

The background of the entire image is a textured, light tan surface. Overlaid on this is a complex pattern of dark brown, almost black, lines and dots. These elements radiate from a central point located slightly to the right of the vertical center. The lines are of varying lengths and thicknesses, some straight and some curved, creating a sense of dynamic movement and energy. The dots are small and scattered, particularly concentrated in the lower right quadrant, adding to the intricate texture.

# LINES AND WAVES

Center for the History of Electrical Engineering



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# **LINES AND WAVES**

**Faraday, Maxwell  
And 150 Years  
Of Electromagnetism**

Robert D. Friedel



Center for the History of Electrical Engineering  
Institute of Electrical and Electronics Engineers

This publication was prepared in conjunction with a traveling exhibit created by the IEEE Center for the History of Electrical Engineering in commemoration of the 150th anniversary of the birth of James Clerk Maxwell and of Michael Faraday's discovery of electromagnetic induction. Funded by the IEEE and a number of its constituent technical societies, the exhibit was circulated by the Association of Science-Technology Centers to museums in the United States and Canada.

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## LINES AND WAVES FARADAY, MAXWELL AND 150 YEARS OF ELECTROMAGNETISM

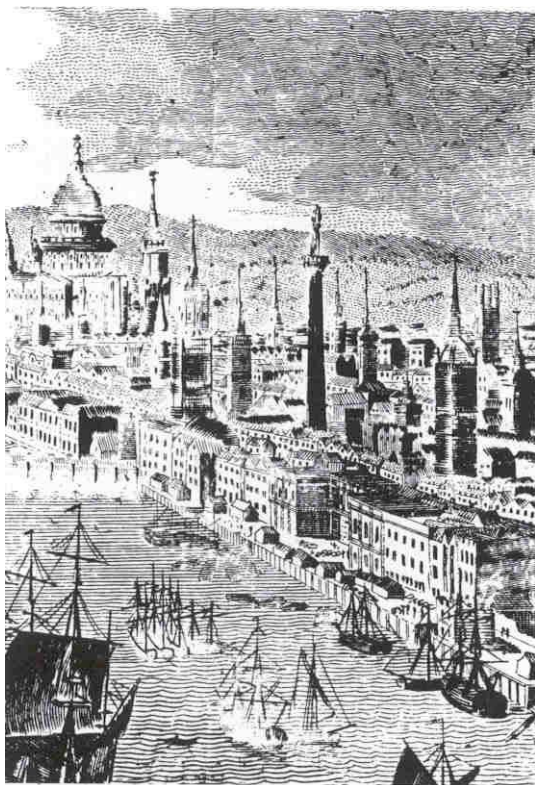
It was 150 years ago that the English scientist Michael Faraday discovered that he could generate electricity with magnets – the phenomenon we call electromagnetic induction. In the same year that Faraday made this discovery, there was born in Scotland the man whose brilliant mathematical interpretation of Faraday's ideas was to become the foundation of our modern concepts of electricity, magnetism and light, James Clerk Maxwell. This exhibit celebrates the life and work of these two men and seeks to highlight their contributions to our understanding of electricity and our ability to make electricity work for us through engineering.

This exhibit is sponsored by the Institute of Electrical and Electronics Engineers and has been produced by the IEEE's History Center. It is hoped that exhibits such as this one will foster among both electrical engineers and the general public an appreciation for the diversity and richness of the heritage of electrical engineering.



FARADAY

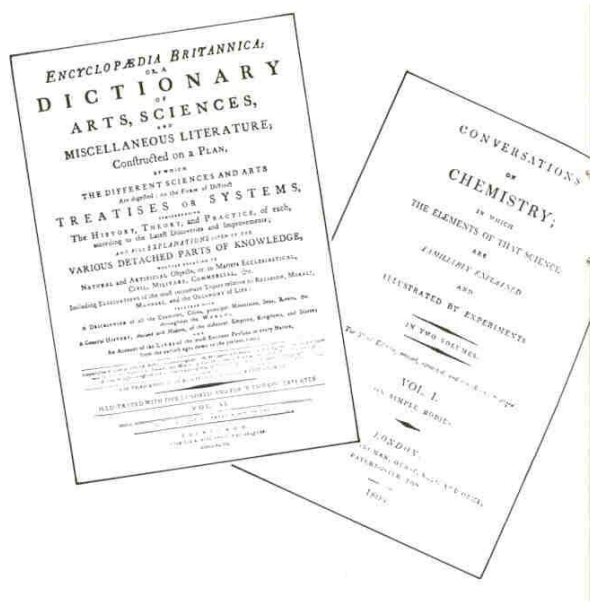




London, about the time of Faraday's birth, New York Public Library

## Origins

Michael Faraday was born on the 22nd of September, 1791 in the small town of Newington, Surrey, near London. He was the son of a poor blacksmith who was able to provide his family with only the most rudimentary schooling, supplied by the local common day-school. Faraday's most important legacy from his parents was his deep religious faith. Born and raised a member of the small dissenting sect known as the "Sandemanians," Faraday never lost, in a long life devoted to science, his strong attachment to his church.



Smithsonian Institution Libraries, Special Collections Branch.

## Education

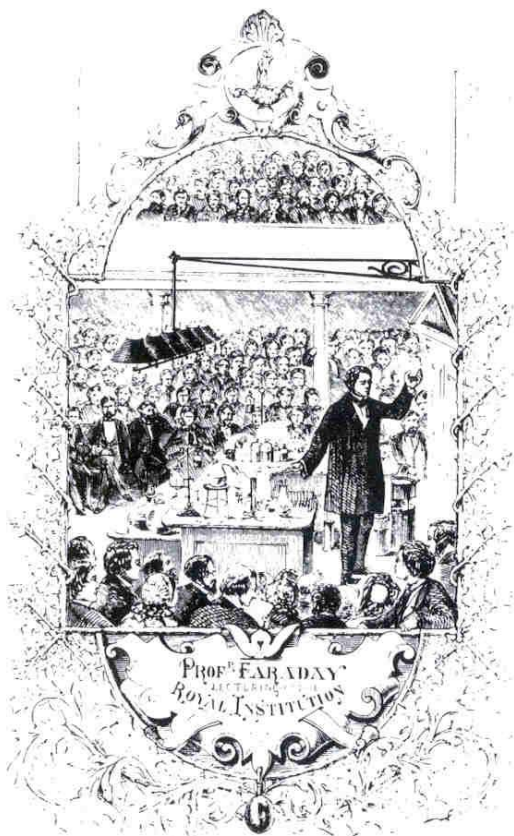
Faraday's formal schooling ended when he was 13. Family circumstances required that he then become an apprentice, both to support himself and to learn a useful trade. It was remarkable good fortune that he was sent to the shop of Mr. G. Riebau, a bookseller and bookbinder, for there began his real education. In the shop, between jobs, he had time to look at the books that came in and to begin reading some of them. As Faraday said to a friend many years later, the two most influential things he read at this time were parts of the Encyclopaedia Britannica and Jane Marcet's Conversations on Chemistry.

*I entered the shop of a bookseller and bookbinder at the age of 13, in the year 1804, remained there eight years, and during the chief part of the time bound books. Now it was in those books, in the hours after work, that I found the beginning of my philosophy. There were two that especially helped me, the "Encyclopaedia Britannica," from which I gained my first notions of electricity, and Mrs. Marcet's "Conversations on Chemistry," which gave me my foundation in that science. . . .*

Faraday to A. De la Rive  
2 September 1858

## Humphry Davy

For a young man, like Michael Faraday, interested in chemistry and electricity, no one could have been more exciting to see or hear than Humphry Davy. Easily the most popular scientific lecturer of his time, Davy was appointed Professor of Chemistry at the Royal Institution when he was only 24. His reputation rested not only on his lectures and his handsome good looks (he was long London's most eligible bachelor), but also on solid scientific work. Not only was he the great pioneer of electrochemistry, but he also invented the miner's safety lamp, wrote a treatise on agriculture, and made contributions to the young science of geology. At age 33, in 1812, Davy was knighted for his work, and in the following year he made what some said was his greatest discovery, Michael Faraday.



