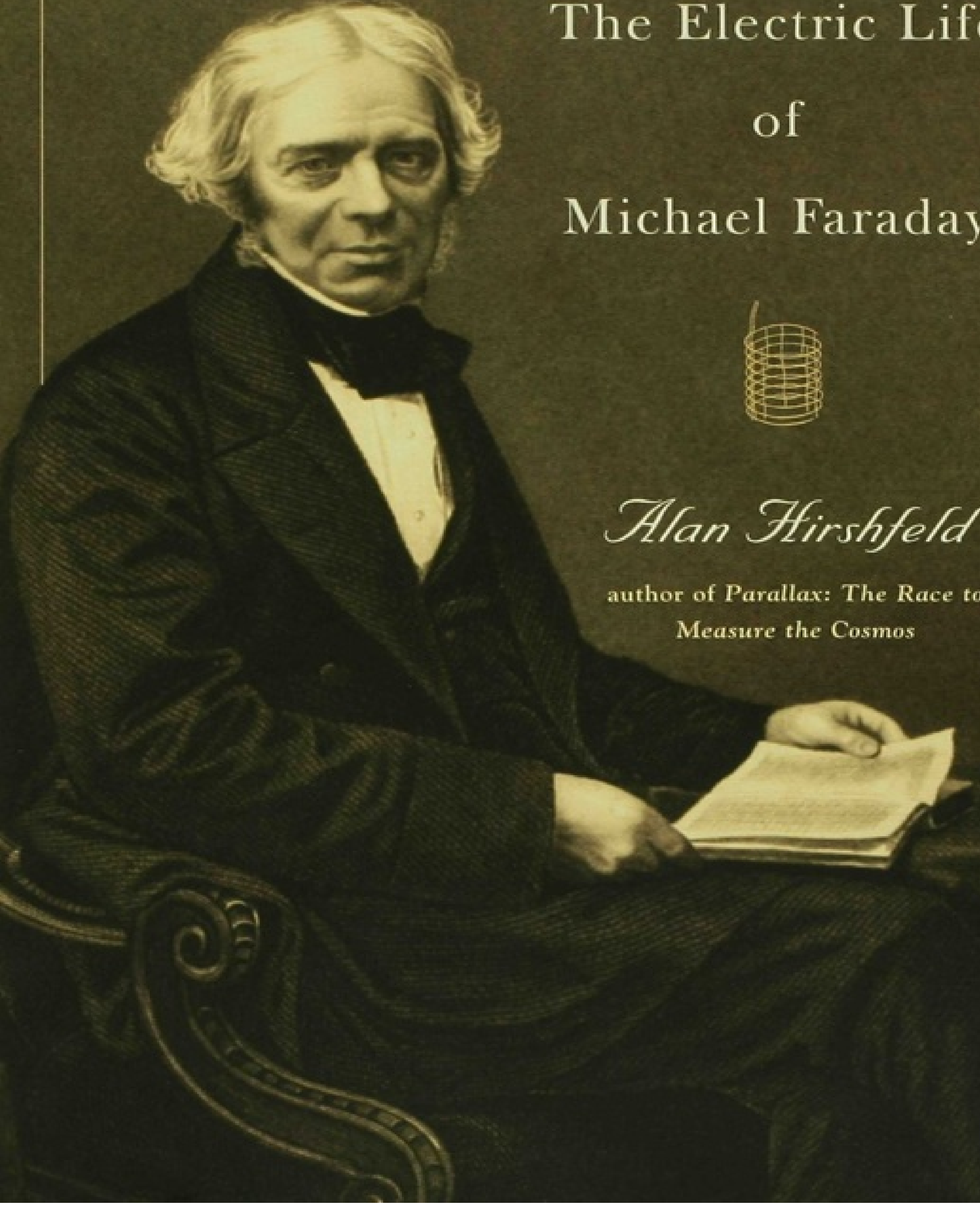
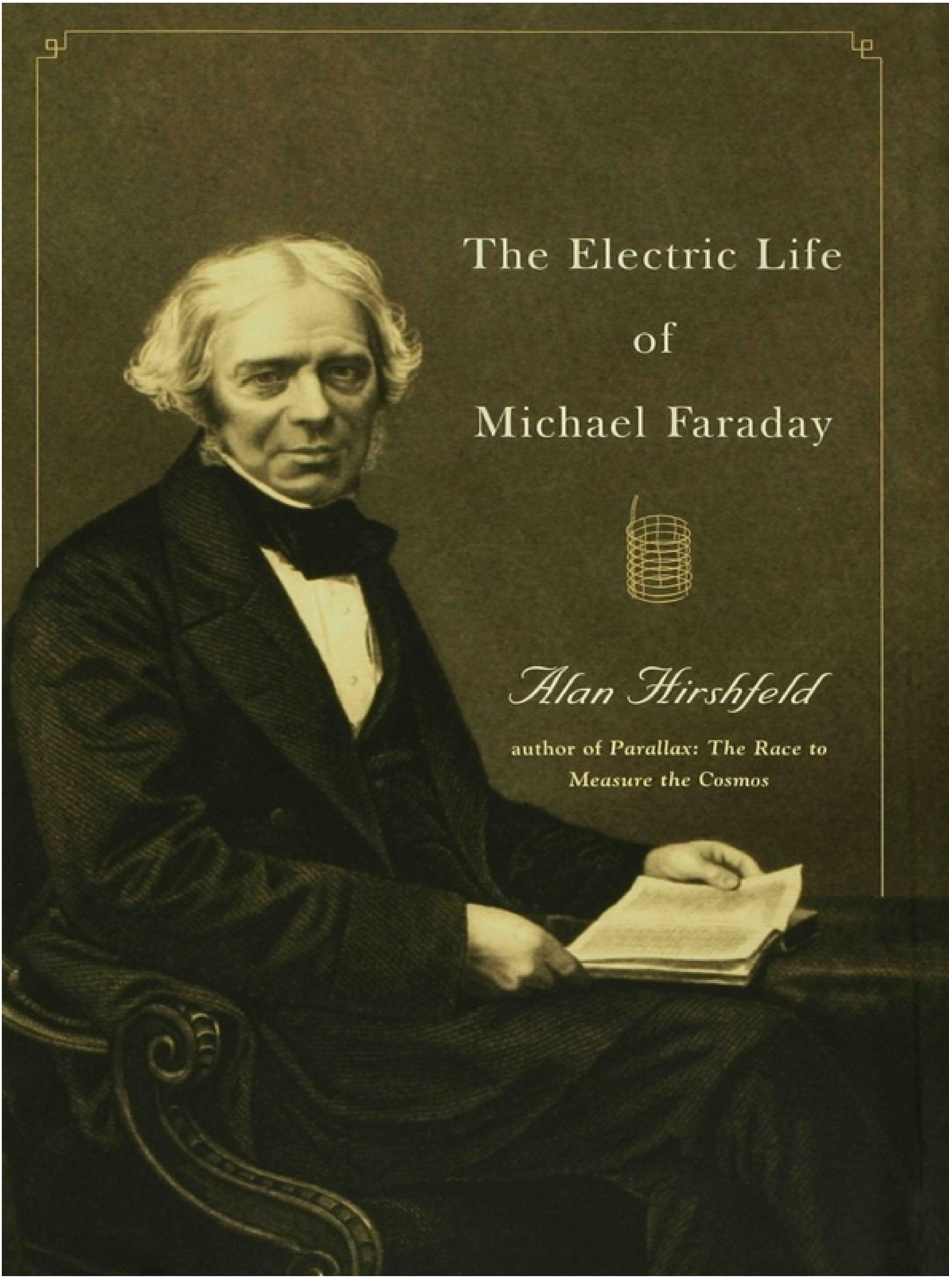
The Electric Life of Michael Faraday



