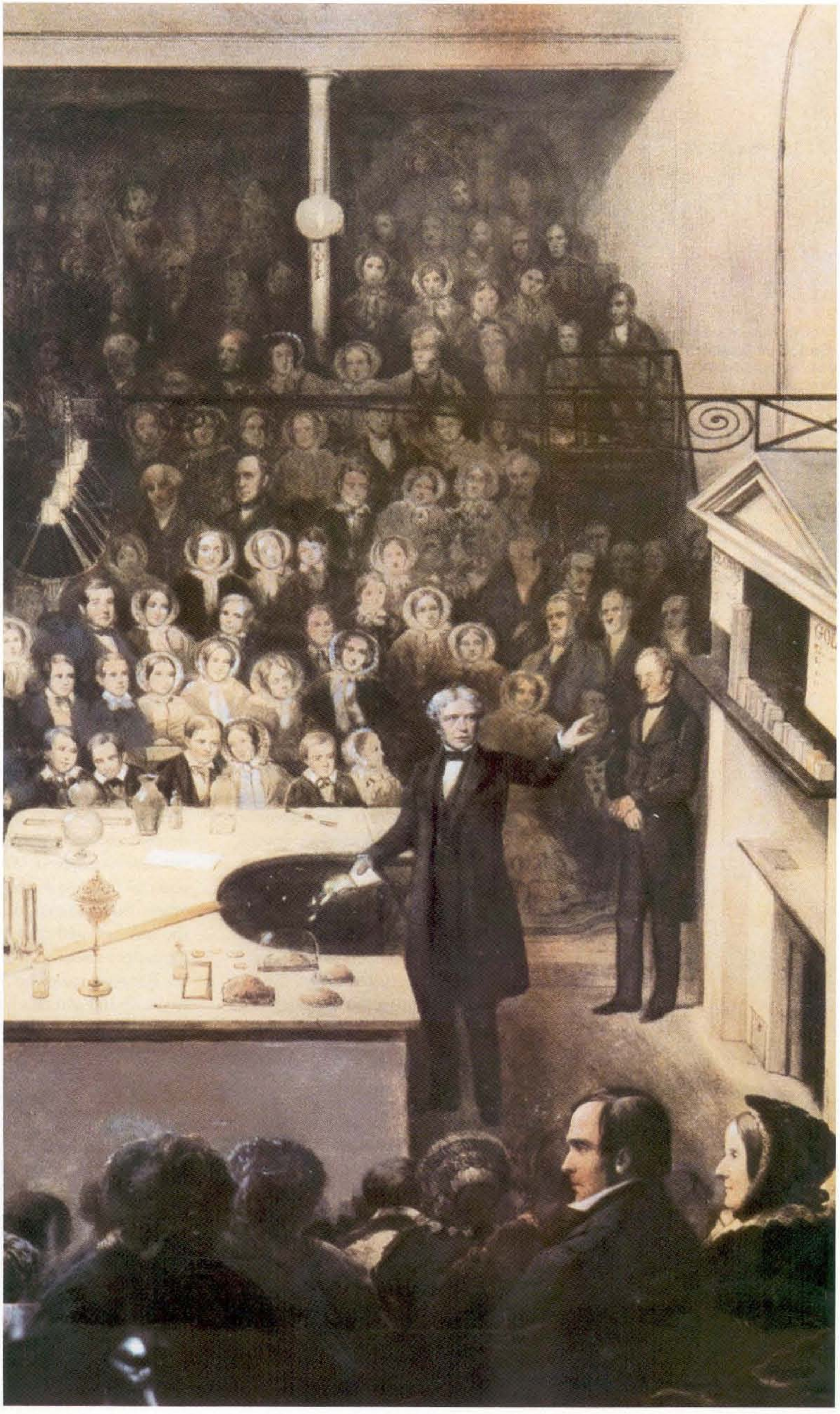
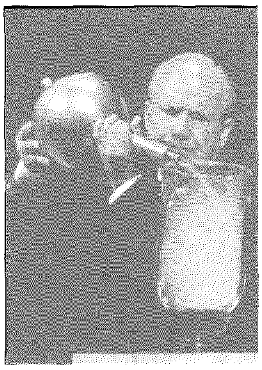


The Genius of Michael Faraday

It was Faraday's faith . . . that the obscure and apparently unrelated curiosities of electricity and magnetism were indeed related.

by Sir John Meurig Thomas



Above: Earnest Watson performs his famous liquid-air demonstration at the opening of Beckman Auditorium in 1964. Left: Faraday lectures at the Royal Institution of Great Britain (detail of painting reproduced on page 25).