*Lecturing at the Royal Institution. Burndy Library*

## The Royal Institution

The Royal Institution of Great Britain was founded in 1799 largely through the efforts of American born Benjamin Thompson, Count Rumford. Still housed in its original building at 21 Abermarle Street in London, the Institution was from the beginning devoted both to popular lectures on scientific and useful subjects and to laboratory investigation of important scientific problems. In Faraday's time, admission was by ticket only, and it was due to the generosity of one of his employer's customers that he got his first chance to hear a lecture by Humphry Davy, the Institution's popular Professor of Chemistry. Just a year later, in 1813, Faraday took the job of Davy's laboratory assistant, and thus began a career at the Royal Institution that was to last more than fifty years.



*Faraday's notes on Humphry Davy's lectures. Royal Institution, courtesy AIP Niels Bohr Library.*



*Humphry Davy. Burndy Library*

## SCIENTIST AND PUBLIC FIGURE

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### Davy's Assistant

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As the young Faraday worked through the years of his apprenticeship in book-binding, he found time to pursue chemical experiments, engage other amateurs in lively scientific debates, and attend whatever scientific lectures were free to a London workingman. In the year 1812, as the apprenticeship drew to a close, Faraday determined that he did not want a life as a binder, but that his future belonged in science. Some months after he attended four of Humphry Davy's Royal Institution lectures, he had the chance to show his careful notes of the lectures and accompanying drawings to Davy, who was flattered and impressed by them. Davy had no job to offer Faraday at that time, but a few months later, in February 1813, his laboratory assistant (or "fag and scrub", as he was called) was dismissed for brawling. When Faraday was offered the opening, he leaped at the chance, and within weeks was deeply immersed in the work of one of the finest chemical laboratories of the day.



*Young Michael Faraday. Burndy Library*

### Faraday the Scientist

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Faraday's position at the Royal Institution gave him the finest education in experimental science that was possible. After only a few years of helping Humphry Davy, Faraday was put in charge of all the laboratory and lecture apparatus of the Institution. He became a well-known analytical chemist, doing important work on steel and glass and discovering new compounds, such as benzene. In 1824, he was made a Fellow of the Royal Society and in the following year was appointed Director of the Laboratory of the Royal Institution. In 1826 he began the Institution's famous series of "Friday Evening Disclosures" to communicate the newest scientific discoveries to the public, and later he started a series of scientific lectures for children, which are still popular Christmas time events in Britain. Recognized as an extraordinary experimental scientist, Faraday was also the greatest popularizer of science in history.

### Faraday the Man

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Faraday's popularity was due not only to his skill as a lecturer and demonstrator, but also to the gentleness of his personality. A modest man, his greatest ambitions were fulfilled by being able to spend his life in the Royal Institution's laboratory and lecture hall. The only thing that matched his preoccupation with science was his devotion to his wife through a marriage of 46 years, and a religious faith that made science for him a humble appreciation of the wonders of creation.

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## Oersted's Discovery

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There were strong philosophical currents in the 18th and 19th centuries that led many experimenters to believe that all the forces of nature – light, electricity, magnetism, gravity – were all but forms of one basic source. Hans Christian Oersted, a Danish chemist was one of those who believed this. Therefore, in 1820, when he observed a compass needle moving under the influence of the electric current in a nearby wire, he was not surprised. He did, however, understand the importance of his discovery, and in a matter of months he sent out to scientists all over Europe his announcement of the magnetic effects of electricity. Written in Latin, the announcement caused a storm of excitement as others rushed to duplicate the simple experiment.



*Hans Christian Oersted.*  
*Burndy Library*



*Andre Marie Ampere.*  
*Burndy Library*

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## Ampere

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One of the many scientists who hastened to study the phenomenon discovered by Oersted was Andre Marie Ampere, Professor of Mechanics at the Ecole Polytechnique in Paris. Ampere extended the investigation of the magnetic effects of electricity to include the interaction between two current-carrying wires, which he showed to be the same as that between a wire and a magnet. Through an extraordinary series of careful experiments, Ampere established the foundations of the science of electrodynamics – the study of the relationship between electric, magnetic and mechanical phenomena, earning himself the title, "the Newton of electricity."

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## Faraday and Ampere

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The correspondence between Faraday and Ampere began in the early 1820's and continued for many years. The two got along very well, but their scientific styles were very different. Faraday was a superb experimentalist who approached his subject with great intuition and imagination, but he was very careful in his speculations and analyzed things in very physical terms. Ampere, also a fine laboratory scientist, was a mathematical genius who sought to describe nature through numbers and abstract symbols. Faraday's lack of mathematical training always limited his appreciation of the accomplishments of theorists like Ampere. A letter from Faraday to Ampere, written in 1825, voices the complaint, "With regard to your theory, it so soon becomes mathematical that it quickly gets beyond my reach. . . ."

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## Electromagnetism

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While the magnetic effects of electric currents were something that many besides Oersted had suspected, the nature of these effects was surprising. What astonished many was the circular nature of the magnetic influence of a current-carrying wire. All other such influences in nature had been observed to be linear.

# ELECTROCHEMISTRY

## Volta's Pile

The first years of the 19th century were an exciting period in the history of electricity largely due to the discovery of Alessandro Volta, an Italian physicist. In 1800, Volta announced that he had found a new source of electricity – what we call the battery. Before that time, the only important means of generating electricity was by friction, as in the creation of static electricity by rubbing fur or hair. Volta showed how to construct a "pile" of discs, alternating silver and zinc, separated by pieces of moistened cloth, to create a source of electric current. The Voltaic pile caused a sensation and quickly became an indispensable tool for a vast number of new experiments.



*Volta's Pile*

## Davy and Electrochemistry

No one made better use of Volta's pile than Humphry Davy at the Royal Institution. There Davy constructed a giant "battery" of piles which he then used in a variety of dazzling experiments. Since Davy was convinced that the source of Voltaic electricity was a chemical reaction, he proceeded to show how it, in turn, could cause other reactions. His most important results were the discovery, by electrolysis, of hitherto unknown chemical elements, including sodium, potassium, calcium, and magnesium. Learning from Davy, Faraday himself became skilled at electrolysis, and, much later (in 1834), discovered the laws that describe the relationship between the amount of a substance decomposed and the quantity of electricity used.



*Alessandro Volta. Burndy Library*

## THE SEARCH FOR RELATIONSHIPS

### After Oersted

Assisted by the Voltaic cell, and spurred on by Oersted's discovery of electromagnetism, in the 1820's scientists throughout Europe and in America explored the nature of electricity and its relationship with other forces. In France, Francois Arago discovered the magnetic effect of a rotating copper disc, a mysterious phenomenon explained years later by Faraday. In England, Charles Babbage, famous as the pioneer of the digital computer, attempted to explain Arago's effect in terms of Ampere's electrodynamics. And in Germany, Georg Simon Ohm performed the experiments that led to the statement of his law, relating the current in a wire to the electromotive force (voltage) and the resistance in the circuit.



*Francois Arago. Burndy Library*



*Charles Babbage.  
Burndy Library*



*George Simon Ohm.  
Burndy Library*

### In America

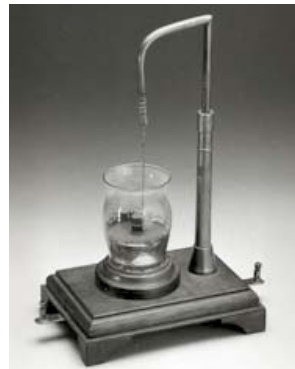
The excitement over electromagnetism was not confined to Europe, but it stirred up interest in the small scientific community of the United States. Unquestionably the most important American experimenter was Joseph Henry, who in the late 1820's was a teacher of mathematics and science in Albany, N.Y. Henry learned how to greatly increase the power of electromagnets, and was one of the first to seek practical uses for them. In 1831, he devised the first electromagnetic telegraph and carried out experiments that led him to the independent discovery of electromagnetic induction. Due to his failure to publish his discovery, he never received the same recognition as Faraday. Henry later became the first Secretary of the Smithsonian Institution in Washington.