Alan Hirshfeld

author of *Parallax: The Race to Measure the Cosmos*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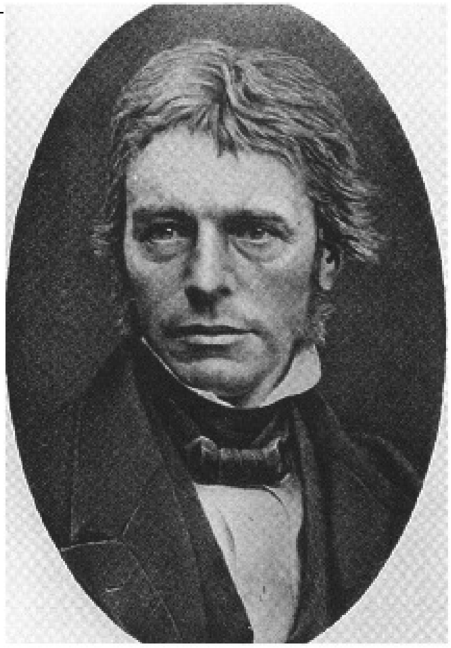

Faraday, from an 1840s daguerreotype by Antoine Claudet.

THE ELECTRIC LIFE OF MICHAEL FARADAY

Alan Hirshfeld

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For Sally, who taught me to riff

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Science is not a collection of facts, any more than opera is a collection of notes. It's a process, a way of thinking, a method based on a single insight—that the degree to which an idea seems true has nothing to do with whether it is true, and that the way to distinguish factual ideas from false ones is to test them by experiment.

—TIMOTHY FERRIS, "NOT ROCKET SCIENCE,"

The New Yorker (JULY 20, 1998), p. 5

[E]ven if I could be Shakespeare, I think
I should still choose to be Faraday.

—ALDOUS HUXLEY

PREFACE

The capsule version of Michael Faraday's life reads like a fairy tale: Through sheer gumption and timely luck, a poor, unschooled bookbinder's apprentice in nineteenth-century England surmounted adversity and class prejudice to become the greatest experimental scientist of his time. We are the beneficiaries of Faraday's good fortune. The electric motors that raise our elevators, spin our fans, an propel our hybrid cars trace their origins to Faraday's laboratory. The generators that electrify our reading lights and computers stem from the copper disk Faraday spun between the poles of a magnet more than a century and a half ago. The transformers that enable electricity to race hundreds of miles across the countryside and then safely into our homes are descendents of Faraday's wire-encased iron rings. And the development of the theoretical principles underlying these electrical, magnetic, and luminous marvels was inspired by Faraday's farsighted speculations.

Faraday's particular gift as an experimentalist was to make visible in the laboratory that which had been invisible, to magnify nature's subtle effects so they could be perceived and measured. He vaulte to fame in the 1830s after developing a host of ideas, processes, and devices that undergird modern technology. Then he embarked on a decades-long quest for the holy grail of nineteenth-century physics: a comprehensive theory of electricity, magnetism, force, and light. Here he entered a realm where experimental verification was difficult, if not impossible—the realm of the mathematician, wh solves equations to find plausible explanations for physical phenomena. And Faraday, facile as he wa in the laboratory, was a grade-school mathematician. The marathon of experimentation and cogitatio produced a raft of important scientific results—but also broke Faraday's health. He suspended his research for five gloomy years, only to return with a triumphant experiment showing that magnetism affects light. It was not until the twilight of Faraday's career that a young admirer, James Clerk Maxwell, cast his hero's controversial speculations about the nature of light and the transmission of force into the abstract symbolism of mathematics. The result-Maxwell's famous field equations-was radically new vision of nature, whose ramifications not only inspired a new generation of physicists, including Einstein, but still resound today.

If there was one overriding element to Faraday's character, it was *humility*. His "conviction of deficiency," as he called it, stemmed in part from his deep religiosity and affected practically every facet of his life. Thus Faraday approached both his science and his everyday conduct unhampered by ego, envy, or negative emotion. In his work, he assumed the inevitability of error and failure; whenever possible, he harnessed these as guides toward further investigation. Faraday adhered to no particular school of scientific thought. Nor did he flinch when a favored hypothesis fell to the rigors experiment. In the personal realm, Faraday subjected himself to constant self-examination and correction. Only his belief in God rested solely on unquestionable faith. Although devout, he kept a strict separation between his religious practice and the methods of science. In fact, to reveal nature's design through scientific study, in his opinion, only affirmed the glory of God. Religion provided motivation, not method, in Faraday's work.

Faraday also made contributions in civic affairs beyond his renowned science lectures for the public. Toward the end of his career, Faraday used the weight of his reputation to crusade for science education and environmental responsibility. His views on these subjects sound remarkably apt today, century and a half later. His complaints about the pollution of the Thames River triggered long-term efforts to improve water quality. Faraday also led a quixotic charge against the public's propensity toward superstition and pseudoscience, which he denounced as a "disgrace to the age." He would be similarly appalled by today's New Age hokum and by attempts of extremists to inject religious ideology into scientific education.

My interest in Michael Faraday runs deep, not just in my capacity as a physics professor at the University of Massachusetts, Dartmouth, but in the arc of my career. Like Faraday, I felt the tug of science at a young age. I, too, immersed myself in books on science and sought out mentors to teach me what I needed to know. I, too, aspired to a life exploring—and explaining to others—the wonders of nature. The name "Faraday" has been in my consciousness since at least 1970, when I took freshman physics and studied his experiments in electricity and magnetism. Yet it was in researching this book during the past two years that I truly discovered who he was.

