wife for a year and a half scientific and educational tour throughout Europe as Davy's "philosophical assistant."

Faraday had never been more than a dozen miles from London and perched atop Lady Davy's carriage (yes, he was made to ride on top of her coach!), the city boy delighted in letters home at the French countryside. The little scientific entourage embarked from Plymouth in October of 1813. Although the 20 year-long war with France was still raging the Great Man carried special credentials from Napoleon them to travel through enemy territory. And so, in spite of grumbling from London's conservative press, Davy pressed forward with safe passage to Paris, then to Montpelier, Genoa, Florence, Rome, Naples, Geneva, Munich, and dozens of other towns in between. During their trip, Napoleon's army was defeated, the Emperor was exiled, escaped, and hostilities renewed. These ominous events led them to cut their trip short, avoid France on their return to England in April of 1815.

This excellent European adventure was Faraday's alternative college education—a continuous "study abroad" experience which brought him into direct contact with all of the scientific luminaries on the continent, some of who he corresponded with for years. Throughout, Davy did experiments with Faraday's assistance. While exhilarating, this experience also made him very aware of his low station in life and how he appeared to others. To make matters worse, Lady Davy's self-appointed role seemed to be the reinforcement of their apparent class distinction which led to many despondent letters home about ill treatment at her hands. Faraday was equal parts gratified for the education and miserable. He wasn't just Davy's scientific assistant but also expected to be Dir Humphrey's valet. Faraday determined to change his manner and his speech and when they returned took elocution lessons and joined reading groups which he attended his whole life. "Self-made man" seems a label designed for Michael Faraday.

With their return, Michael spent the rest of his life working within the Royal Institution, eventually with his wife in provided apartments. Davy later commented that his most famous discovery was "Michael Faraday," but the good feelings didn't last, as much later the temperamental Davy wrongly accused Faraday of plagiarism and unsuccessfully tried to block his election to the Royal Academy of Science...a sorry chapter in an otherwise heart-warming relationship.

Davy quickly came to totally depend on Faraday. He chafed under the assistant's role, but broke through—by 1820 he started his own researches and naturally took up electrolysis as a study and methodically characterized both his procedures and his results. It is to him that we owe the terms "ion" and "electrode" among others.[1]

While an extraordinary experimenter—imaginative as well as skillful, he was notoriously mathematically illiterate. He knew it, everyone knew it. Yet without any formal training, his contributions were often guided by a natural and highly developed mathematical intuition. He "thought" mathematically,

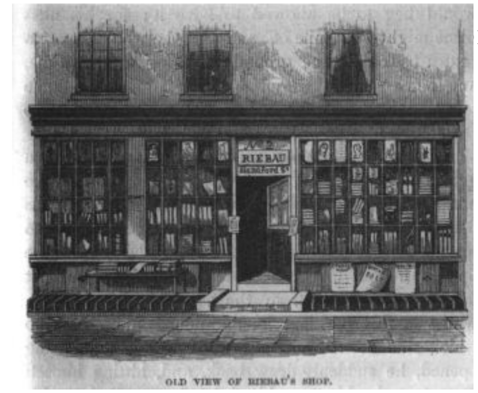
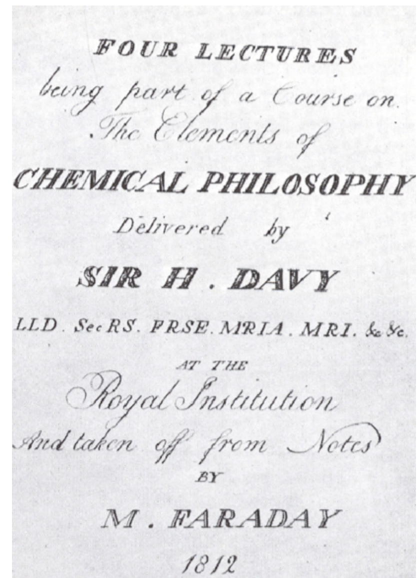


Figure 11.2: George Reibau's book bindery.



FOUR LECTURES
being part of a Course on
The Elements of
CHEMICAL PHILOSOPHY
Delivered by
SIR H. DAVY
LLD. Sec RS. FRSE. MRIA. MRI. &c &c.
AT THE
Royal Institution
And taken off from Notes
BY
M. FARADAY
1812

Figure 11.3: The book of Davy lectures compiled by 19 year old Michael Faraday.