*Joseph Henry. Burndy Library*

### Faraday's Rotator

Among the scientists who turned their attention to the investigation of Oersted's electromagnetism was Michael Faraday himself. It did not take Faraday long to make an extraordinary contribution of his own – the first electric motor. Intrigued by the apparent circular nature of electromagnetic effects, Faraday constructed a "rotator", consisting of a magnet stuck upright in a cup of mercury, with a current-carrying wire hanging down from above, with one end in the mercury. When the circuit of the wire, mercury, and battery was completed, the wire began rotating around the magnet. Faraday also demonstrated that a magnet could be made to rotate similarly around a wire. It was more than 50 years before a practical electric motor was invented, but Faraday clearly demonstrated the principle.



*Faraday's rotator. National Museum of American History, Smithsonian Institution*

### Thermoelectricity

The widespread belief that all the forces of nature were related to one another was given powerful support by the discovery of electromagnetism. This spurred the search for further relationships. In 1821, the German Thomas Johann Seebeck discovered a connection between electricity and heat by his observation of what is known as the "Seebeck effect." In this instance of thermoelectricity, heat applied at the junction of two different metals causes a current to flow. This is the principle applied in the thermocouple, which is used for very accurate measurements of temperature. Seebeck announced his discovery in a paper published in 1823.

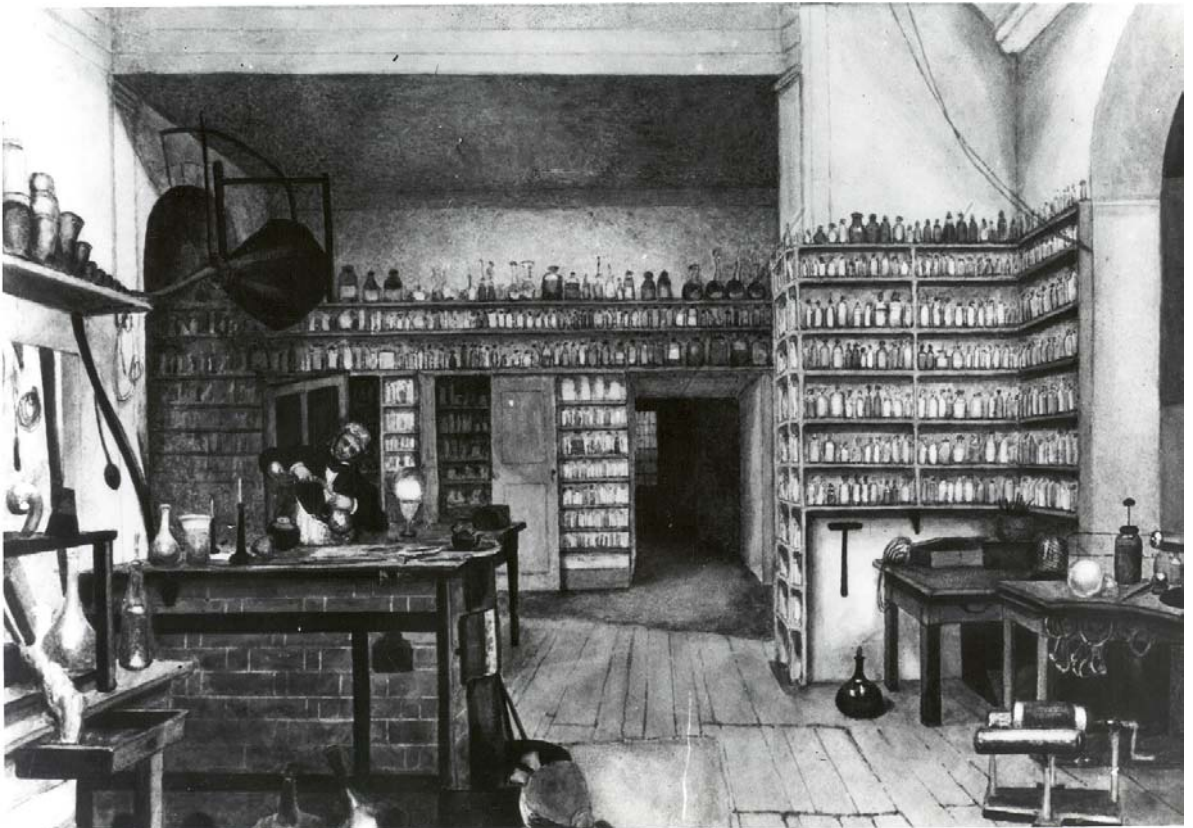
## THE GREAT EXPERIMENTALIST

### Faraday in the Laboratory

Faraday's motto was "Work, Finish, Publish." No scientist in the 19th century excelled Faraday in the laboratory, for there he combined superb technique with a scientific intuition that was the wonder of his colleagues. His training as an analytic chemist under Humphry Davy, added to the natural ability he had shown even as a book-binder, gave him skills at physical manipulation in the laboratory that were unmatched. To these skills he added extreme care in making and recording his observations, as his laboratory notes show. Equally important, he brought to his work a fruitful yet disciplined imagination, shunning wild speculation but always receptive to well-argued new ideas.

### The Apparatus

Faraday's laboratory at the Royal Institution was a well-equipped one, but his most important experiments were done with very simple devices. The crucial work that he did in the summer and fall of 1831, leading to the discovery of electromagnetic induction, was done with a simple ring of soft iron, wrapped with copper wire, with a trough battery supplying current and a compass needle as a meter. Another important device consisted of a paper cylinder wrapped with copper wire and connected to a galvanometer. With these simple tools, Faraday revolutionized electrical science. The originals are still preserved at the Royal Institution in London.



*Faraday in the laboratory at the Royal Institution. Royal Institution, courtesy AIP Niels Bohr Library.*



*Faraday's coil and magnet. Royal Institution, courtesy AIP Niels Bohr Library*



*Faraday's induction ring. Royal Institution, courtesy AIP Biels Bohr Library*

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### The Crucial Experiments

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Between 1821, when he invented his rotator, and 1831, Faraday was too busy with other matters to give much attention to electromagnetism. In August of 1831, however, he undertook experiments to test some notions he had about the nature of electricity. He rejected the idea that electricity consisted of a fluid or a stream of particles, but the action of his rotator convinced him that something must move through a wire. Some experiments on sound suggested to Faraday that electricity might consist of vibrations moving through matter.

If this were so, Faraday reasoned, perhaps he could cause the vibrations in one current-carrying wire to set up similar vibrations in a nearby, but separate, wire. Thinking that these vibrations might be intensified by acting through an electromagnet, he made one out of an iron ring wrapped with wire on one side. On the other side of the ring, he wrapped another coil of wire, which he attached to a galvanometer (simply a compass with a wire connected). When, on August 29th 1831, he connected the first side of the ring to a battery, he was watching the galvanometer needle – it jumped, then returned to normal. On disconnecting the battery, the needle jumped again. By starting or stopping a current in the first wire, he had induced, for an instant, a current in the second wire. Faraday had made a great discovery, but it was only the beginning of his work, not the end.

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### Using a Magnet

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Faraday quickly realized that his ring experiment not only supported his notions about electricity, but it also revealed something about the relationship between electricity and magnetism. Faraday embarked on a series of experiments to further clarify this relationship. The most important of these was with a paper cylinder wound with several coils of copper wire, connected to a galvanometer. When Faraday thrust a bar magnet into the hollow of the cylinder, the meter's needle jumped, then when he pulled the magnet out, the needle jumped again, but in the opposite direction. Induction did not require the creation of a magnet (as in the ring experiment), but was caused simply by moving a magnet near a wire. This was truly, in Faraday's words, "the production of electricity from magnetism."

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### Reporting the Results

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Faraday was well aware that he had made a very important discovery, but he also knew that he did not understand what he had found. He therefore took time over the next few months to experiment and further work out his ideas. Finally, in late November, 1831, he felt he knew enough to announce his findings to the Royal Society. He then wrote a letter to Richard Phillips, one of his best friends, explaining the research program that he had set out for himself, the results of which were to appear as his *Experimental Researches in Electricity* over the next twenty years. To Phillips, Faraday would confess that "It is quite comfortable to me to find that experiment need not quail before mathematics, but is quite competent to rival it in discovery."