The more I got to know Faraday through his many scientific reports, letters, journals, and diaries, the more I enjoyed "having brim around." I felt as though I were there in his laboratory, peering over his shoulder as he unraveled nature's mysteries. And at his Friday evening lectures, witnessing spectacular science demonstrations. And on his walks in the countryside, admiring the hue of the sunset or the spectacle of a thunderstorm. I shared his joy in discovery, his pain in failure, his sheer exuberance in the scientific endeavor. Frankly, at times my identification with Faraday went too far, as when I was writing the chapter about his collapse from overwork-only to suffer a similar bout of exhaustion myself. So much a living spirit did he become to me that I found it difficult at the end of the book to pen his death. (I felt compelled to "resurrect" him in an epilogue.)

In sum, Michael Faraday was one of those rare scientists in the mold of Galileo, Newton, and Einstein, free of blinding preconceptions about nature and thus endowed with a vision denied his contemporaries. Yet he was also an everyman with whom we can identify: the dreamer whose dream comes true; the genius whose genius falls short; the human whose humanity rules his actions. Faraday was truly one of us.

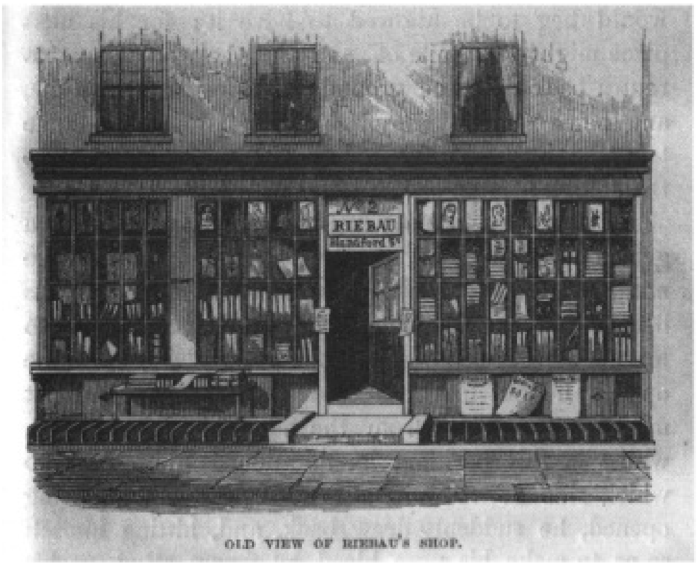
1

IMPROVEMENT OF THE MIND

Some see nature all ridicule and deformity . . . and some scarce see nature at all. But to the eyes of the man of imagination, nature is imagination itself

—WILLIAM BLAKE

Step back two centuries and through the front door of George Riebau's bookbindery at 2 Blandford Street near Manchester Square in London. Smell the pungent aroma of leather, glue, and varnish. Hea the murmurous drumbeat of the binder's mallet tamping gathered pages. Books are everywhere—on shelves, on tables, even wedged into the cubby like window frames, where they eclipse the light struggling to enter. In this dim paper-and-leather universe of long ago, Riebau and his three apprentices stand at their benches, plying the bookbinder's craft. Around them lie the accoutrements their trade: needles, thread, Jaconette cloth, engraving tools, standing press, cutting boards. The room buzzes with conversation, for Riebau is a genial man who likes to keep his workers and his customers happy. Yet for all the chatter, the binding and selling of books appear to be the sole order of business here. In short, George Riebau's modest establishment is the last place one would suspect as an incubator for a would-be scientist—especially in 1812.



The London bookbindery where Faraday apprenticed until he was twenty-one.

But move beyond the benches to the small fireplace that keeps the workers' fingers supple through the frigid London winters. There on the mantelpiece, arrayed in no particular order, is a curious assortment of devices that bear no connection to the binding of books: voltaic piles-batteries, in today's parlance; copper and zinc electrodes; coils of wire; bottled acids; glass cylinders for generating and storing electricity. Nearby, meticulous pencil sketches of electrical machines.

Alongside these, jottings about electrical phenomena. Here is the after-hours "laboratory" of young Michael Faraday, one of George Riebau's apprentices, who is at present probably counting the minute until he can set aside his tools and resume his homespun experiments. Faraday's teachers, such as the are, do not wear silken robes or roam ivy-covered buildings; they speak to Faraday silently from the printed pages that pass through his hands on the way to more advantaged customers. To Faraday, Riebau's shop is truly library, classroom, and laboratory. The mantelpiece curios are manifestations o a dream by a young man whose ambitions are pressing ever more despairingly against the harsh realities of British society. This in an age when the term "upward mobility" holds no practical meaning for the mass of humanity-when, for the most part, scientists are born, not made.

In a few short months, Michael Faraday's apprenticeship will end and he must take up the career fo which he trained: bookbinding. And therein lies the source of his searing realization that his life migh be spent in the mindless packaging of countless words on countless subjects, and not one of his own devising. For Faraday longs to uncover nature's secrets, not as a hobbyist in some dusty shop corner, but as a professional man of science in a real laboratory. Now with both time and hope running short, he can only wait for opportunity to extend its hand and, God willing, sweep him into the ranks of England's scientific elite.

In the winter of 1791, blacksmith James Faraday moved his wife and two children from Outhgill in northern England to what was then the village of Newington Butts, now the Elephant and Castle section of London just south of the Thames. By the time his third child, Michael, was born in September, the brighter prospects James Faraday was seeking had not yet materialized. Nor did they ever.

In fragile health, James Faraday worked intermittently, and at times only the charity of others kept the family from outright starvation. Nevertheless, the Faradays were buoyed by their bedrock religio faith and belief in the blessings of a simple, if impoverished, life. In 1796, the family, now six in number, moved to cramped quarters over a stable in Jacob's Well Mews in central London. As a chil Michael Faraday passed the hours running with the neighborhood boys, shooting marbles in nearby Spanish Place, or entertaining his baby sister Peggy in Manchester Square. Schooling was brief: Faraday's mother withdrew him when the schoolmistress attempted to cane a speech defect out of hir (He could not pronounce his *r's*, and referred to his brother as "Wobert.") Occasionally he visited his father at James Boyd's forge a few blocks east on Welbeck Street. Once, while playing in the loft, he fell through a hole onto his father's back, averting sure disaster on the anvil's edge. In 1804, thirteen-year-old Faraday was hired as an errand boy for George Riebau, a French emigre, political radical, an proprietor of a book shop around the block. A year later, on October 7, 1805, Faraday entered a seven year apprenticeship with Riebau. So impressed was Riebau with his charge's skill and seriousness of purpose that he dashed off a letter to a London magazine putting Faraday's example forward as a model for the city's youth. (Riebau didn't have much luck bringing his apprentices into the fold: of Faraday's coworkers, reads one account, William Oxberry became a comedian and Edward Fitzwilliam a professional singer.)