[1] In his life-long self-improvement project, Faraday met and befriended many classical scholars and consulted them when he felt the need to name something. He often wanted to use a word with an appropriately stately pedigree in Latin or Greek.

he just couldn't express his ideas in that language. Later when James Clerk Maxwell codified his work in sophisticated mathematical form, he marveled at Faraday's intuitive and pictorial sense of the phenomena. In fact, arguably it was precisely his lack of formal training that freed him to make heretical suggestions which were quite outside of the standard wisdom. . . and which were often right. As his fame grew, it didn't immunize him from scathing criticism from his more sophisticated colleagues who would object on grounds that he was out of his league. What these colleagues couldn't appreciate was that not only was Faraday out of his league—he'd invented a whole new sport: Michael Faraday and James Clerk Maxwell were the first modern physicists.

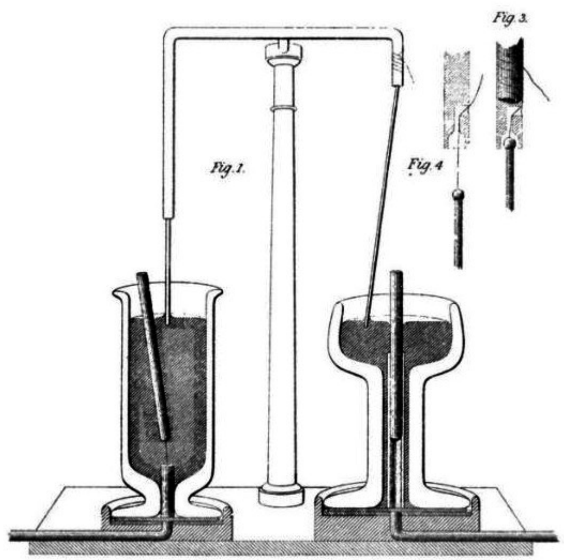


Figure 11.4: The arrangement of a wire free to rotate around a vertical axis (right) while maintaining electrical contact with the Mercury and the opposite situation on the left where a magnet rotates around a fixed wire also connected to the Mercury-circuit was proof of their reciprocal natures.

11.2 Faraday's Experiments in Electricity and Magnetism

By the time Faraday was working on his own, he knew all of chemistry. Davy had been a pioneer and was devoted to an atomistic-molecular view which rubbed off on Faraday who tended to think in terms of particulate matter all of his working life. His skills as an analytic chemist were second to none and he was in considerable demand for industrial consultation, fitting right into the goals of the Royal Institution. He created compounds of chlorine (discovered by Davy) and carbon, he isolated Benzine (and other organic molecules), liquefied chlorine, and discovered paramagnetism. He made important advances in alloying of steel. He was the go-to man in Britain for industrial chemistry innovation. Our concern is with this research into electricity and magnetism. Let's consider each of his major discoveries in their historical order.

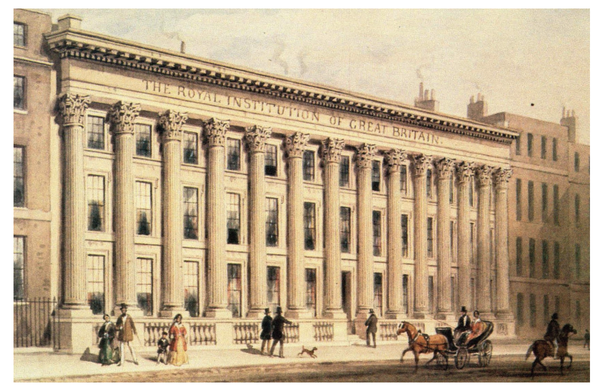


Figure 11.5: The Royal Institute of Great Britain which evolved into three roles. First, practical application of science for the good of industrial Britain. Second, a home for basic research— often at odds with its first mission. Finally a home for public science education. This latter role served as a fund-raising mechanism and was enhanced under Faraday's leadership.

11.2.1 The Motor

Oersted's results in 1820 electrified the Davy-Faraday laboratory.[2] Their lab was proficient in electrochemistry and so they must have had many of the materials required in order to repeat Oersted's experiment, and they did in great detail. It was Faraday who imagined that Oersted's compass demonstrating a circular relationship around a current-carrying wire might imply that magnets might themselves feel circular force around a wire. He had the clever idea to construct such a device, making use of the fact that mercury is a good conductor of electricity, while still being a fluid. Look at the left side of Fig. 11.4. The beaker of mercury has a bar magnet attached on a swivel at the bottom and at the top of the pool of liquid, a wire just breaks the surface. The wire running off the bottom to the left is attached to a battery and the vertical wire (ignoring the right hand part of the picture) is attached to the other terminal of the battery. When current flows through the mercury and the wire, the magnet swivels around its base in a circle around the upper wire.

[2] Get it?