## INTERPRETATION AND APPLICATION

### Lines of Force

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While Faraday was always careful in his theorizing, he did not shrink from attempting to explain the effects he discovered. In his first report to the Royal Society on electromagnetic induction, in November 1831, he proposed a number of concepts to help explain how magnetism could produce electricity. The most important of these was the idea of magnetic "lines of force". An electric current was produced, Faraday suggested, when a conductor passed across these lines of force. Furthermore, it seemed that the direction and strength of the current depended in the direction and speed of the relative motion of the conductor and the lines of force. This turned out to be one of the most powerful ideas in all electrical science, though its true power was only realized by James Clerk Maxwell more than thirty years later.

### A New Source of Electricity

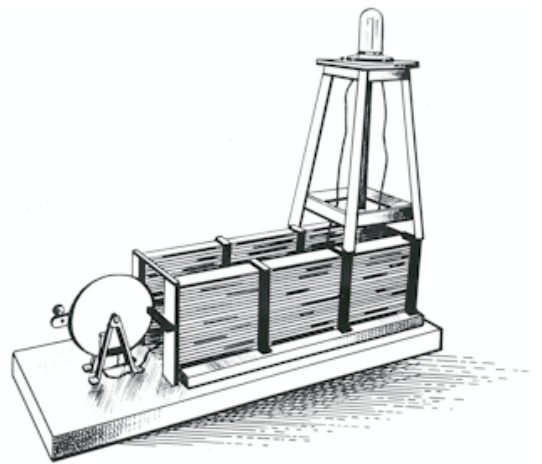
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In the course of his experiments in the Fall of 1831, Faraday asked himself this question: if he could produce a momentary current by moving a magnet in and out of a coil of wire, was there a way to produce a continuous current? Faraday ingeniously devised a way, rigging up a copper disc that rotated between the poles of a large magnet. When the disc was turned, a wire was applied to its edge and another to the axis. A meter between the wires revealed that a steady current was being produced. Faraday had invented the electric generator -- one of the most important discoveries in the history of technology.

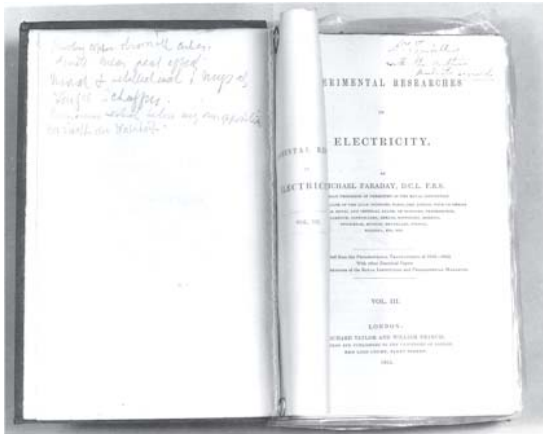
### Experimental Researches

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Faraday's announcement to the Royal Society in November 1831 of his discovery of electromagnetic induction was the first of the long series of papers that were collected together and printed as *Experimental Researches in Electricity*. In their final form, the *Experimental Researches* filled three volumes, which became the bible of electrical science for most of the nineteenth century, guiding such disparate figures as John Tyndall, Faraday's successor at the Royal Institution, and Thomas Edison, to whom Faraday was the "Great Experimenter."



*Faraday's first generator, Burndy Library*



Faraday's *Experimental Researches in Electricity* from the copy belonging to John Tyndall. Burnby Library

### Faraday on Electric Waves

*I am inclined to compare the diffusion of magnetic forces from a magnetic pole to the vibrations upon the surface of disturbed water, or those of air in the phenomenon of sound, i.e., I am inclined to think the vibratory theory will apply to these phenomena as it does to sound, and most probably light.*

in observations deposited  
at the Royal Society  
12 March 1832

## APPRECIATION

### An Engineer on Faraday

*Perhaps the greatest discovery of Faraday's long career of scientific research was that of electromagnetic induction in the year 1831. . . . Faraday's discovery was a great step; it revealed the action of magnetic force in apparently empty space, it inaugurated that deeper insight into the mechanism, still only dimly guessed, which connects matter with all other matter in space; and it invested the all pervading ether with a dignity and power that in the hands of many great men since his time, has probably paved the way for our future comprehension of magnetism, gravitation, and radiant energy. . . . The development of this discovery of electromagnetic induction had practically created electrical engineering."*

Arthur E. Kennelly  
Trans. AIEE, 1890

### A Scientist on Faraday

*When we consider the life work of Faraday it is clear that his researches were guided and inspired by the strong belief that the various forces of nature were inter-related and dependent on one another. It is not too much to say that this philosophic conviction gave the impulse and driving power in most of his researches and is the key to his extraordinary success in adding to knowledge.*

*The more we study the work of Faraday with the perspective of time, the more we are impressed by his unrivalled genius as an experimenter and natural philosopher. When we consider the magnitude and extent of his discoveries and their influence on the progress of science and industry, there is no honor too great to pay to the memory of Michael Faraday – one of the greatest scientific discoverers of all time.*

Lord Rutherford  
1931

### Faraday's Place in History

Michael Faraday was one of the most respected and admired scientists of his day. Held in high regard by his colleagues, his skill as a lecturer and his life-long dedication to spreading the gospel of science to all earned him a widespread popular appeal. His humility led him to refuse some of the honors that might have been his, but he was, in his last years, given a house rent-free by Queen Victoria. There he died in 1867.

The place of Faraday in the history of science and technology is best described by scientists and engineers themselves. In particular, all those who studied and applied electricity in the following years found themselves in Faraday's debt.

## APPRECIATION

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### Faraday's Place in Science and Technology

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His identification with the discovery of electromagnetic induction would be monument enough for a humble man like Michael Faraday, but we owe much more than that to him. Faraday's Laws are the most fundamental principles of electrochemistry. The Faraday Effect, in which he showed how a magnetic field affected polarized light, was the first experimental clue to the electromagnetic nature of light. His experiments in 1833 on the conductivity of silver sulfide provided the first glimpse at the wonderful properties of semi-conductors, the materials at the heart of transistors and all microelectronics. Statues, plaques and medals honor the man in many places, but the electrical engineers' own token of esteem was created in 1891, when the International Electrical Congress voted to name the electrical unit of capacitance the Farad in his honor.

## LINES AND FIELDS

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### The Pursuit of Theory

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Faraday continued to develop and extend his concept of lines of magnetic or electric force in the 1830's and 1840's. Because this concept was not mathematical, however, and seemed to be crudely intuitive, it was rejected by most scientists. There were two important exceptions, however: William Thomson and James Clerk Maxwell. Thomson (who was later made Lord Kelvin) was born in Belfast, Ireland, in 1824, and after excelling as a student of mathematics and physics, he became a professor at the University of Glasgow, where he stayed for more than fifty years. In 1845, Thomson published a paper showing how Faraday's lines of force could be interpreted mathematically, and he subsequently showed how Faraday's concepts of magnetic and electrostatic force could be treated analogously to theories of heat and mechanics, thus laying the mathematical foundations of field theory.