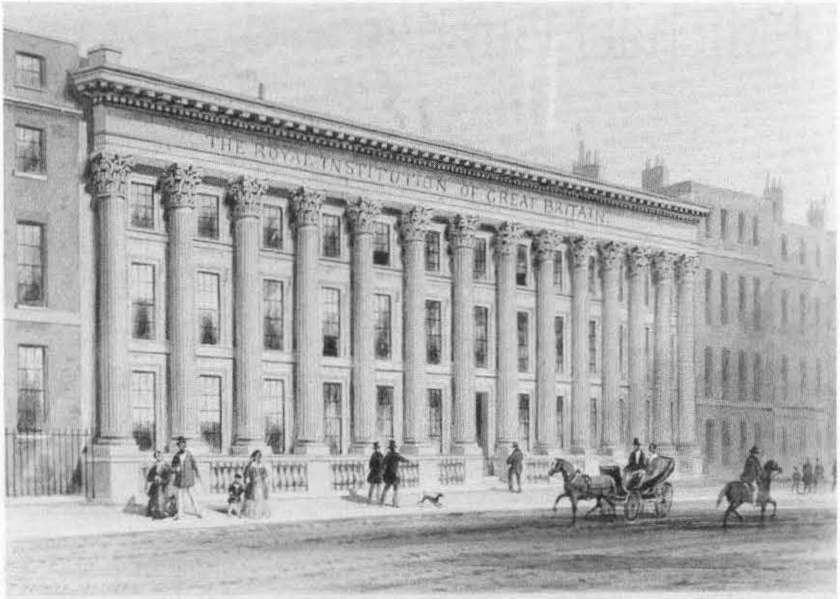
Caltech's centennial coincided with the bicentennial of the birth of one of the greatest experimentalists of all time, the self-taught genius Michael Faraday. One of his lesser known talents was the popularization of science. The Friday Evening Discourses, which he founded at the Royal Institution of Great Britain in 1826, could have been the model for Caltech's Earnest C. Watson Lectures. Watson, who wrote an article about Count Rumford and the Royal Institution in the June 1949 issue of E&S, *was clearly familiar with this tradition. He founded Caltech's Friday Evening Lecture Demonstrations in 1922, first giving his own demonstration of the properties of liquid air in January 1923. A 1925 announcement attested to the lectures' popularity: "This series of popular public lectures covering the whole of the field of physical science and accompanied by a wealth of interesting experiments which has been given for the past three years by the staff of the California Institute of Technology, has met so hearty a response and seems to be filling so real a need in the life of Southern California, that the authorities at the Institute have yielded to the general demand for their continuation." In 1964 Watson's now-famous liquid air demonstration re-inaugurated the public lecture series in the new Beckman Auditorium, and in 1972 the series was named after him.*

Last fall Sir John Meurig Thomas, director of the Royal Institution from 1986 to 1991, who currently holds the Fullerian Professorship of Chemistry, the chair created for Faraday, gave a Watson Lecture on Faraday, his work, and the links of his legacy to Caltech. The following article is adapted from that lecture. Thomas is also the author of a 1991 book on Faraday's life and work, Michael Faraday and the Royal Institution: The Genius of Man and Place.

Albert Einstein had a portrait of Michael Faraday, the blacksmith's son from London, on the wall of his study in Berlin. How appropriate, for it was Faraday's grand revision of humanity's view of the nature of the physical world that laid the foundation for Einstein's work. Newton's picture of the world has permitted us to predict solar and lunar eclipses; it has enabled us to build bridges and space vehicles, to land men on the moon, and to foretell the ebb and flow of the tides. It did not, however, lead to the telegraph, the telephone, radio, television, the magnetic disc, the compact disc, or the fax machine. All those devices, so much a feature of the ferment of modern life, can be traced, step by step, back to Faraday and to his picture of lines of force and the concept of a field.