The right hand picture shows what he did first. Ignoring the left hand side, now the wire comes in and attaches to a straight wire that's free to swivel around the top. Now a bar magnet is fixed vertically in the pool of mercury and is attached to the other end of the wire and battery. When current flows, the hanging, straight wire moves in a circle around the magnet. In each case (left and right) the circuit is completed through the mercury and the vertical wires.

Faraday connected the two experiments together as a show-and-tell stunt demonstrating the complimentary aspects of the same phenomenon: electrical energy is converted into mechanical motion, which is...the first motor.

Electrical energy can induce circular mechanical motion in a circuit. *Key Observation 17*

Faraday knew that this was a significant discovery. In his notebook he wrote, "Very satisfactory, but make a more sensible apparatus." But his 14 year old brother-in-law, who was in the lab with Faraday's wife, Sarah noted later that they all danced around the apparatus and then went to the circus to celebrate.[3] (He even prepared small hand-held versions of the Faraday Motor that he gave to colleagues for their amusement.) Faraday had none of the "Newton upbringing" and so his mind created different pictures. This idea of circular forces didn't fit into a Newtonian force-world and in this regard, Faraday was completely on his own.

[3] Michael and Sarah Faraday had no children, but was an active uncle with his nieces and nephews often playing in his laboratory. They later remembered his reactions to successes and failures and their descriptions of an excited uncle contrasted with his always sober lab notebook recording of his results.

At this point, Faraday is still a young researcher—he was 29 years old—and he made a rookie mistake: he published his results without properly acknowledging people who had supported him and done preliminary work themselves. One of those was Davy, who appeared to never forgive him raising the issue to the level of a complaint of plagiarism. It was a gross overstatement and everyone understood that to be the case. Except, apparently, his former mentor who tried to block Faraday's election to the Royal Society.

In 1821, young Faraday was asked to write an article which would summarize the all of the known electrical and magnetic phenomena. By this point, he was an extraordinarily careful experimenter and exceedingly clever with his notebooks, inventing an indexing system that he'd use his entire career. In-

Faraday's record-keeping was remarkable. Very early in his career he fell into the habit of numbering every paragraph in his logbook. Then periodically he would add to an index so he could efficiently refer back to his notes. He produced his massive reports on Electricity and Magnetism later in life which summarized his careful experiments, as well as his far-reaching conclusions. He maintained tens of thousands of numbered paragraphs in his career!

stead of just reviewing the literature, he decided to repeat all of the experiments that had ever been done on electricity which for a genius like Faraday, led him into new territory.

His Day Job

By 1825 Faraday was the director of the Royal Institute and inherited fund raising and financial affairs which were a considerable burden, as the place was nearly broke. Its purpose was originally to assist British industry with solutions which could be sold or which would increase efficiency in the nation's factories. That contrasted with Faraday's own personal desire to continue to do fundamental research, undirected by practical application. He found time to do so, but it was less than he would have liked. It was not until 1831—the year that Davy died—that he was able to return to basic research in electricity and magnetism. But he was always working on matters of public good and industrial progress. Basic research was inserted when he had time.

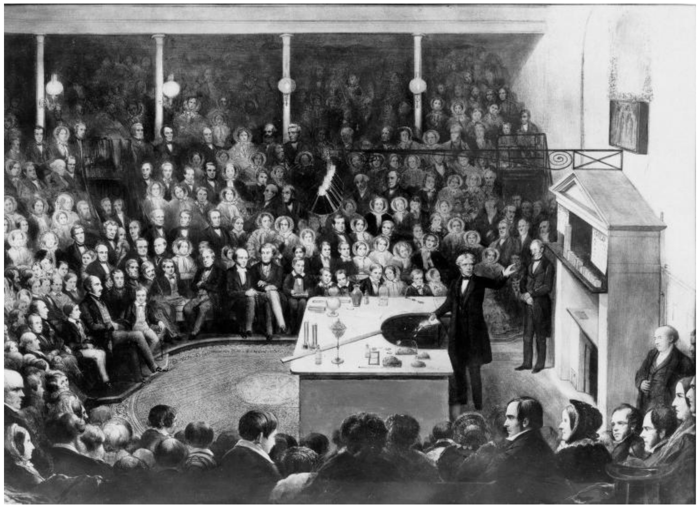


Figure 11.6: Faraday at the 1856 Christmas Lectures, one of his last. He gave 19 of them over his career—one of his earliest was on the chemistry of flame which he turned into *The Chemical History of a Candle*, a book for a non-expert reader.