### Faraday and Maxwell

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Even in his later years, in failing health and memory, Faraday kept up a widespread correspondence with the leading scientists of his time. He also paid generous attention to the younger generation of scientists, even though his lack of formal training, especially in mathematics, often limited his appreciation of their work. James Clerk Maxwell was only 26 when his often highly abstract work elicited this response from Faraday:

*When a mathematician engaged in investigating physical actions and results has arrived at his conclusions, may they not be expressed in common language as fully clearly and definitely as in mathematical formulae? If so, would it not be a great boon to such as I to express them so – translating them out of their hieroglyphics that we also might work upon them by experiment.*

### The Debate on Lines of Force

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In one of the last scientific papers of his life, Faraday acknowledged the debate over his ideas, and recognized the assistance he had received from supporters like Thomson:

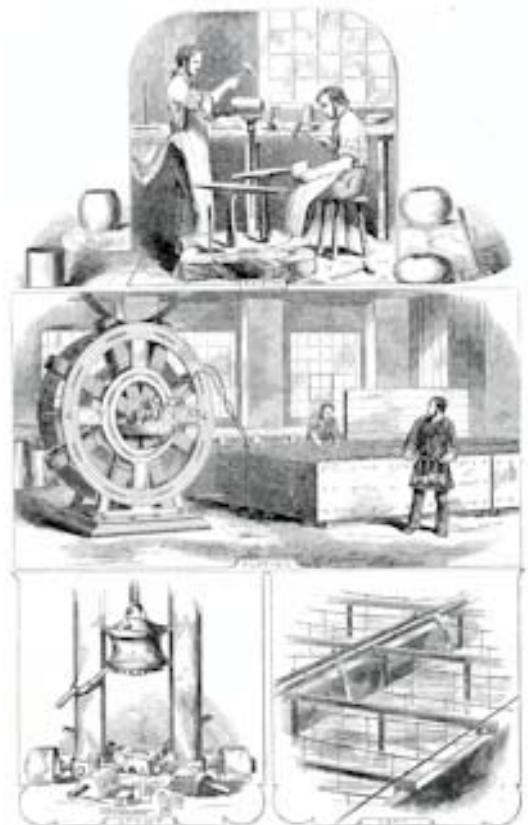
*The attention of two very able men and eminent mathematicians has fallen upon my proposition to represent the magnetic force; and it is to me a source of great gratification and much encouragement to find that they affirm the truthfulness and generality of the method of representation.*

## Application

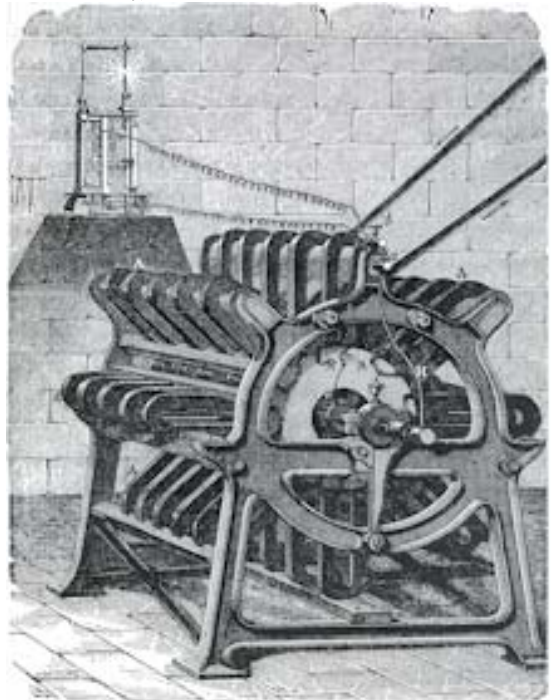
The practical implications of Faraday's discovery of electromagnetic induction in 1831 were quickly recognized. Only a year later, Hyppolyte Pixii, in France, devised the first effective electric generator. Within a decade, in the 1840s, generators were being used for electroplating. In the 1850s, the first efforts were made to apply them to electric lighting, using bright, glaring arc lights. Skeptical at first, Faraday himself was finally persuaded that they would be useful in lighthouses.



*Model of Pixii generator, National Museum of American History, Smithsonian Institution*



*Electroplating works, with generator, 1840s. National Museum of American History, Smithsonian Institution.*



*Generator for arc lighting, 1085s.  
National Museum of American History,  
Smithsonian Institution*



MAXWELL



## BEGINNINGS



*John Clerk Maxwell. Courtesy Prof. C.W.F. Everitt.*



*Glenair. Courtesy Prof. C.W.F. Everitt*

### Origins

James Clerk Maxwell was born in Edinburgh, Scotland on the 13th of June, 1831. The Clerk Maxwells (that was the family name) were comfortably well-off land owners, and John Clerk Maxwell, James' father, was an educated man, trained in the law and interested in science and invention. Since his mother died when he was only eight, his father had great influence on the young Maxwell's education, and provided considerable encouragement for his scientific bent.

### Childhood

Maxwell's childhood years were divided between Edinburgh and the family estate of Glenair, in the Galloway region of Scotland. At Glenair, Maxwell spent his boyhood in a fashion typical of more liberal landed gentry of the day. His most important companion was his cousin, Jemima Wedderburn, and it is thanks to her that we possess such a charming picture of the more comfortable aspect of life in rural Scotland in the middle of the 19th century. Both she and James Clerk Maxwell himself proved to be talented sketchers, as shown by these examples of her work.



*Pictures by Jemima Wedderburn,  
From the collection of  
Briggadier John Wedderburn-Maxwell  
Courtesy of Prof. C.W.F. Everitt*



### Education

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Education was valued highly in the Scotland of Maxwell's youth, and he had the advantage of the best Edinburgh could offer. He began to show signs of brilliance as a student at the Edinburgh Academy, and had a paper read before the Royal Society of Edinburgh when he was 14. At age 16, he entered the University of Edinburgh, where he first began to direct his attention to physics. Finally, in 1850, he entered the University of Cambridge, where, as a student at Trinity College, he was exposed to the finest mathematical and scientific minds in Britain. At Cambridge, Maxwell acquired the scientific sophistication and academic polish that permitted him to move quickly into the most elevated circles of British science.

### Professor Maxwell

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Unlike some other great scientists of his time, like Faraday and William Thomson, Maxwell's academic career took him to many places. Soon after leaving Cambridge he became Professor of Natural Philosophy in Aberdeen, Scotland. In 1860, he moved to London as a professor at King's College, but after five years he moved back to Scotland to take care of the family estate. Finally, in 1871, he was appointed the first Cavendish Professor of Experimental Physics at Cambridge, and there he devoted his time to building up the new Cavendish Laboratory, which, by the time of Maxwell's death in 1879, was on its way to becoming one of the foremost physics laboratories in the world.

### The Gentlest of Men

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Few men have so combined high intellectual achievement with a reputation for gentle character and rich good humor as James Clerk Maxwell. Short of stature and hesitant of speech, Maxwell nonetheless made a deep impression on those around him. His devotion to his wife and his quiet religious faith were aspects of his humble side. The exuberant good humor that shows in his poetry (which he wrote throughout his life) shows, however, that he was anything but dour.



*Maxwell as a student at Cambridge, 1855. Burndy Library*

## GENTLEMAN AND SCHOLAR

### Excerpts from a Poem Written while a Student at Cambridge

*Deep St. Mary's bell has sounded,  
And the twelve notes gently rounded  
Endless chimneys that surrounded  
My abode in Trinity.  
(Letter G, Old Court, South Attics),  
I shut up my mathematics,  
That confounded hydrostatics –  
Sink it in the deepest sea!*

*In the grate the flickering embers  
Served to show how dull November's  
Fogs had stamped my torpid members,  
Like a plucked and skinny goose.  
And as I prepared for bed, I  
Asked myself with voice unsteady,  
If of all the stuff I read, I  
Ever made the slightest use.*  
from "A Vision," 1852



Maxwell, his wife, Katherine Mary Dewar, and their dog, Toby.  
Courtesy Prof. C.W.F. Everitt

### Valentine by a Telegraph Clerk ♂ to a Telegraph Clerk ♀

*"The tendrils of my soul are twined  
With thine, though many a mile apart,  
And thine in close-coiled circuits wind  
Around the needle of my heart.*

*"Constant as Daniell, strong as Grove,  
Ebullient through its depths like Smee,\*  
My heart pours forth its tide of love,  
And all its circuits close in thee.*