Riebau's shop proved a fertile environment for the inquisitive, but virtually unschooled, Faraday. Books came in, books went out, a steady stream of treacle and treasure that Faraday sampled haphazardly in his off-hours. This week's "lesson" might be the *Arabian Mights;* next week's, a collection of Hogarth illustrations; and after that, Fanny Burney's edgy take on English society, *Evelina.* But it was books on science that excited Faraday the most.

At the dawn of the nineteenth century, science and its institutions were in flux, spurred as much by new discoveries as by the growing belief that scientific research might enhance a nation's agricultura and ~~industrial development. The fundamental building blocks of matter—atoms—were as yet~~ unknown. Electricity, magnetism, heat, and light were variously "explained," none convincingly. Through careful measurement, the mathematical character of nature's forces could be determined, bu their underlying mechanisms, interrelationships, and means of conveyance through space were subjects of dispute. Faraday plunged headlong into this melange of ideas, trying with his meager knowledge to sort out fact from fancy. All around was God's handiwork, in plain sight, yet inextricably bound up in mystery, a seemingly limitless horizon of possibilities for off-hours study. Riebau described his apprentice as perpetually scouring the countryside, "searching for some Minera or Vegitable curiosity . . . his mind ever engaged."

Faraday's scientific musings tumbled joyfully, almost uncontrollably, in his head. In a letter to his best friend, Benjamin Abbott, we see an energetic twenty-year-old dancing through one rain-splashe evening with the unfettered exuberance of a Gene Kelly: "I set off from you at a run and did not stop until I found myself in the midst of a puddle and a quandary of thoughts respecting the heat generate in animal bodies by exercise. The puddle however gave a turn to the affair and I proceeded from thence deeply immersed in thoughts respecting the resistance of fluids to bodies precipitated in them . . My mind was . . . suddenly called . . . by a very cordial affectionate and also effectual salute from spout. This of course gave a new turn to my ideas and from thence to Black Friars Bridge it was busil bothered amongst Projectiles and Parabolas. At the Bridge the wind came in my face and directed my attention . . . to the inclination of the pavement. Inclined Planes were then all the go and . . . on the other side of the Bridge . . . slipping introduced the subject of friction and the best method of lessening it. . . The Velocity and Momentum of falling bodies next struck not only my mind but my head, my ears, my hands, my back and various other parts of my body . . . [F]rom thence I went home sky-gazing and earnestly looking out for every Cirrus, Cumulus, Stratus, Cirro-Cumuli, Cirro-Strata and Nimbus that came above the horizon."

From the start, Faraday's investigations were more than a joyous commune with nature; they were sincere attempt to discern God's invisible qualities through the very design of the world. Through well-constructed observations and experiments, he sought to distill nature's seemingly diverse phenomena to a common, irreducible basis—and in this fundamental unity of the universe, he would witness the divine signature. The intense spirituality that imbued Faraday's science derived from his upbringing in the Sandemanian faith, a tightly knit Protestant sect founded in the mid-1700s by Scottish minister John Glas and his son-in-law Robert Sandeman. Inspired by a literalist reading of t New Testament, Sandemani-ans eschewed pride and wealth in favor of piety, humility, and community with fellow Sandemanians. Much of Faraday's overt serenity owed itself to the affirmativ aspects of his religion. "He drinks from a fount on Sunday which refreshes his soul for a week," note friend and biographer John Tyndall. Faraday, the Sandemanian, took human fallibility as a given, so he never staked his ego on the correctness or acceptance of his own ideas. He was a scientific pilgrim inching his way toward the heart of a complex universe. Whether his chosen path proved mistaken w of little consequence; there was always another path. The joy was in the journey.

Although Faraday might have fancied himself a protoscientist, he was too grounded not to see who stared back at him from the mirror: a rough-edged, ill-educated son of a blacksmith. He needed a mentor-a Henry Higgins, really-to smooth the edges and guide his further education. The "mentor" arrived at Riebau's door in 1809-not surprisingly, in the form of a book.

In the opening paragraphs of *Improvement of the Mind,* the Reverend Isaac Watts spoke directly to young Michael Faraday: "Even the lower orders of men have particular callings in life, wherein they ought to acquire a just degree of skill." Preacher, writer, and composer of hymns (most notably, 'Joy the World"), Isaac Watts labored twenty years on his commonsense self-help guide before it was published in 1741. Faraday read the 1809 edition *oi Improvement of the Mind* cover to cover and, as Riebau noted, often carried it in his pocket. In this single volume was a system by which he might organize his swept-up jumble of facts and observations about nature, a system that might help him penetrate the more rarefied strata of English society. It was Watts, Faraday once told a friend, who first made him think.

In unwavering conviction, Watts dispenses advice and encouragement on every facet of self-improvement, from attending lectures to conversation to meditative study. "Do not content yourselve with mere words and names," Watts counsels, "lest your labored improvements only amass a heap of unintelligible phrases, and you feed upon husks instead of kernels." He promotes the importance of direct observation and cautions against the use of imprecise language, twin credos to which aspiring scientist Faraday adhered with almost biblical devotion. And although Watts may have been his readers' most ardent champion, he reins in their wilder aspirations: "Let not young students apply themselves to search out deep, dark, and abstruse matters, far above their reach, or spend their labor on any peculiar subjects, for which they have not the advantages of necessary antecedent learning, or books, or observations."

Faraday hurled himself into Watts's self-improvement plan. Characterizing his own language as "that of the most illiterate," he took elocution lessons two hours a week for seven years. He ordered his friends to mercilessly correct his speech, spelling, and grammar. He began a commonplace book titled "The Philosophical Miscellany," whose pages he filled with facts about light and color, electric fish, meteorites, lightning, water spouts, the formation of snow, loosening glass stopples, oxygen gas galvanism. He took drawing lessons from French artist Jean Jacques Masquerier, who had fled Paris 1792 and lodged in a room above Riebau's shop.

In early 1810, Faraday was binding a volume from the 1797 edition of the *Encyclopaedia Britannica*. Poring through it, he discovered the 127-page entry on electricity. The author was the notorious Scottish surgeon and inventor James Tytler, whose many exploits include the first manned hot-air balloon ascent in Britain—a feat he then repeated to a paying crowd. (The Montgolfier brothers had ascended in France a year earlier, in 1783.) In their acknowledgments, the *Britannica*'s editors refer drolly to Tytler as "a man who, though his conduct has been marked by almost perpetua imprudence, possesses no common share of science and genius."