But one thing he had time for was pay-back. Remember his good fortune in life had come with an opportunity of a chance public lecture. Faraday devoted himself, throughout his life, as an engaging and entertaining presenter of science to the public. As director, he instituted a nearly weekly series on Fridays—always exactly one hour—and he created a Christmas series for children. The Royal Institution Christmas Lectures have been given every year (except during WWII) from a virtual "who's who" of British scientists. Look at that overflow crowd in one of his last lectures Fig. 11.6! Michael Faraday was the world's first "Mr Wizard."

11.2.2 Induction

By 1831, he managed to clear his research decks sufficiently to take on a problem that had plagued him, as well as others. Clearly there were two ways to produce electricity: one could use friction—the silk and fur rubbed on glass and amber (your socks on the carpet) or use chemistry—a battery. And, Oersted and Ampère had shown that electricity—in the form of a current—could produce magnetism.[4] So surely magnetism should be able to produce electricity.

[4] Ampère had proposed that magnetism was caused by molecular electricity—little loops of current. So the challenge to Ampère was then how to tease magnetism out of matter. Faraday, while an atomist himself, was not enamored of this speculation.

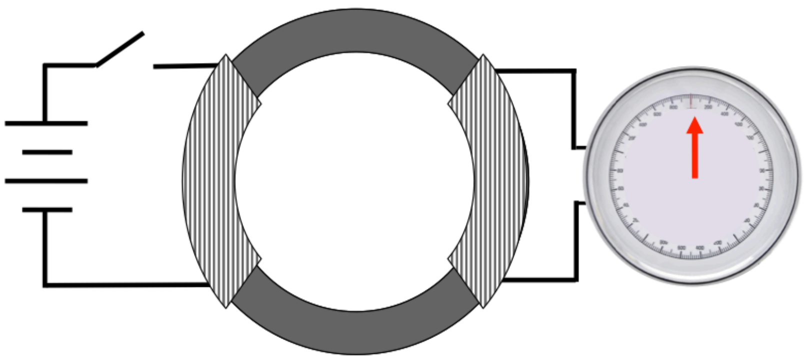


Figure 11.7: When the switch on the left is closed, then current flows through the circuit encircling one part of the iron core. The right-hand circuit contains no current source, but yet the needle on the galvanometer moved indicating that a current had been produced. Faraday interpreted the source to be a changing magnetic field, enhanced and contained within the iron toroid.

Faraday went into a furious series of experiments trying all manner of materials and conductors which mostly consisted of trying to take adjacent circuits and get one to cause a current in another. His inspiration came when he took two long wires and wrapped them individually in paper and then wove them together around a core of a circular iron ring. The paper insulated the wires from touching, but they were all very close to one another. He hooked one set to a battery and looped the other circuit over a sensitive magnetic needle as shown in Fig. 11.7. If the needle moved when the current flowed in the first circuit, then it would have been induced by the interwound, but insulated wires.

Figure 11.8: One of Faraday's original coils. Now called a "trans-

Multiple tries didn't succeed until he noticed that the needle moved when the circuit was closed and then when it opened...and was stationary when the current just flowed. That was the key which everyone had missed, including after seven years of effort by Faraday: currents don't induce magnetism, but *changing* currents do!

Subsequently, he found another demonstration of a similar sort, but more directly and forcefully a magnet inducing electricity. Figure 11.9 is just a loop of wire connected to a Galvanometer.[5] No battery. No currents. Pointed at the loop is a bar magnet. That's it. Hold the magnet still, nothing happens. But, move the magnet toward or away from the loop and a current flows in it! Here, the changing magnetic influence is caused by a mechanical motion of the magnet. Current is created by a changing magnet, which is the principle behind a Generator. Keep this little experiment in mind.

[5] A Galvanometer is a sensitive meter that detects the presence of very small currents. If they go one way, a needle moves. If the currents go in the opposite direction, the needle moves the other way.