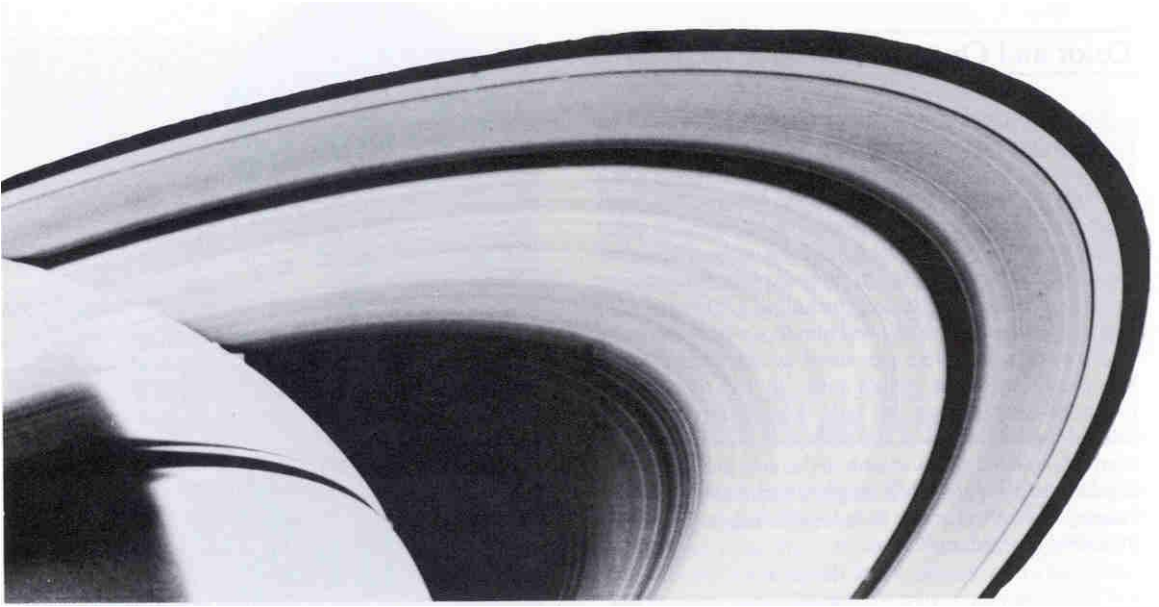
*"O tell me, when along the line  
From my full heart the message flows,  
What currents are induced in thine?  
One click from thee will end my woes."*

*Through many an Ohm the Weber flew,  
And clicked this answer back to me, --  
"I am thy Farad, staunch and true,  
Charged to a Volt with love for thee."*

*\*Daniell, Grove and Smee are types of batteries  
used by telegraphers.*



Maxwell about the time he became Professor at Cambridge, 1872.  
Courtesy Prof. C.W.F. Everitt.



*Saturn's rings as taken by Voyager I. Courtesy NASA Jet Propulsion Laboratory.*

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### What are Saturn's Rings?

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When, in 1610, Galileo first pointed a telescope toward Saturn, he saw what appeared to be little stars attached to the side of the planet. Almost 50 years later, the Dutch scientist Christian Huygens discovered that these were in fact rings circling Saturn. Since that time, Saturn's rings have fascinated observers, and have posed a riddle -- what are they? Now, in the 1980's, thanks to the Voyager space probes, we can see for ourselves that the rings are made of millions of particles, ranging in size from dust to many meters in diameter. In this result, at least, Voyager's wonderful pictures came as no surprise, because scientists have believed for more than 100 years that the rings were made of particles, thanks not to an astronomer, but to a mathematical physicist, James Clerk Maxwell.

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### The Power of Physics

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When Maxwell was still a Fellow at Cambridge, he wrote a paper, "On the Stability of the Motion of Saturn's Rings," which the Astronomer Royal of England described as "one of the most remarkable applications of Mathematics to Physics that I have ever seen." Here, Maxwell showed that the only structure of Saturn's rings that was consistent with the accepted laws of mechanics was "one composed of an indefinite number of unconnected particles." Maxwell achieved this result by skillful mathematical analysis, but he then, typically, went on to illustrate his argument with a model, which can still be seen in the Cavendish Laboratory, Cambridge.

# MAXWELL AT WORK

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## Color and Optics

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Maxwell's chief contributions to science were based on his mathematical skills and his ingenuity in applying them to physics. He was never without an interest in experiment, however, and he distinguished himself in several areas with his experimental work. For his work on color perception, Maxwell was awarded the Rumford Medal of the Royal Society in 1860. In these experiments he constructed a number of devices, including a "color wheel" and a "color box," that allowed him to see how mixtures of different colors were perceived by different people. His most important collaborator in this work was Katharine Mary Dewar, his wife. Maxwell's work constituted the beginnings of the science of quantitative colorimetry. Related achievements in this area included making the first true color photograph, which he displayed to Faraday and others at the Royal Institution in 1861, and inventing the "fish-eye" lens.



## Thermodynamics

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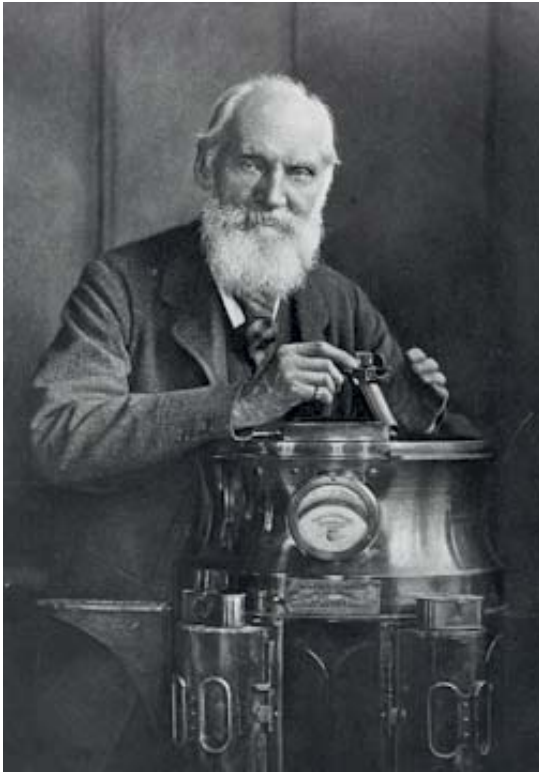
The field of science, beside electromagnetism, with which Maxwell's name is most closely associated, is thermodynamics, or, more precisely, the study of the motion of molecules. Here, Maxwell's contribution consisted of both mathematical analysis and experimental observations. Beginning with Rudolf Clausius' work on the kinetic theory of gases, Maxwell was one of the primary figures in the development of statistical mechanics – the analysis of the behavior of large numbers of molecules. To point out the statistical nature of the second law of thermodynamics (which says that heat can never pass on its own from a colder to a warmer body), he invented "Maxwell's demon" – the fantastic creature that would be necessary to sort out fast and slow molecules in a gas.

## Maxwell's Experimental Method

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*There is a tradition in Trinity that when I was here I discovered a method of throwing a cat so as not to light on its feet, and that I used to throw cats out of windows. I had to explain that the proper object of research was to find how quick the cat would turn round, and that the proper method was to let the cat drop on a table or bed from about two inches, and that even then the cat lights on her feet.*

Maxwell writing to his wife, 1870



Lord Kelvin, National Museum of American History, Smithsonian Institution.

### William Thomson, Lord Kelvin

No scientist had greater influence on Maxwell's work on electricity than William Thomson. It was Thomson, like Maxwell a graduate of Cambridge, who provided a glimpse of the possibilities inherent in Faraday's concept of lines of force. He also made important contributions to magnetic theory and wrote one of the earliest studies of electrical oscillations (using a Leyden jar). Thomson was one of the most honored scientists of his day, due largely to his contributions to electrical engineering. He applied himself to many of the problems that arose with attempts to lay a telegraphic cable under that Atlantic between Britain and America. The ultimate success of the Atlantic cable in 1866 owed much to Thomson, who accompanied the cable layers aboard the ship, *Great Eastern*. Thomson was elected president of the Royal Society and three times president of the Institution of Electrical Engineers.