According to Tytler, everyone agreed that electricity exists in two varieties, which Benjamin Franklin had termed "positive" and "negative." Further, no one disputed that the transfer of electric charge, whatever it was in fact, could be envisioned as the flow of an imponderable fluid that coursed freely through ordinary matter; or that these electrical fluids somehow influenced one another at a distance. Here the agreement ended. French scientists promoted a two-fluid theory, one positive and the other negative, flowing simultaneously in opposite directions. English scientists generally supported Franklin's one-fluid theory, in which electrification results from a surplus or deficit of a single type of charge. (Franklin guessed that the mobile charge was positive; in fact, it turned out to b negative.) Tytler, in the *Encyclopaedia*, put forward a fanciful variation of Franklin's single-fluid theory that not only explained all electrical phenomena—at least in his own inflated opinion-but linked electricity to light and heat. To Faraday, the notion that learned minds might disagree about th nature of such fundamental phenomena as electricity, light, and heat must have been-well, electrifying.

Improvement of the Mind, Faraday's "mentor," Isaac Watts, whispered into his ear about "the ~~importance of the observed fact." Do not merely read about electrical phenomena; witness them~~ firsthand. For seven pence, Faraday bought a pair of glass jars from a secondhand shop on Little Chesterfield Street. The larger jar became the core of an electrostatic generator—a device that uses friction to build static electricity—and the smaller one a Leyden jar, to store the electrical charge produced by the generator.(In my own introductory physics classes, students make the generator out a nested Styrofoam dinner plate and aluminum pie pan, and the Leyden jar out a foil-wrapped, water-filled, film canister with a protruding nail.) With his crude apparatus, Faraday electrified common objects, zapped his outstretched finger with sparks, and tasted electricity's sting on his tongue. No doubt he performed these experiments for Riebau and subjected him to monologues about the one-fluid-versus-two-fluid debate. Riebau could only listen admiringly to the tale of a science disunited. As to how his energetic apprentice might resolve such an issue, he had no idea. But Isaac Watts did, right of *Improvement of the Mind:* "There is something more sprightly, more delightful and entertaining in the living discourse of a wise, a learned, and well-qualified teacher, than there is in th silent and sedentary practice of reading." On Monday evening, February 19, 1810, Faraday took a borrowed shilling and marched through central London to his first lecture on science.

Faraday's London bubbled with scientific and pseudoscientific spectacle. Astronomy, meteorology, chemistry, optics, electricity— the stuff of wonder that drew both king and commoner to exhibition halls throughout the city. On any given evening, audiences could thrill to lightning bolts at the Theatr of Science on Pall Mall; watch the guillotined "head" of the great French chemist Antoine Laurent Lavoisier materialize from the mists of the Phantasmagoria at the Lyceum; or witness hair-raising fulminations of the "devil's element," phosphorus, at the Royal Institution on Albemarle Street. On lecture nights, the convergence of carriages was so dense in front of the Royal Institution that the street had to be designated one-way. As the great demonstrators entertained awestruck throngs, their more reserved counterparts lectured at hospitals, private homes, rented halls, and philosophical societies. Citizens excluded from formal schooling could attend these ad hoc "classrooms" and hear about developments in science. Increasingly, knowledge and career choices, technology and societal well-being were linked in the minds of artisans like Faraday.

Taking paper and pencil, Faraday set out for the evening lecture at John Tatum's house on Dorset Street near Salisbury Square. The storefront advertisement had suggested at least a workmanlike recitation of facts and principles on a variety of subjects: fluids, optics, geology, mechanics, chemistry, astronomy, meteorology. But there were also to be demonstrations, likely with apparatus he could ill afford. Faraday was already versed in this evening's topic-electricity— from Tytler's entr in the *Encyclopaedia.* Arriving at Tatum's, he settled into a front-row seat, placed his hat on his knee and laid a sheaf of paper on top, looking very much the incarnation of Isaac Watts's ideal pupil.

That the lecture would be delivered by Tatum himself—a silversmith, not a "bona fide" scientist-was no surprise. The professional ranks were largely closed to those outside the Cambridge-Oxford axis—unless, of course, one were wealthy or titled. Tatum, like many others at the time, had forged his own parallel universe of science: conducting experiments, giving lectures, even founding a modes scientific organization, the City Philosophical Society, which Faraday subsequently joined. The CPS met every Wednesday and comprised a cross-section of trades: clerk, warehouse worker, landscape painter, solicitor, pharmacist, minister, medical student—all of whom shared an abiding interest in contemporary science. A more like-minded group Faraday could not have found if Isaac Watts had conjured it up himself. For harmony's sake—and in deference to that era's politically repressive environment—only two discussion subjects were off-limits: politics and religion. (The CPS was briefly banned in 1817 under the Seditious Meetings Act.)

Faraday recorded the essence of Tatum's electricity lecture and sketched the various pieces of demonstration equipment. When he arrived home, he composed a second, more detailed account base on his lecture notes, and over the succeeding days, transcribed these into an extended narrative, appending his own opinions on the subject. With each succeeding Monday lecture, he added another chapter to what would become his own sourcebook on the sciences. When it was all done, he bound the volumes and dedicated them to his master, George Riebau. "To you . . . ," he wrote, "is to be attributed the rise and existence of that small portion of knowledge relating to the sciences which I possess . . ."

In the matter of electricity, Tatum was an avowed Franklinian-a "one-fluid" man. Faraday's take o the evidence was different. He set aside the various theories of electricity advanced by Benjamin Franklin, James Tytler, and the French in favor of an obscure two-fluid model developed in the 1770 by Henry Eeles. No matter that England's venerable Royal Society, bulwark of the science establishment (and not affiliated with the Royal Institution), had repeatedly spurned the work of Eele Faraday was convinced that it better explained electrical phenomena. Evidently, Faraday made his views known to Tatum, for several weeks later he was standing at the lectern delivering his first publ lecture. He left nothing to chance: His lecture notes form a precise script, from the opening "Ladies and Gentlemen" to the extended passages lifted from Tytler. As to why his favorite theory of Eeles had not come to the fore, Faraday had prepared a volley against the "Spirit of Party and bigotry whic is to be found as much among *Philosophers* [i.e., scientists] as among *Politicians* and enthusiasts." But he never fired the shot; the words are crossed out in his notes. Instead, Faraday performed demonstrations in support of the Eeles model: passing a spark through a suspended stack of paper; administering electric shocks of increasing intensity to his own body; observing electrical discharge in a partly evacuated tube. In truth, the demonstrations were inconclusive; Franklinians and Frenchmen could spin them to their own advantage.