It was Faraday's faith, nourished by the experiments of others, that the obscure and apparently unrelated curiosities of electricity and magnetism were indeed related; and in the late summer of 1831 Faraday brilliantly elucidated the nature of electromagnetic induction. In just 10 days of effort, spread over a period of 10 weeks, he showed that—and explained how—with the aid of a magnet, electricity could be generated. The dynamo was discovered. That work, together with his demonstration in 1842 that magnetism and light were also connected, coupled with the work of Clerk Maxwell in Cambridge, Hertz in Karlsruhe, Marconi in London, and others, initiated the world of modern communications.

Michael Faraday, the third child of an ailing and impoverished journeyman blacksmith, was born on September 22, 1791, in a part of London



Rumford's idea in setting up the Royal Institution was to create a center "for teaching by courses of Philosophical Lectures and Experiments the application of science to the common purposes of life."

now called the Elephant and Castle, two miles or so south of and across the river Thames from St. Paul's Cathedral. He left school at 13, having had only the most basic education. He became an errand boy and later an apprentice to a kindly bookbinder and bookseller, who encouraged Faraday's propensity to read books—those handed to him for binding and any others that he could lay his hands upon. By his late teens he had read the "Electricity" entry in the third edition of the *Encyclopaedia Britannica.* It was 120 pages long and dealt entirely with static electricity, and it prompted him to build a hand-operated electrostatic generator.

A few years after Alessandro Volta was invited to demonstrate to the Emperor Napoleon (about 1805) his pile of copper and zinc interspersed with sheets of paper soaked in a solution of common salt, Faraday built himself a voltaic pile, and he wrote about it in excited terms to a friend. At about that time he also read hymnwriter Isaac Watts's book on self improvement and Mrs. Marcet's book, *Conversations in Chemistry*, for well-mannered young ladies. His habit of keeping a detailed diary—a practice in which he was to persist with meticulous devotion for over 50 years—was already well formed.

Toward the end of his seven-year apprenticeship he had the good fortune to receive from one of his master's customers tickets for four lecture-demonstrations given in the spring of 1812 at the Royal Institution of Great Britain by one of Europe's foremost scientists, Sir Humphry Davy. The Royal Institution had been founded in 1799 by a colorful and inventive American, Sir Benjamin Thompson, better known as Count Rumford, once described as:

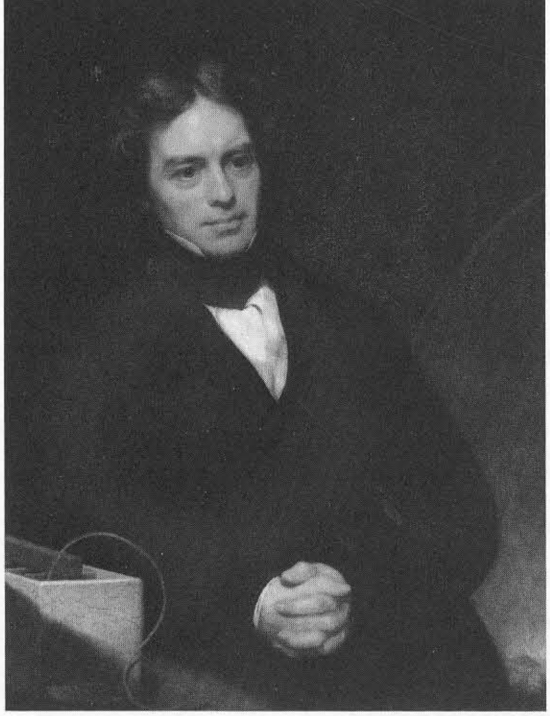
> . . . a loyalist, traitor, spy, cryptographer, opportunist, womaniser, philanthropist, egotistical bore, soldier of fortune, military and technical advisor, inventor, plagiarist, expert on heat (especially fireplaces and ovens) and founder of the world's greatest show-place for the popularization of science, the Royal Institution.