### Maxwell on Thomson

*I was aware that there was supposed to be a difference between Faraday's way of conceiving phenomena and that of the mathematicians, so that neither he nor they were satisfied with each other's language. I had also the conviction that this discrepancy did not arise from either party being wrong. I was first convinced of this by Sir William Thomson, to whose advice and assistance, as well as to his published papers, I owe most of what I have learned on the subject.*

Maxwell, *Treatise on Electricity and Magnetism*, 1873

### Galvanometers and Recorders

Foremost among William Thomson's contributions to electrical engineering and to the success of submarine telegraphy were the instruments he invented for receiving the very weak signals that emerged from a cable over 2,000 miles long. Thomson's mirror galvanometer was the first satisfactory receiver, and was so sensitive that it clearly registered a round-trip transatlantic signal powered by a thimble-sized battery. Later, his siphon recorder proved to be even more sensitive and had the advantage of making a permanent record on paper of signals received.



Kelvin's mirror galvanometer. National Museum of American History, Smithsonian Institution.

# ELECTRICITY: SCIENCE AND ENGINEERING

## Maxwell's Practical Side

Maxwell was much less interested in engineering problems than William Thomson, but he did make contributions in at least one area -- standards. As a member of a Committee organized by the British Association (at the suggestion of Thomson) to determine a standard unit of electrical resistance Maxwell was particularly useful. While a professor at King's College, London, Maxwell joined with others to make the fundamental measurements needed to define the ohm, the unit of electrical resistance.



*The British Association standard ohm. National Museum of American History, Smithsonian Institution.*

## MAXWELL'S EQUATIONS

### Maxwell's Equations

*To the question, "What is Maxwell's theory?", I know of no shorter or more definite answer than the following: Maxwell's theory is Maxwell's system of equations.*

Heinrich Hertz, 1891

### A Theory in Mathematical Form

Maxwell's greatest work was his contribution to electromagnetic theory. As stated by Heinrich Hertz, who helped confirm Maxwell's predictions, the theory was embodied in Maxwell's famous equations of the electromagnetic field. These equations were mathematical interpretations of Faraday's concepts, transforming the ideas about lines of force into precise formulas. Out of this transformation emerged a new picture of the relationship between electricity and magnetism. And from Maxwell's propositions about how electricity and magnetism were propagated through space came a startling new theory of electromagnetic waves, seen in their most familiar form as light.

$$\nabla \cdot \mathbf{D} = \rho$$

### Electric Force

An electric charge is a source of an electric field. In terms more familiar to Faraday, this equation says that electric lines of force begin and end on electric charges (though this is not necessarily true in a changing magnetic field).

$$\nabla \cdot \mathbf{B} = 0$$

### Magnetic Force

There are no such things as "magnetic charges," therefore, magnetic lines of force always form closed loops (and never diverge from a point source).

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

### Electromagnetic Induction

Voltage is generated in a conductor as it passes through a magnetic field (or cuts magnetic lines of force). This was Faraday's great discovery of 1831.

$$\nabla \times \mathbf{H} = \mathbf{j} + \frac{\partial \mathbf{D}}{\partial t}$$

### Magnetic Effect of Electric Current

An electric current is always surrounded by a magnetic field (or lines of force). This was the conclusion that Faraday had derived from Oersted's experiment.

There are many ways of writing Maxwell's equations. The important symbols in the forms use here are:

$\mathbf{D}$  = electric flux density

$\rho$  = electric charge density

$\mathbf{B}$  = magnetic flux density

$\mathbf{H}$  = magnetic intensity

$\mathbf{E}$  = electric field strength

$\nabla$  is a "vector operator", indicating that the equations refer to conditions in all directions in space.

# INTERPRETING FARADAY

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## On Faraday's Lines

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Most 19th century physicists rejected Michael Faraday's concept of lines of magnetic force. The idea seemed too fuzzy and crude to mathematically trained men, who felt comfortable only with motions and forces that could be precisely measured. Maxwell, however, after reading the work of William Thomson and of Faraday himself, believed that the lines of force did indeed represent something real. He then set out to show how Faraday's intuitive concept could be put into mathematical form. Beginning in 1856, with his paper "Faraday's Lines of Force", Maxwell produced a long series of articles which were to revolutionize ideas about electricity, magnetism, and light. In these papers he carefully explored the implications of Faraday's ideas, developed analogies and models to show how these ideas related to more familiar concepts, and finally formulated the mathematical expressions that made up his famous equations.



Maxwell in 1868. Courtesy of Prof. C.W.F. Everitt

## Maxwell on Faraday

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*As I proceeded with the study of Faraday, I perceived that his method of conceiving the phenomena was also a mathematical one, though not exhibited in the conventional form of mathematical symbols. I also found that these methods were capable of being expressed in the ordinary mathematical form, and thus compared with those of the professed mathematicians.*

Treatise on Electricity and Magnetism, 1873

## Mathematical and Mechanical Reality

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It was widely accepted in the middle of the 19th century that there was a fundamental difference in the descriptions of nature used by mathematicians and those with a more purely physical outlook. This is one of the reasons that Faraday's theoretical ideas were not closely looked at by mathematicians. The work of Maxwell changed all of this. He said that one of the reasons for his studies in electromagnetism was to demonstrate that the gap that others perceived between the intuitive notions of Faraday and the mathematical approach found in the universities could be bridged. Not only did Maxwell succeed in closing this gap, but his work later became the key influence in extending the application of mathematical analysis beyond the boundaries of science and into the realm of engineering.

## The Treatise

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Maxwell's Treatise on Electricity and Magnetism appeared in 1873. It represents the one effort that Maxwell made to bring all of his ideas about electricity and magnetism together in a single work, and its influence was enormous. Almost all the elements of Maxwell's theory had appeared in his earlier papers, but the Treatise allowed scientists to see his ideas as parts of a complete (if not polished) theory.

Even for scientists, however, the Treatise was a very difficult book, and for others it was largely incomprehensible. It required decades, therefore, for the true importance of Maxwell's accomplishment to become generally known and appreciated.

The Electromagnetic Nature of Light

*...we have strong reason to conclude that light itself -- including radiant heat, and other radiations if any -- is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws.*

Maxwell, "Dynamical Theory of the Electromagnetic Field," 1864

Electromagnetic Waves

The most wonderful product of Maxwell's interpretation of Faraday was his conclusion that electrical and electromagnetic phenomena acted through waves. Like Faraday, Maxwell rejected the common notion that these phenomena were the product of forces that acted instantaneously between bodies at a distance, with no intervening medium. Instead, Maxwell said that there was a medium -- an "ether" -- that surrounded everything, filling all space, even a vacuum. Electricity acted through disturbances in this medium, disturbances that traveled in the form of waves. Using his equations, he showed that all such waves must be both electrical and magnetic in nature and that the speed with which the wave travels is equal to the ratio between the electrostatic and the electromagnetic units in which a given quantity of electricity is measured. This ratio was already known from experiment to yield a speed of about 300,000,000 meters per second.

This value was so close to the accepted figure for the velocity of light that Maxwell wrote in a long letter to Faraday (1861):

*I think we now have strong reasons to believe, whether my theory is a fact or not, that the luminiferous and the electromagnetic medium are one. . . .*

The Speed of Light

The first serious efforts to determine the speed of light were made in the 17th century, and beginning in the middle of the 19th century very careful measurements were made by a number of experimenters. After Maxwell pointed out the correlation between the figures for the speed of light and those for the electromagnetic/electrostatic ratio, many measurements were made of both in an effort to confirm experimentally their agreement.

DATE	INVESTIGATOR	OPTICAL (X 10 <sup>8</sup> meter)	ELECTRICAL (sec.)
1849	Fizeau	3.153	
1856	Weber & Kohlrausch		.107
1862	Foucault	2.98	
1868	Maxwell		.842
1869	Wm. Thomson & King		.808
1872	Michelson		.896
1878	Comu	3.004	
1879	Ayrton & Perry		.960
1879	Michelson	2.9991	
1880	Shida		.995
1882	Newcom	2.9984	

Implications

The implications of Maxwell's theory of electromagnetic waves and his identification of light with these waves were enormous. It took many years, however, for many of Maxwell's concepts to be widely accepted and for the implications to be worked out. One thing suggested by the theory was that there should exist electromagnetic waves of a form other than light -- of the same speed but differing in frequency and wavelength. It took more than two decades after Maxwell's first prediction of these waves before they were detected by the German physicist, Heinrich Hertz. Another result of Maxwell's theory was that it focused attention on his electromagnetic medium, the ether. Experimental efforts to detect the ether, such as those of the American physicist Albert A. Michelson, led to such anomalous results that many physicist were thrown into confusion, only to be rescued by Albert Einstein's special theory of relativity, published in 1905.