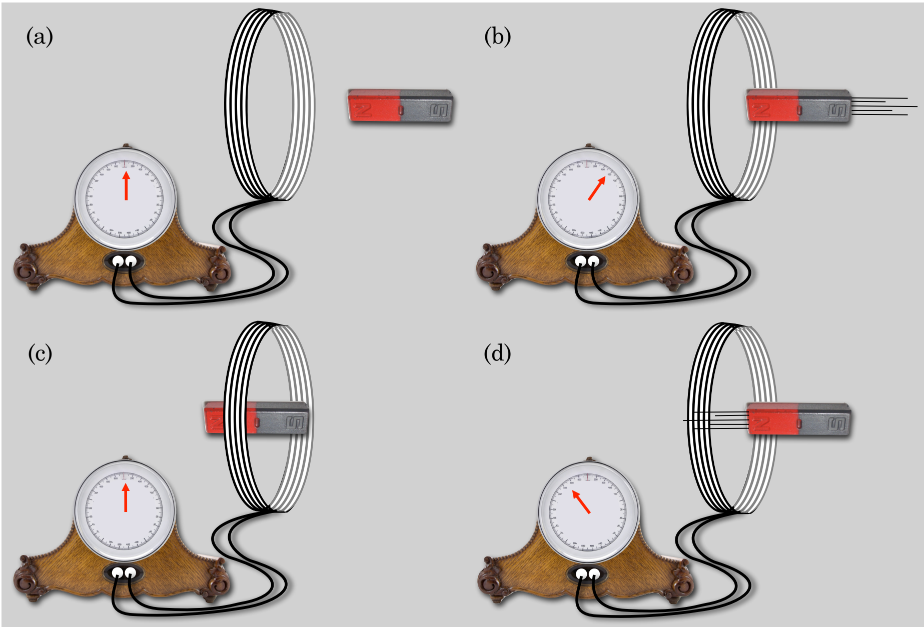


Figure 11.9: This is a standard demonstration of induction, but as we'll see, it is also a fundamental demonstration of the need for Einstein's Theory of Relativity. You wait. In (a) a magnet is stationary outside of a coil of wire. The wire in each stage is connected to a galvanometer and here we see that no current is flowing. ("Nothing up my sleeve" here means: there is no battery—no source of current.) In (b) the magnet just starts to move towards the coil and current flows. In (c) the magnet is inside the coil, and motionless and no current registers. And finally in (d) the magnet is just started to be removed from the coil and current flows, but in the opposite direction from (b).'

The ability for current to flow seems to be inside of the wire and by changing a magnetic field in the vicinity of the wire, that current is *induced* to flow. This phenomenon is called Electrical Induction and it's the principle behind all generators—creating current out of magnetic motion—and motors, its inverse—creating motion out of currents.

A changing magnetic influence creates a current. *Key Observation 18*

What's responsible for all of these various phenomena? Faraday had the standard repugnance for Action at a Distance, and knew that that wasn't an explanation of anything anyway. He wasn't so bound to the idea as were his classically trained colleagues, and so he thought about it in his own, fresh mind.

Faraday announced his discovery to the world at a meeting of the British Royal Society on November 24, 1831. That led to a priority struggle, as the publication of the effect was in early 1832, by which time the effect had been repeated in France and Italy...and where popular press reported that Faraday had confirmed the effect, rather than discovered it. He never again announced a discovery before formally publishing it in an international journal. The French and Italian scientists all acknowledged his priority and so trouble was averted. By now "Professor" Faraday—the uneducated printers apprentice—was world-renown and what he said and did mattered.

Out of Action

Faraday handled mercury and other dangerous materials as a matter of course. In his middle age he suffered a serious lack of memory and bouts of dizziness that took him out of action from about 1839 until 1845. It must have been terrifying. He was forced into months of seclusion and was absent from research only giving a few public lectures in the 1840s. Speculation is that he had poisoned himself. Can you imagine someone as energetic and inspired as Faraday, unable to work? Neither could Sarah, who enforced strict social access to her husband throughout his convalescence. He eventually recovered and resumed his activities. The challenge that seemed to energize him was his evolving view of space and the vacuum.

11.3 Lines of Force

Look carefully at Figs. 11.10 and 11.11, the proverbial 1000-words'-worth kind of pictures. The first is from Faraday's notebook, and so a sketch made by him sometime in the early 1830's. The second is a photograph from our lecture hall. What you see is a bar magnet surrounded by little bits of iron filings, each a little magnet of its own. By tapping the surface one frees them from any friction with the surface and they respond to an unseen presence—what Faraday called "lines of force."

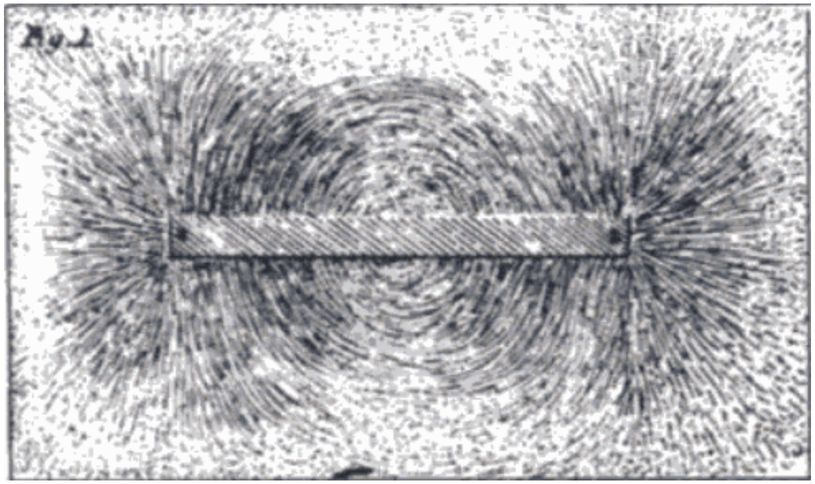


Figure 11.10: A patient sketch from Faraday's notebook showing the lines of force due to a bar magnetic on the accumulated action on little iron filings.