Rumford's idea in setting up the Royal Institution (RI) was to create a center "for teaching by courses of Philosophical Lectures and Experiments the application of science to the common purposes of life." In the prospectus and charter of the RI there are words that resonate with those used by the founders of Throop University, later to become Caltech:

> The two great objects of the Institution being the speedy and general diffusion of the knowledge of all new and useful improvements, in whatever quarter of the world they may originate, and teaching the application of scientific discoveries to the improvements of arts and manufacture in this country and to the increase of domestic comfort and convenience.

The laboratories that Rumford set up in the heart of London's Mayfair predate those of the Cavendish (Cambridge) and the Clarendon (Oxford) by more than 70 years. They are the oldest continuously used scientific laboratories in the world. And the unique lecture theater, which Rumford personally designed and which is still in daily use, has been described by an eminent British broadcaster as "the best studio in the world." Nowadays, the RI is part university, part museum, part research center, part classroom, part library, part club, part exhibition hall, and part broadcasting center. Over the years it has been the scene of perhaps the greatest number of scientific discoveries per unit area anywhere on Earth. Though it has never had a large staff, 15 of its professors have been recipients of the Nobel Prize.

Rumford also knew how to pick winners. In 1801 he appointed two promising young West-country Englishmen. One was 28-year-old Thomas Young from Somerset, later renowned as a physician, physicist, philologist, and physiologist—famed for his work on the modulus of elasticity, wave-theory of light, color vision, capillarity, and the Rosetta Stone. Young was versed in some nine languages, including Syriac, Left: **The Royal Institution of Great Britain on Albemarle Street, London, painted by Thomas Hosmer Shepherd. Right: A copy of this portrait of Michael Faraday by Thomas Phillips hung on the wall of Albert Einstein's study in Berlin. (Reproduced with permission of the National Portrait Gallery, London.)**



In 1826 Faraday initiated two brilliantly successful educational ventures in the public understanding and popularization of science, which continue to this day: the Friday Evening Discourses for lay audiences and the Christmas Lectures for children.

Samaritan, and Chaldean, and had read the Bible from cover to cover at the age of four. But he was an irredeemably poor lecturer—in contrast to the other appointee, Humphry Davy, the 22-year-old Cornishman, who was a coruscatingly brilliant lecturer. By the time Faraday heard him in 1812, Davy had already discovered sodium, potassium, calcium, barium, strontium, and magnesium, and had isolated boron; he had invented the electric arc (in 1802), as well as methods for bleaching cloth, for copying paintings on ceramics, for tanning leather; and, before his arrival at the RI, as a lad of 20, he had discovered the anesthetic properties of nitrous oxide. Later he invented the miner's lamp and the technique of cathodic protection for arresting the corrosion of ships.

Faraday was mesmerized by Davy's carefully prepared, well-rehearsed, fluently delivered performances and breathtaking demonstrations. He took copious notes, rewrote them with illustrations, indexed and bound them, and sent them to Davy along with his request to be employed in the service of science at the RI. On March 1, 1813, Faraday started his duties, essentially as a bottle-washer. But such was his promise, dexterity, devotion to duty, mental alertness, and general intellectual awareness, that by September of that year Faraday was already engaged in helping Davy with preparations such as that of the capriciously explosive compound nitrogen trichloride.

In October 1813, Davy and his new bride set out from Plymouth on a grand European tour, taking the young Faraday with them as secretary and amanuensis. And so Faraday, who had not hitherto traveled more than 12 miles from home, was visiting Paris, Geneva, Milan, Rome, Genoa, Florence, and other European cities. He and Davy met the great scientists of Europe—Ampère, Arago, Gay-Lussac, Cuvier, Humboldt, and Volta. And they conducted numerous experiments along the way. They discovered iodine while in Paris, and burned a diamond completely in oxygen to carbon dioxide, thereby demonstrating that a diamond is a polymorph of carbon—a contentious issue at the time. In a sense it could be said that Faraday received his university education in the course of his 18-month tour of Europe. He probably had almost daily tutorials with Davy, and he kept a detailed diary of his first and second thoughts, as well as records of the experiments that he performed.

In mid-1815 he recommenced his duties at the RI, quickly acquiring great skills as an analytical chemist, then as a physical and organic chemist. His laboratory was occupied by only one other person, Serjeant Anderson, a loyal assistant who worked alongside him (although the two shared few words with each other) for some 40 years. In 1821 Faraday married Sarah Barnard, a silversmith's daughter who, like him, had been born of parents who belonged to a strict religious sect—the Sandemanians, a Scottish offshoot of the Methodist church. He remained devoutly religious all his life, and their marriage, though childless, was a happy one.