## APPRECIATION

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### Albert Einstein on Maxwell

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The greatest alteration in the axiomatic basis of physics -- in our conception of the structure of reality -- since the foundation of theoretical physics by Newton, originated in the researches of Faraday and Maxwell on electromagnetic phenomena.

### A Radio Man on Maxwell

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*The whole system of wireless telegraphy is a development of the original and surprising theory of Clerk Maxwell, embodying in mathematical form the experimental researches of Faraday.*

Sir Oliver Lodge

### A Physicist on Maxwell

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*His name stands magnificently over the portal of classical physics, and we can say this of him: by his birth James Clerk Maxwell belongs to Edinburgh, by his personality he belongs to Cambridge, by his work he belongs to the whole world.*

Max Planck

### Recognition

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James Clerk Maxwell was highly regarded by scientists of his day, for his mathematical brilliance was apparent to everyone. He had no popular following like Faraday, however, for he was not a particularly good lecturer. He did not seek the public eye like William Thomson, and thus was not sought out by engineers and industrialists. Up to his death at the age of 48 in 1879, Maxwell was known for his devoutness and modesty, as well as for his fine sense of humor. Widespread public recognition of his contribution to science and, thereby, to technology, came only in the last years of the 19th century, when confirmations of his theory began to be commonplace and some glimpses could be seen of the wonderful uses to which it could be put, in the form of radio, power generation, and what was to be known as electronics.



*The Cavendish Laboratory, Cambridge. Courtesy Cavendish Laboratory, University of Cambridge (copyright).*

### The Cavendish

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The most substantial recognition Maxwell received in his lifetime was his appointment in 1871 as the first Professor of Experimental Physics at the University of Cambridge. In this position, he was also the first Director of the Cavendish Laboratory, which was to become one of the most famous physics laboratories in the world. While he was best known for his theoretical work, Maxwell took seriously the responsibility of designing the laboratory and setting up a course of study in experimental physics. Thanks to Maxwell and his successors, the Cavendish was for decades the unquestioned center of British contributions to atomic physics. One of Maxwell's proudest achievements as Cavendish Professor was the editing and publishing of the experimental writings of the electrical pioneer, Henry Cavendish, whose birth preceded Maxwell's by exactly a century.



Heinrich Hertz,  
Burndy Library



Henry A. Rowland,  
Smithsonian Institution.

## Heinrich Hertz

Unquestionably the most dramatic and persuasive confirmation of Maxwell's theory of electromagnetic waves was the detection of nonoptical waves by Heinrich Hertz between 1886 and 1888. Made Professor of Physics at Karlsruhe University in Germany at the age of 28, Hertz was one of relatively few European physicists who believed Maxwell's theory. He had to solve some very difficult problems in designing a source (transmitter) of electromagnetic waves, a detector, and means for confirming the wave-like nature of the phenomena with which he was dealing. He used the oscillating sparks of an induction coil and a Leyden jar to produce what we would call short radio waves. Focusing the waves with a reflector, he showed their presence by means of sparks in a wire-loop gap a few meters away. Further experiments showed that the "Hertzian" waves behaved just like light -- they could be polarized and could show patterns of interference. And, as was to be shown only a few years later, they could be used for "wireless" communications -- radio.

## Ludwig Boltzmann

While other efforts to confirm Maxwell's predictions were less spectacular than Hertz's, they were still important. Another European who quickly took up Maxwell's ideas was Ludwig Boltzmann, an Austrian. Throughout his career, Boltzmann dealt successfully with many of the same problems that Maxwell studied, especially in statistical mechanics and electromagnetism. Maxwell's theory predicted that the influence that an electric field had on a material, measured by the "dielectric constant" or "permittivity" of the material, should be equal to the square of the refractive index (the measure of how much a material bends light passing into it). Boltzmann performed experiments that showed this was indeed the case for such substances as air, hydrogen, and carbon dioxide. He reported his findings in 1875.

## Henry Rowland

Henry Rowland was one of the first American physicists to take up the challenge of testing Maxwell's theory. While spending a year in the laboratory of the great German physicist, Herman von Helmholtz, Rowland demonstrated that an electric charge on a moving body had exactly the same magnetic effect as an electric current moving through a conductor, just as Maxwell had predicted. Later, after he had become Professor of Physics at the new Johns Hopkins University, Rowland made very accurate measurements of the electromagnetic/electrostatic ratio, further confirming that it was equal to the speed of light.

## Further Confirmation

The physicists discussed here were just a few of those who worked to test Maxwell's theory. Other predictions that were tested, and eventually confirmed, included the relationship between the conductivity of a material and its reflection of light, the slight physical pressure that light exerts on things shined upon, and the relation of light-scattering to reflection and refraction. The importance of the work done under the stimulus of Maxwell's theory lay not only in the confirmation of the theory, but also in the spur that this work gave to such areas as optics, solid-state physics, molecular and atomic theory, and relativity.



Ludwig Boltzmann, Lande Collectin, AIP Niels Bohr Library.

## APPLICATION

### The Importance of Waves

*The discovery of electrical waves has not merely scientific interest though it was this alone which inspired it. Like Faraday's discovery of electromagnetic induction, it has had a profound influence on civilization; it has been instrumental in providing methods which may bring all the inhabitants of the world within hearing distance of each other and has potentialities social, educational and political which we are only beginning to realize."*

Sir J.J. Thomson, 1931

### Radio

Radio and the application of other parts of the electromagnetic spectrum are the most obvious technological products of the work of Maxwell. Before the statement of his theory and his equations, few people even suspected the existence of electromagnetic waves. More than 25 years elapsed between the time Maxwell predicted such waves and Hertz actually produced and detected them. It did not take long after that, however, for men like Oliver Lodge, Guglielmo Marconi, and Aleksandr Popov to begin transforming radio into a practical means of communication. In 1896, Marconi and Popov both sent radio messages over short distances, and five years later Marconi transmitted the first radio message across the Atlantic. In 1912, the extraordinary growth of the new technology was marked by the formation, in New York, of the Institute of Radio Engineers (IRE). Fifty years later, the IRE would become part of the Institute of Electrical and Electronics Engineers.

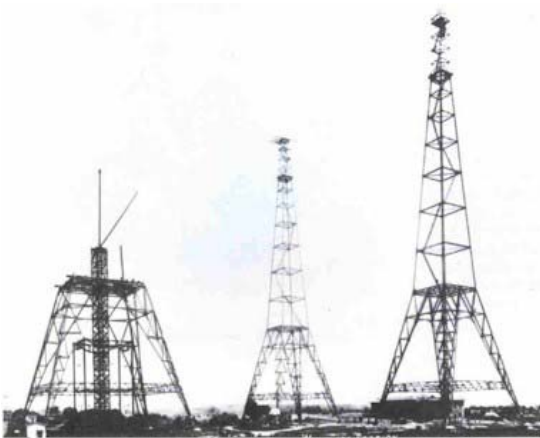
### The Equations in the 20th Century

One measure of Maxwell's achievement is the extent to which his equations are still a basic part of the equipment of the electrical engineer. The design of tools and devices for an enormous range of electrical technologies -- radio, microwave, radar, optical communications, lasers, power generation and transmission, electronic components, and others -- must be based on the proper understanding and application of Maxwell's equations.

The application of Maxwell's theory is at the heart of some of the most exciting new technologies -- lasers, fiber-optics, induction motors, and the like. There is little question that the future holds still more marvels stemming from the use of Maxwell's wonderful equations.



G.C. Southworth with waveguide, Bell Laboratories



Radio towers, about 1912.  
National Museum of American History,  
Smithsonian Institution