If Faraday basked in the glow of his first public lecture, it was only briefly. Tatum followed up wit a presentation that revealed to Faraday the backward state of his knowledge. Faraday's electrical "bible"-Tytler's *Encyclopaedia* article-dated from 1797. Its conclusions were drawn solely from observations of *static* electricity, the transient rush of surplus electric charge from one body to another. Whatever Faraday had gleaned from Tytler placed him, unwittingly, at least a decade behin the times. Now Tatum described Alessandro Volta's revolutionary invention in 1800 of the battery, th first means of *continuous* electrical flow. Then he spoke about the burgeoning field of electrochemistry, in which electric currents are used to probe the structure of matter. He gave accounts of observations and experiments not even contemplated in Tytler's dated treatise. One thing Faraday learned from Tatum's lecture: It was time to find a newer book.

Among the works that gravitated to Riebau's shop-and into Faraday's hands-in early 1810 was one of the most enduring science books of the nineteenth century. First published four years earlier, Jane Marcet's *Conversations on Chemistry* went through eighteen British, four French, and twenty-three American printings. Born to a wealthy Swiss merchant family living in England, Marcet was educate by private tutors in mathematics, astronomy, philosophy, and the arts. When she was thirty, she married a fellow Swiss, who was a physician and chemistry lecturer at Guy's Hospital in London. Marcet took an active interest in her husband's work and became a familiar figure within his professional and social network. To their scientist friends, she was the ideal conversation partner, eve eager to hear the latest theory or experimental finding. Marcet became a regular at scientific lectures ~~most notably those of England's celebrated chemist, Humphry Davy. It was the charismatic Davy~~ wh inspired Jane Marcet to write her layperson's guide to chemistry. And it was her book, in turn, that inspired Michael Faraday to focus his wide-ranging interests on that subject.

Conversations on Chemistry features a series of dialogues between a teacher, Mrs. B., and her two pupils, sober-minded Emily and impetuous Caroline. The book's structure echoes that of Galileo's *Dialogue on the Two Chief World Systems,* which portrays the discourse among a knowledgeable tuto an inquisitive nobleman, and a dimwitted Aristotelian who repeatedly stumbles over his own illogic. In the Preface, Faraday read about Marcet's presence at lectures, her scientific conversations, her reliance on proof by experimentation-all familiar elements of self-improvement a la Isaac Watts. Marcet's alter ego, Mrs. B., "spoke" to Faraday in revelatory language that promised fresh insight int the mysteries of nature's "laboratory"— the universe. "I assure you," she said, "that the most wonderful and the most interesting phenomena of nature are almost all of them produced by chemica powers." She buttressed that promise, not with conjecture or blind allegiance to tradition, but with proven facts. Further, Marcet explicitly confirmed Faraday's notion of science as a spiritual exercise —in her words, "a lesson of piety and virtue." In Jane Marcet, Faraday had found both teacher and kindred spirit. And like the book's fictional Emily, he became a diligent pupil.

"Do not suppose that I was a very deep thinker or was marked as a precocious person," Faraday wrote many years later. "I was a very lively, imaginative person, and could believe in the Arabian Nights as easily as in the Encyclopaedia. But facts were important to me and saved me. I could trust a fact, but always cross-examined an assertion. So when I questioned Mrs. Marcet's book by such little experiments as I could perform, and found it true to the facts as I could understand them, I felt that I had got hold of an anchor in chemical knowledge and clung fast to it."

Conversations in Chemistry covers a diverse array of "chemical" topics, reflective of the era: individual elements, light and heat, metals, acids, pharmaceuticals, geochemistry, fermentation, and living organisms. Marcet describes experiments that anyone, using common household materials, car perform at home or in a classroom. Educational reformers, especially at women's academies in the United States, preferred her focus on theory and experiment to the various metaphysical, religious, or narrowly utilitarian approaches of competing texts. On the controversial issue of chemical affinity— the tendency of certain substances to combine in chemical reactions—Marcet allies herself with her friend, Davy. In their view (not the majority opinion at the time), chemical affinity is based on matter's inherent electrical properties. The notion that electricity is a phantom fluid unlinked to its host matter is countered, they believed, by a simple observation: When a battery's electricity is applied through a pair of immersed electrodes—conductors connected to the battery's positive and negative terminals-water splits into its constituent hydrogen and oxygen. Further, the sundered elements appear at opposite electrodes, reflecting their innate electrical charge.

Marcet's electrochemical tales turned Faraday into an amateur chemist-and a Humphry Davy devotee. Davy had risen from modest roots and now held an esteemed position at the Royal Institutio on Albemarle Street, barely a mile from Riebau's shop. What a thrill it would have been for Faraday t catch a glimpse of the famed chemist, maybe even exchange greetings-or, better yet, hear from the man himself about the particulars of his research. But Faraday knew that in early nineteenth-century England the distance between a bookbinder's apprentice and a renowned scientist was vastly greater than a few city blocks. His hero, Davy, might as well have been on the far side of the earth.

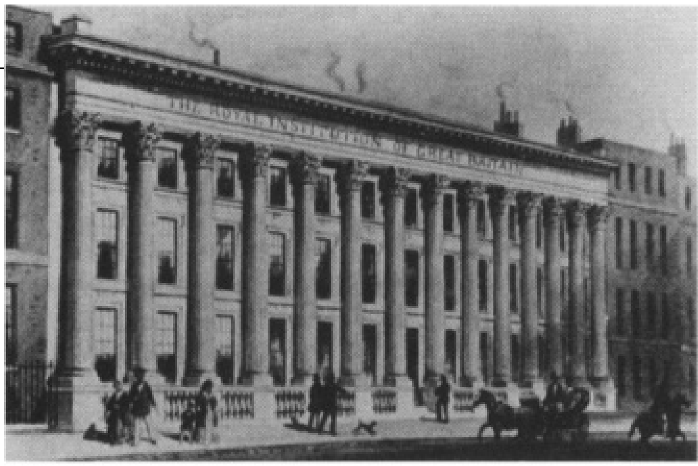
One winter evening in 1812, George Riebau retrieved the notes of Tatum's lectures that his apprentic

Michael Faraday, would someday bind and dedicate to him. He must have felt a paternal pride ~~carrying the thick stack of pages, carefully handwritten and illustrated by one of his own. Riebau~~ always encouraged Faraday's scientific activities—as remote as these were from the needs of his own business. He often lent him books from his private collection and shooed the other apprentices out of the backroom "laboratory." This evening, Riebau displayed Faraday's work to one of his customers, a Mr. Dance, who belonged to a prominent London family and was a member of the Royal Institution. Impressed, Dance arranged for Faraday to be admitted to the Institution for the series of farewell lectures by Humphry Davy. The nation's most acclaimed communicator of science to the masses, Davy was scheduled to speak only four more times, between February and April 1812. After that, he would devote himself exclusively to research and travel.