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Faraday's principal contributions to chemical science

1816	(With Davy) evolution of miner's safety lamp.
1818–24	Preparation and properties of alloy steels (study of Indian Wootz). Metallography.
1812–30	Analytical chemistry. Determination of purity and composition of clays, native lime, water, gunpowder, rust, dried fish, various gases, liquids, and solids.
1820–26	Organic chemistry. Discovery of benzene, isobutylene, tetrachloroethylene, hexachlorobenzene, isomers of alkenes and of naphthalene, sulphonic acids (α and β), vulcanization of rubber. Photochemical preparations.
1825–31	Improvements in the production of optical-grade glass.
1823, 1845	Liquefaction of gases (H_2S, SO_2, and six others). Recognized existence of critical temperature and confirmed the reality of continuity of the state.
1833–36	Electrochemistry and the electrical properties of matter. Laws of electrolysis. Equivalence of voltaic, static, thermal and animal electricity. First example of thermistor action. Fused salt electrolytes; superionic conductors.
1834	Heterogeneous catalysis: poisoning and inhibition of surface reactions. Selective adsorption; wettability of solids.
1835	"Plasma" chemistry (discharge of electricity through gases).
1836	Dielectric constant, permittivity.
1845–50	Magnetochemistry and the magnetic properties of matter. Magneto-optics. Faraday effect. Diamagnetism. Paramagnetism. Anisitropy.
1857	Colloidal metals. Scattering of light. Sols and hydrogels.

Had there been Nobel Prizes in Michael Faraday's day, he probably would have won several.

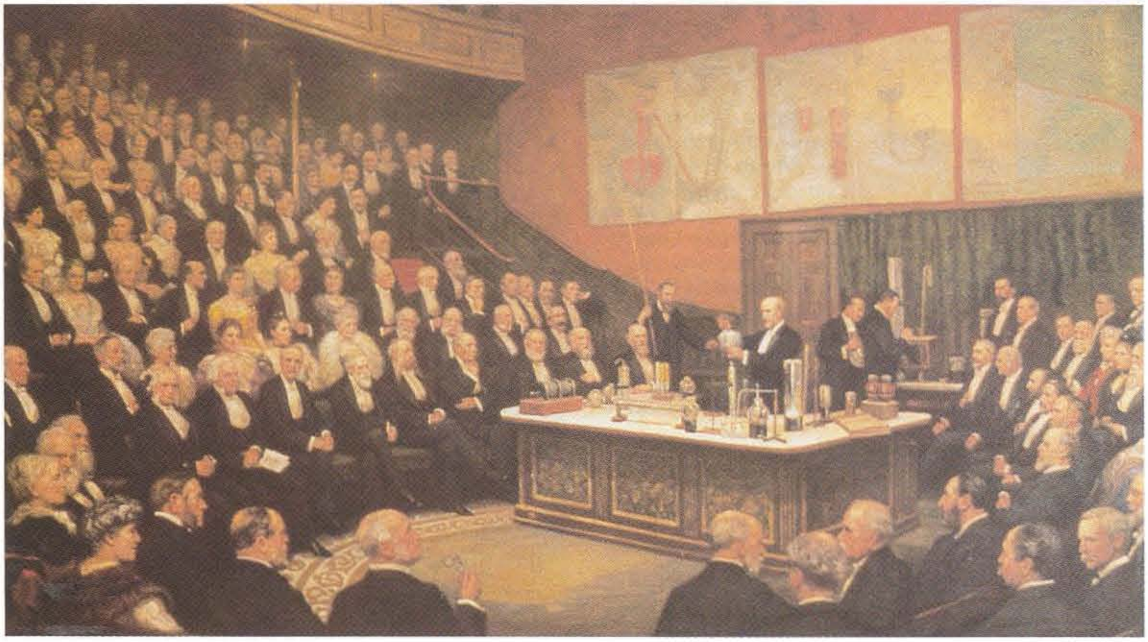
Faraday's principal contributions to physical science