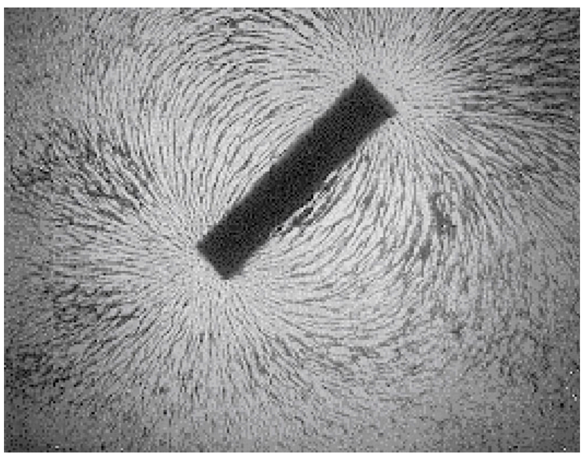


Figure 11.11: A modern photograph of a bar magnet, repeating Faraday's experiment.

One really cannot help but be mesmerized by this picture when you think about what it suggests. At first Faraday used the image of "lines of force" as a visualization...but by 1831 (in his diary) and 1845 in public and in print, he began to speak of the reality of what he coined a "field." While a compass points north, responding to an apparently invisible quality, these pictures revealed to Faraday that there's *something there*, hidden from view. Like a ghost materializing out of thin air in a Halloween cartoon, these lines of force reveal themselves by their spooky influence on the iron filings.

Faraday, like everyone, had trouble with Newton's action at a distance—that one body could reach out and influence another body with nothing in-between. But the scientific community—especially those in Newton's Britain—and come to peace with instantaneous, Action at a Distance. But his simple experiment shows that there's *something there*. Faraday played with this idea for years but slowly became committed to the reality of the lines of force—that empty space was not empty at all, but full of this almost material substance that seemed to propagate magnetic influence from one place to another. [6]

Faraday was aware that these were not going to be popular notions. First these lines of force were not Newtonian in character—they *curved*. They were *circular*. Maybe even worse: they seemed to *endow space itself with something to do*. In the Newtonian way of thinking, all space did was establish "place." It just defined separations between objects and staked out occupied regions. But Faraday's lines of force, if real, filled all of space. The effects of magnetism required space-filling lines of force. Or so his ideas went. But he didn't publish these ideas.

[6] Of course, these tiny magnets are laying on a flat piece of paper and so they sample a plane-slice of the actual three dimensional magnetic influence.

He went so far as to induce currents from the tiny magnetic influence of the Earth and he began to speculate the gravity was of the same nature. In fact he tried unsuccessfully for years afterwards to try to induce a current by dropping wires in his lab.

Instead, for years he amassed his evidence. Look at Fig. 11.12, again from his notebooks. Here we see the cross section of a wire (top) and two wires (bottom) all carrying currents. Iron filings were sprinkled on the sheet of paper punctured by the wires and again, by their orientation and arrangements, the filings signal the presence of magnetic lines of force. From the Oersted experiment, he knew that a current creates a magnetic effect and here he's shown it to be of the same sort of disturbance as from a bar magnet. It was time to come clean.

Finally, in 1837 he read what was the 11th of a series of *Experimental Researches in Electricity* to the Royal Society and he proposed that rather than being just a mental crutch, perhaps the lines of force were real. This was a frontal assault on (British) scientific belief and the reaction was not pleasant. In particular in the audience was the young William Thomson (the future Lord Kelvin), who was disgusted with the idea. Until he worked on it. What Thomson did was to apply the mathematics of heat conduction to the "streamlines" of Faraday's lines of force. He found that it hung together and by 1845, when he first actually met Faraday, he proposed that magnetic forces might actually affect the passage of light through materials.

Faraday set out to try to observe Thomson's effect, obviously encouraged that someone who was of the traditional scientific establishment, and a mathematical person to boot, would take his ideas seriously. He worked feverishly without results for almost a week, until he found the effect, which is today called the Faraday Effect: the presence of a magnet affects the polarization of light in some materials.