Scottish critic Thomas Carlyle described the Royal Institution, where Davy lectured, as "a kind of sublime *Mechanics' Institute* for the upper classes." Davy's lectures had not only elevated science in the minds of Londoners, it made the acquisition of scientific knowledge fashionable. His audience included government ministers, politicians, dignitaries from overseas, and a significant number of young women. For many of the latter, the draw was the poetic, handsome Davy himself. Faraday, of course, was well acquainted with Davy's electrochemical discoveries, courtesy of Jane Marcet. But now, unexpectedly, he would have the chance to hear of these and other experiments from the very source.

Just before 8 P.M. on February 29, 1812, Faraday joined the throng of some seven hundred well-heeled visitors squeezing through the front door of the Royal Institution. He crossed the vestibule and climbed the elegant stone staircase to the lecture hall. He sat in the gallery, as befitted his station. Bookbinders, invited or not, never ventured onto the main floor, which was reserved for the upper classes and distinguished guests. From his seat, just over the clock, he had a clear view of the large U-shaped table up front, laden with Davy's equipment. Behind the table were a blackboard and furnace. And in the basement lay the world's most powerful battery, whose electricity Davy tapped from wires that rose through the floor. Looking around at the crowded tiers of seats, Faraday must have thanked providence for his good fortune. Entry to Davy's lectures was by subscription, affordable only to those with means. His own budget strained at the shilling fee for John Tatum's lectures. Nevertheless, here he was, in this exalted institution, in the presence of his hero. As Davy began to speak, Faraday feverishly took notes.

Davy lectured from memory, his script and performance as carefully prepared as an actor's. The presentation was equal parts instruction, performance, and inspiration. Every theoretical assertion was backed by an experiment that he demonstrated on the spot. Davy was animated by the joy of discovery. He delighted in presenting controversial issues, making his argument in a crescendo of logic and experiment. Look what I have found, he seemed to say to the audience, marvel at how it fits into the divine pattern, how it reveals "the power, wisdom, and goodness of the Author of nature." Davy's distrust of speculation echoed Faraday's own. Hypotheses are, as Davy had previously written, "mere points for employing the lever of experiment." The advancement of truth inevitably requires their destruction. Theory is mutable; only facts are eternal.



The Royal Institution of Great Britain area 1840.

In his final series of lectures, Davy brought his electrochemical wizardry to bear on a seemingly simple question: What is an acid? Acids, such as lemon juice or vinegar, had long been recognized fo their common properties: They taste sour (the term *acid* comes from the Latin *acere*, or sour); are corrosive to metals; and give a reddish tinge to litmus, a dye extracted from lichens. The existing chemical paradigm—that oxygen renders compounds acidic—was established during the previous century by Antoine Laurent Lavoisier, who had already proven oxygen's key role in combustion (burning). Davy disputed Lavoisier's claim. He had applied powerful electric currents to muriatic aci and transformed it into a pungent, greenish gas. Most chemists believed the gas to be an oxygen compound, but in years of laboratory analysis Davy was unable to detect any sign of oxygen. He instead determined that the gas was a combination of hydrogen and a new element, which he named chlorine. Lavoisier's acid theory, in Davy's view, was unfounded. It was not the presence of oxygen, but some overall electrical property of a compound, that gives rise to acidic properties. (Specifically when dissolved in water, acids release positive ions-atoms or groups of atoms that are electrically positive. Other substances, called bases, release negative ions when they are dissolved in water.) The chemical establishment castigated Davy, accusing him of jumping to conclusions and using faulty lal technique. Oxygen, they believed, would eventually be found by other more capable chemists. In Davy's four lectures, Faraday heard his hero detail the case for the overthrow of Lavoisier's theory. Afterward, there was no doubt in Faraday's mind that Davy was right about acids-and that electrochemistry was a promising path of research.

In July 1812, having saved up money for proper supplies, Faraday decided to launch his own electrochemical experiments. First, he needed a battery. From all he had read and heard, constructing a battery was straightforward. Alessandro Volta had been clear twelve years earlier when he notified Joseph Banks, president of England's Royal Society, of his invention of the battery:

"The apparatus . . . which will, no doubt, astonish you, is only the assemblage of a number of good conductors of different kinds arranged in a certain manner. Thirty, forty, sixty, or more pieces of copper, or rather silver, applied to a piece of tin, or zinc, which is much better, and as many strata of water, or any other liquid which may be a better conductor, such as salt water, ley, &c. or pieces of pasteboard, skin, &c, well soaked in these liquids, such strata interposed between every pair or combination of two different metals in an alternate series, and always in the same order of these thre kinds of conductors, are all that is necessary for constituting my new instrument."

Volta was equally voluble about the physiological effects of such chemically generated electricity, which he applied liberally to various parts of his body. To the fingers: " . . . a very disagreeable quivering and pricking." To the mouth: " . . . a sensation of light in the eyes, a convulsion in the lips, and ~~even in the tongue, and a painful prick at the tip of it, followed by a sensation of taste." To the~~ ears: " . . . a kind of crackling with shocks, as if some paste or tenacious matter had been boiling. . . The disagreeable sensation, and which I apprehended might be dangerous, of the shock in the brain, prevented me from repeating this experiment."

Volta's letter was published, and scientists all over Europe were soon building their own batteries. In England, William Hyde Wol-laston made a simple voltaic "pile" by stacking English shillings, zin and pasteboard. The noted chemist Jons Jakob Berzelius in Sweden couldn't afford silver so he used disks of copper instead. And an up-and-coming chemist named Humphry Davy tried his own hand at battery construction at Bristol's Pneumatic Institution, where he was employed. By the time Michael Faraday marched down to Knight chemists on Foster Lane to buy a sheet of zinc in 1812, anyone wit a mind to could assemble a battery. (You can make a battery from a Dagwood "sandwich" of alternating pennies, dimes, and moistened paper; its feeble power won't light a bulb, but will run a small calculator.)