1821	Electromagnetic rotations.
1831	Electromagnetic induction. Acoustic vibrations.
1832	Identity of electricities from various sources.
1833	Electrolytic decompositions.
1835	Discharge of electricity through evacuated gases. (Plasma physics and chemistry.)
1836	Electrostatics. Faraday cage.
1845	Relationship between light, electricity and magnetism; diamagnetism; paramagnetism.
1846	"Thoughts on ray vibrations."
1849	Gravity and electricity.
1857	Time and magnetism.
1862	Influence of a magnetic field on the spectral lines of sodium. Lines of force and the concept of a field. The energy of a magnet lies outside its perimeter. The notion that light and magnetism and electricity are interconnected.

Discourses for lay audiences and the Christmas Lectures for children. Faraday gave the Christmas Lectures on 19 occasions. His most famous series, "The Chemical History of the Candle," first published in 1850, became a classic and was translated into many languages; it is still recommended summer-vacation reading for Japanese schoolchildren.

Faraday established a tradition of inviting not only the leading scientists of the age, but also poets, politicians, musicians, actors, artists, and men and women of letters, to present Friday Evening Discourses. He himself persuaded, among others, T. H. Huxley, John Dalton, Lord Kelvin, Clerk Maxwell, Hermann von Helmholtz, and John Ruskin to lecture at the RI. This tradition has continued. In 1895 the then director, Sir James Dewar, himself a polished presenter of Discourses, arranged for the great actor Sir Henry Irving to give a special Discourse on "Acting: An Art," attracting an audience of more than a thousand. In 1909 he arranged for Caltech's George Ellery Hale to describe at the RI his work on solar vortices: this turned out to be a particularly memorable Discourse as it demonstrated the general magnetic field of the sun and the effects of magnetic fields upon spectral lines, ideas that had been close to Faraday's heart. Several Caltech scientists have given Friday Evening Discourses since Hale's day, including Linus Pauling (three times), Murray Gell-Mann, and (in 1991) Ahmed Zewail. And Caltech's Earnest C. Watson Lecture Series follows the tradition of the Discourses inaugurated by Faraday.

The extraordinary speed of Faraday's develop-



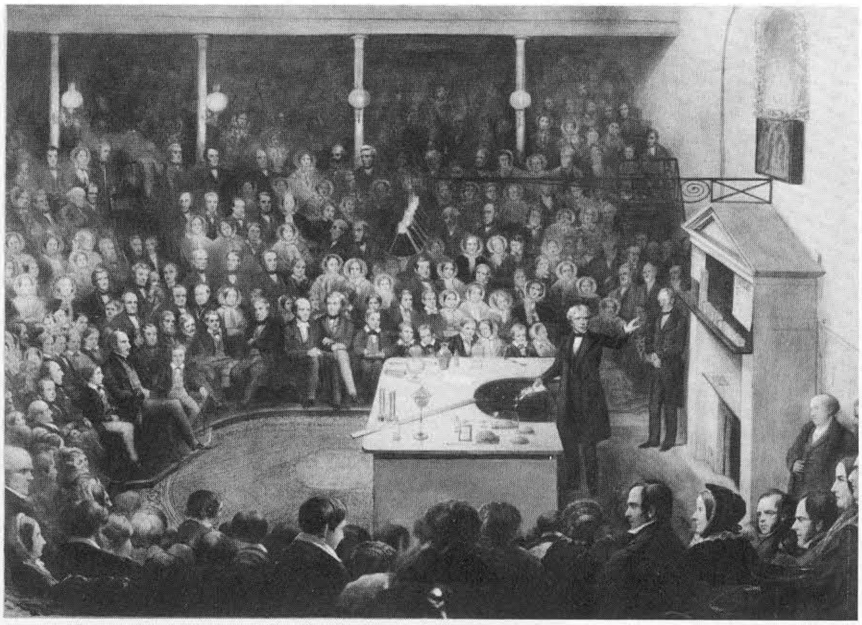
As director of the Royal Institution, Sir James Dewar, known for his work on low-temperature phenomena and the vacuum flask named after him, was also a regular Discourse lecturer. Here he presents what might be the original production of Earnest Watson's liquid-air show. Seated in the front row are Lord Rayleigh, Sir William Crookes, and Prime Minister A. J. Balfour. Stokes, Marconi, and Kelvin are also in the audience.