Aha. A magnetic disturbance affecting the propagation of light...were they connected?

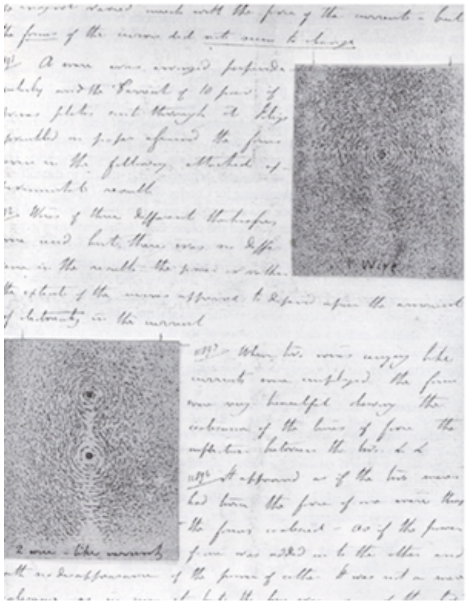


Figure 11.12: Another sketch from Faraday's notebook showing the arrangement of iron filings surrounding a current in a wire (upper right) and two wires (lower right). Notice that they are circular and surround the wires.

11.3.1 The Ether

Light is an undulatory phenomenon—it's a wave. For his colleagues the idea of light propagating through a vacuum was ludicrous. There had to be something "waving" for the light beams to undulate. In the classic sense of naming something being satisfying, but not really explaining, this "something" was called the Ether...specifically, the "Luminiferous Ether" for the Ether that propagated light (there were thought to be other ethers that propagated electricity and magnetism).

The Luminiferous Ether was a strange beast: It was everywhere. It didn't impede the motion of the Earth. It couldn't be seen, felt, tasted, or nudged and yet it could delicately react to light which stretched and compressed it as it propagated from one place to the other. Yet, since the speed of light was known to be very fast, the ether would have to be stiffer than steel to vibrate at that rate! The idea is very strange.

Too much so for Faraday whose views on space were extreme. He had no time for this unrealistic, invisible ether. Rather than imaging space to be just a big container that keeps everything from being all in the same place(!), he imagined a space that was full of electric and magnetic lines of force.

Figure 11.13: A daguerreotype of a mature Faraday from the 1840s.

For example his induction experiment could be explained this way. Look again at Fig. 11.9. As the magnet approaches the patiently waiting, inert coil of wire, more and more lines of flux are "cut" (his word) by the wire and it's the cutting of the "flux" (his word) that starts the current to flow. In fact, he even imagined that this magnetic flux would take time to reach the wire, so it was not instantaneous. Were a wire to be parallel to the lines of force, there would not be any current. Only when the lines of force cut a wire, would current flow.

The degree to which it is close to our quantum field ideas is almost spooky, as we'll see. To him what magnets, currents, and charges do is "pluck" the force lines into action...into wave-like action to transmit energy from one place to another at a finite speed.

Box 11.1 Filling In

Here's a story of how he publicly spilled the beans. One Friday evening in 1846 as he and the Royal Institution"s public speaker (Charles Wheatstone, of the "Wheatstone Bridge" fame) were walking to the hall, Charles saw that a renowned heckler was in attendance and being pathologically shy, beat a hasty exit leaving a full auditorium and nobody to speak. So Faraday took over...spending a little time trying to explain what the vanished lecturer would have told them. Then for the rest of the hour (because the lectures were always exactly 1 hour) he described his idea of a light, quite off the cuff.

"The view which I am so bold to put forth considers, therefore, radiation as a kind of species of vibration in the lines of force which are known to connect particles and also masses of matter together. It endeavors to dismiss the aether, but not the vibration."

Throw out the medium, but keep the wave. He began to write of a space that's full of magnetic, electric, and gravitational lines of force.

Figure 11.14: faradaylab

After that public exposure, Faraday tried to be more specific in a letter to Philosophical Magazine.

> "The propagation of light and therefore probably of all radiant action, occupies time; and, that a vibration of the line of force should account for the phaenomena [sic] of radiation, it is necessary that such a vibration should occupy time also...I think it is likely that I have made many mistakes in the preceding pages, for even to myself, my ideas on this point appear only as the shadow of a speculation, or as one of those impressions on the mind which are allowable for a time as guides to thought and research. He who labours in experimental inquiries knows how numerous these are, and how often their apparent fitness and beauty vanish before the progress and development of real natural truth."

He was roundly criticized for this speculation. He chalked it up to his learned colleagues being overly cautious and hide-bound to their preconceptions. His colleagues basically indicated that Faraday was a brilliant experimenter, but out of his depth when he ventured into speculative ideas about nature and mathematics. Faraday needed a hero and we'll meet his champion in the next chapter.