ment and the astonishing range of his output can be seen in the chronological record of his achievements in chemical and physical science at left. Following his work with Davy on the miner's lamp, on the protection of ships against corrosion, and on the preparation of many dangerously unstable chemical compounds, Faraday was already by 1819 the foremost analytical chemist in Britain, and in demand as an expert witness; and he had started with James Stodart, a surgical instrument maker, his pioneering work on the composition and preparation of alloy steels. In 1823 he discovered and analyzed the first recorded example of a gas hydrate, a material now termed a clathrate (from the Latin word for grating) because the guest molecule, chlorine, is enclosed in a cage formed by molecules of the host, in this case the crystallized water. Faraday also liquefied chlorine, an achievement that aroused the jealousy of Davy, who felt that he had initiated the work and was entitled to the credit. During this year and again in 1845 he succeeded in liquefying many more gases and confirmed the existence of the critical temperature above which, no matter how high the pressure, a gas will not liquefy.

Faraday's most important contribution as an organic chemist came in 1825. His interest had been aroused by the fact that at the bottom of containers of gas delivered to the RI by his brother Robert, who worked for the London Gas Company, was a clear aromatic liquid, now known as benzene, which Faraday soon produced by an independent method involving the thermal treatment of fish oil. The skill with which he characterized benzene and established its chemical formula elicited the admiration of Europe's foremost chemist, Berzelius, in Stockholm. (The actual sample prepared by Faraday was recently analyzed: it is 99.7 percent pure.) Benzene and the closely related naphthalene, the various derivatives of which were first prepared by Faraday, are the premier members of an enormous family of compounds called aromatic hydrocarbons. Such molecules, benzene especially, apart from their role as fuels, are important building blocks in the modern pharmaceutical industry, and form the basis of the aniline dyes that are responsible for the wealth of color in modern man-made materials.

Had there been Nobel Prizes in Michael Faraday's day, he probably would have won several. His discoveries included:

- Electromagnetic induction, which, along with his earlier related work on the relationship between electricity and magnetism, brought forth the first transformer, dynamo (electric generator), and electric motor.
- The laws of electrolysis, which rank among the most accurate generalizations in science. These led, through the subsequent work of Johnstone Stoney, Helmholtz, and J. J. Thomson, to the realization that matter is electrical in nature. It also led to the idea of ions, electrodes, and electrolytes—all terms that Faraday coined (along with his polymathic Cambridge friend, William Whewell)—as well as to electrodeposition, electroplating, coulometry, and electrochemical analysis.



The Prince Consort frequently attended the Friday Evening Lectures and brought his young family to the Christmas Lectures at least once, as captured in this painting. Prince Albert (with mustache) sits at left directly opposite Faraday, the lecturer.

•The magnetic properties of matter and the foundations of magnetochemistry (the terms paramagnetism and diamagnetism were coined by him, and he was the first to discover the paramagnetism of oxygen).
•Benzene and the analysis of its composition. Faraday was as much the founder of the chemical—certainly the dyestuffs and explosives—industry as of the electrical power generation and electroplating industries.
•The Faraday effect—the rotation of the plane of polarization of light by a magnetic field—and the foundations of magneto-optics.
•The notion of a field. Unlike his contemporary scientists, Faraday refused to be guided solely by the mathematical precision of Coulomb's law in interpreting the force between charges. He reflected deeply upon what occurred in the intervening space. This led him, in turn, to discover induction, inductive capacity, and permittivity. He also convinced himself that the energy of a magnet could extend beyond the perimeter of the magnet itself.

Faraday's lifelong interest in platinum—in the 1920s he and Stodart had given stainless-steel razors of platinum-containing steel to friends, and it was the subject of one of his most famous Friday Evening Discourses at the RI in 1861—led him to the study of catalysis. He discovered that minute quantities of gas bound to the surface of platinum (that is, adsorbed) could radically diminish its ability to promote chemical reactions. This discovery prompted him to experiment with the phenomenon of selective adsorption in which one gas in a mixture is preferentially retained by the surface of a finely divided solid, a technique which has been further developed for the purification of natural gas.

Among Faraday's later experiments was the study in 1856 of the scattering of visible light, often with brilliant color effects, by liquid suspensions of very finely divided metals such as gold, platinum, copper, and silver. This study of matter in an ultramicroscopic state paved the way for his colleague and admirer John Tyndall (and later Lord Rayleigh, the first RI professor to win the Nobel Prize) to explain the blueness of the sky, the opalescence of certain solutions, and the colors of birds and butterflies.

In 1862 (he died in 1867), the very last of his experiments to see if a magnetic field changed the quality of the orange light from a gas flame seeded with common salt, yielded nothing. Yet Faraday's intuition was sound for, nearly 40 years later, Pieter Zeeman found the effect that now bears *his* name and provided the first hints of what was to become the modern theory of atomic structure. If through his success Faraday changed the world he knew, even his failures pointed toward changes in a world he could not have foreseen.

To say that Faraday was an experimenter of genius is to risk exhibiting him as little more than a skilled manipulator; that he certainly was, but one for whom skill was the servant of imagination. His true genius lay in the ability to notice some oddity, to devise some experiments to test its significance and, with astonishing economy of effort, to discover how, if at all, his picture of the physical world must be modified. And though he never mastered anything beyond the basic elements of mathematics, his mind worked with such precision and lucidity that Lord Kelvin and Clerk Maxwell found in his constructs their inspiration for the mathematical theory of electromagnetic fields, a cornerstone of modern physics.

Faraday's detailed diaries illustrate how he thought and worked. He tells of his failures as well as his successes, and reading his work one senses his abundance of optimism (even elation), self-control, and self-criticism. There is also the sense of wonder with which, as a natural philosopher, he contemplated the world and the forces and mechanisms that hold it together. In his diary entry of March 19, 1849, shortly after he began to think that a relation existed between gravity and electricity, Faraday wrote:

> All this is a dream. Still, examine it by a few experiments. Nothing is too wonderful to be true, if it be consistent with the laws of nature and, in such things as these, experiment is the best test of such consistency.

"Nothing is too wonderful to be true, if it be consistent with the laws of nature and, in such things as these, experiment is the best test of such consistency."

Two years later, after extensive experimentation, he ended his lengthy article in *Philosophical Transactions of the Royal Society* (1851) with the following words:

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

In September 1845, using a special lead borate glass that he himself had prepared almost 20 years earlier, Faraday discovered the so-called Faraday effect, the rotation of the plane of polarization of light by a magnetic field. This was the first demonstrated link between light and magnetism, and it marked the birth of magneto-optics. The opening paragraph of the paper entitled "On the magnetization of light and the illumination of magnetic lines of force," which he dispatched on November 5 of that year to the Royal Society, read:

> I have long held an opinion, almost amounting to conviction, in common I believe with many other lovers of natural knowledge, that the various forms under which the forces of matter are made manifest have one common origin; or, in other words, are so directly related and mutually dependent, that they are convertible, as it were, one into another, and possess equivalents of power in their action.

Faraday's genius is the consequence of a unique combination of a uniquely large subset of major qualities: an infinite capacity to take pains, a restless intellectual energy, and an inexpugnable intellectual honesty, coupled with a measure of technical virtuosity that encompassed the manipulative dexterity and constructive imagination to produce new instruments and new techniques of unsurpassed power and sensitivity. His torsion balances and coulometers were more sensitive, his electromagnets stronger, his glass specimens heavier and of superior optical quality, than those of his predecessors or contemporaries. Always convinced that there were solutions to the problems he pursued and intelligible answers to the questions he raised, he had the supreme gift of selecting those that were really important and also of knowing precisely what to do next. Both his strategy and his tactics were impeccable. Add to all this his prodigious physical stamina, endless curiosity, penetrating intuition, complete mastery of detail, and exceptional facility for arguing from the particular to the general—on his own, and with his own brand of self-criticism and self-discipline—and one sees why Faraday's reputation is deserved. I think Rutherford spoke for all scientists when, in 1931, he said:

> 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 a natural philosopher. When we consider the magnitude and extent of his discoveries and their influence on the progress of science and of industry, there is no honour too great to pay to the memory of Michael Faraday—one of the greatest scientific discoverers of all time. □