Faraday's health was a constant concern in his 50s and later. He might have suffered from Mercury poisoning. He was terribly worried about his memory losses and found that only trips to the country and a heavily-enforced isolation from anything scientific would restore him to working form. However, he had to exit himself for a couple of years to recover from a particularly bad episode and it never quite left him alone after that.

Faraday continued to experiment and unravel a number of mysteries in both chemistry and physics. He never forgot his modest education and worked hard to perfect a speaking and demonstration ability, giving many public talks in London through his senior years.

What we take from Faraday's work is of course the list of phenomena that he demonstrated. But, as important, or maybe even more so since other natural scientists would have come upon these same events. It was rather that mathematical intuition which when combined with his naivety about how things were "supposed" to be, that is his enduring contribution. Those lines of force, which he carefully mapped and measured in a number of electrical and magnetic configurations were the direct inspiration to arguably the most accomplished mathematical physicist apart from Newton and Einstein.

He died at the age of 73. Increasingly aware of his inability to remember and function, he resigned from the Royal Institution. His last lecture was given on a Friday and his notes bear some scorch marks where apparently they got too close to an open flame. He announced his retirement at that lecture to what must have been a stunned audience.

Figure 11.15: Michael and Sarah Faraday, 1851.

> "It is with the deepest feeling that I address you.
>
> I entered the Royal Institution in March 1813, nearly forty-nine years ago, and, with exception of a comparatively short period, during which I was absent on the Continent with Sir Humphry Davy, have been with you ever since.
>
> During that time I have been most happy in your kindness, and in the fostering care which the Royal Institution has bestowed upon me. I am very thankful to you, and your predecessors for the unswerving encouragement and support which you have given me during that period. My life has been a happy one and all I desired. During its progress I have tried to make a fitting return for it to the Royal Institution and through it to Science.
>
> But the progress of years (now amounting in number to threescore and ten) having brought forth first the period of development, and then that of maturity, have ultimately produced for me that of gentle decay. This has taken place in such a manner as to render the evening of life a blessing:—for whilst increasing physical weakness occurs, a full share of health free from pain is granted with it; and whilst memory and certain other faculties of the mind diminish, my good spirits and cheerfulness do not diminish with them.
>
> Still I am not able to do as I have done. I am not competent to perform as I wish, the delightful duty of teaching in the Theatre of the Royal Institution, and I now ask you (in consideration for me) to accept my resignation of the Juvenile lectures… I may truly say, that such has been the pleasure of the occupation to me, that my regret must be greater than yours need or can be."

He and his wife, Sarah, never had children but they were very content with one another, as evident in a letter her on one of his last trips,

> "My head is full, and my heart also, but my recollection rapidly fails, even as regards the friends that are in the room with me. You will have to resume your old function of being a pillow to my mind, and a rest, a happy-making wife."

He referred to himself as "altogether a very tottering and helpless thing, and requested a small funeral, attended by only his family. He died in 1867 and at the ceremony planned for family, friends and colleagues "came out from the shrubbery" to say goodbye.

The *Times of London* obituary said in part,

> The Late Professor Faraday
>
> "The world of science lost on Sunday one of its most assiduous and enthusiastic members. The life of Michael Faraday had been spent from early manhood in the single pursuit of scientific discovery, and through his years extended to 73, he preserved to the end the freshness and vivacity of youth in the exposition of his favourite subjects, coupled with a measure of simplicity which youth never attains...as a man of science he was gifted with the rarest of felicity of experimenting...It was this peculiar combination which made his lectures attractive to crowded audiences in Albemarle-street for so many years, and which brought, Christmas upon Christmas, troops of young people to attend his expositions of scientific processes and scientific discovery with as much zest as is usually displayed in following lighter amusements...

Faraday was beloved around the world and the *Times* listed a few of his honors:

> Oxford conferred on him an honorary degree...He was raised from the position of Corresponding Member to be one of the eight foreign Associates of the Academy of Sciences. He was an officer of the Legion of Honour, and Prussia and Italy decorated him with the crosses of different Orders. The Royal Society conferred on him its own medal and the Romford medal. In 1858 the Queen most graciously alloted to him a residence at Hampton Court, between which Albemarle-street where he spent the last years of his life, and where he peaceably died on Sunday...No man was ever more entirely unselfish, or more entirely beloved. Modest, truthful, candid, he had the true spirit of a philosopher and of a Christian...
>
> The cause of science would meet with fewer enemies, its discoveries would command a more ready assent, were all its votaries imbued with the humility of Michael Faraday."