"I, Sir, I my own self, cut out seven discs [of zinc] of the size of half-pennies each!" Faraday wrote his friend Benjamin Abbott on July 12, 1812. "I, Sir, covered them with seven halfpence and I interposed between seven, or rather six pieces of paper soaked in a solution of muriate of soda [i.e., salt water]!!! But laugh no longer, dear A., rather wonder at the effects this trivial power produced." (From a modern perspective, chemical reactions between the metal electrodes and the fluid, or electrolyte, create a surplus of negatively charged electrons at one electrode and a dearth at the other Thus, one battery terminal becomes the "negative" and the other the "positive." This electrical imbalance impels electrons within an external wire connecting the terminals to flow, as long as the chemical reaction proceeds.)

Faraday next attached copper wires to the ends of his battery-stack, dipped these into a dissolved solution of Epsom salts-magnesium sulfate—then watched in amazement as the electricity did its work. "[B]oth wires became covered in a short time with bubbles of some gas, and a continued strean of very minute bubbles, appearing like small particles, ran through the solution from the negative wire. My proof that the sulphate was decomposed was, that in about two hours the clear solution became turbid: magnesia was suspended in it." Somehow the electrical influence had separated the dissolved magnesium sulfate into its constituent parts, just as Marcet and Davy had asserted.

Fired up by his initial success, Faraday returned to Knight's for more zinc and, this time, a sheet of copper. From each metal, he cut out twenty disks, about 1% inches in diameter. These he layered wit flannel scraps moistened with salt water. He applied this stronger battery to a number of compounds: magnesium sulfate again, copper sulfate, lead acetate. All decomposed into their constituent parts. Then he tried to decompose water from the shop's lead cistern. The result—a white precipitate—was at odds with what he had read. The anomalous outcome he attributed (probably correctly) to impurities in the water: lead, iron, salt, carbon dioxide.

But, Faraday informed Abbott, there was more. "[0]n separating the discs [of the battery] from eac other, I found that some of the zinc discs had got a coating . . . of metallic copper, and that some of th copper discs had a coating of the oxide of zinc. In this case the metals must both have passed through the flannel disc holding the solution of muriate of soda, and they must have passed by each other." What, Faraday wondered, was the precise action that ripped these metals from their native plate, then guided them to their destination? And if, as conventional wisdom held, the mutual force of the zinc and copper plates plucked particles from each other, and if these migrating particles were oppositely charged-again mutually attractive—how did the particles manage to slip past one another without combining? By the time Faraday teased out the answers to these questions, decades hence, he would have completed his own journey, guided by the inexorable force of curiosity.

As remarkable as his experiments might have seemed to him at the time, it must have crossed Faraday's mind what he might accomplish with more than the "trivial power" at his disposal. He knev that the Royal Institution had provided Davy with powerful banks of batteries, including one with tw thousand pairs of metal plates that took up an entire bunker in the basement. Shocking various solutions with these, Davy had isolated pure forms of elements, both known and unknown at the time sodium, potassium, calcium, magnesium, barium, strontium, and chlorine. Connecting his mega-battery to a pair of carbon electrodes, Davy had also created the first continuous electric light, which blazed as brightly as the sun, according to one witness.

What might have appeared as magic to most, Faraday recognized as the judicious use of equipmen—admittedly in very capable hands. He had carried out basic chemical experiments and now wished go further. However, he was trapped by his own procedural philosophy: his need to prove-or disprove assertions through experiment. "I was never able to make a fact my own without seeing it," he wrote a friend. "[H]ow terrified I should be to set about learning science from books only." His experiment aspirations required a true laboratory, not a mantelpiece toy. As long as he was a bookbinder, he would have neither the time nor the means to pursue science the way he wanted.

As the end of his apprenticeship loomed, a career in the sciences seemed increasingly remote, and "the binding of other men's thoughts in leather backs, seemed the only means of livelihood open to him." In desperation, he wrote to Joseph Banks, president of the Royal Society, begging for a scientific position, "however menial." He checked back with the porter several days later. No answer. He returned three more times. Still no response. Finally, the porter delivered Banks's reply-"the lette required no answer." In the eyes of the scientific establishment, Michael Faraday did not exist.

2

PERCEPTIONS PERFECTLY NOVEL

When the mind is ready, a teacher appears.

—CHINESE PROVERB

England's county Cornwall juts boldly into the Atlantic at the island's southwest extremity. This haunted landscape of moors, cliffs, and beaches lies about as far as one can get from the rattle and hum of London without wading into the sea. Its secluded coves once sheltered a ragtag navy of privateers who struck at passing vessels. It's not surprising that the coastal town of Penzance, nestled picturesquely against Mounts Bay, is known more for its fictional pirates than for the famous flesh-and-blood scientist who was born there.

Eldest of five children of a wood carver and his milliner wife, Humphry Davy showed intellectual promise from an early age. In grammar school, he regaled his fellow students with ghost stories and tales from the *Arabian Mights,* and by his teenage years was already a practiced chemist. Among his homemade creations was "thunder powder," which he routinely exploded for his friends. He tramped the Cornish countryside, fishing, hunting, collecting rocks, and otherwise finding inspiration for his poetry.

Davy's high-spirited romp through childhood ended abruptly at age sixteen when his father died. Apprenticed by his godfather in 1795 to a local apothecary-surgeon, Davy appeared headed for a medical career. His diary lists an ambitious plan of self-study indicative of his intellectual energies: theology, geography, logic, languages (seven in all, including Hebrew), physics, mechanics, rhetoric and oratory, history and chronology, mathematics, plus a host of medical-related fields. His increased access to chemical supplies stoked a simmering interest in experimentation—specifically, in chemistry. Through chemical manipulation, he developed his own pigments for painting and analyzed the makeup of local seaweed. After a friend took him to see a chemistry laboratory in Hayle, Davy realized that a life as a country practitioner was not for him.

Davy's entry into the world of chemistry couldn't have been more timely. The investigation of matter's innate properties had thrown off its long-held ties to medicine and pharmacy and established itself as a field in its own right. Nations turned to chemistry for solutions to practical problems in manufacturing, agriculture, and warfare. Davy's primary resource was Antoine Laurent Lavoisier's *Elementary Treatise on Chemistry*. More than anyone else, Lavoisier transformed chemistry from a magical art into a modern science. Lavoisier proved that fire is a form of energy derived from chemical reactions of substances with oxygen. He demonstrated that water, previously believed to be an indivisible element, is a compound of hydrogen and oxygen. He further posited that the total quantity of matter before and after a chemical reaction is the same, although some fraction might change form. "Upon this principle," Lavoisier wrote, "the whole art of performing chemical experiments depends." In Lavoisier's zero-sum game—mass in equals mass out—chemists were compelled to quantify every product of a chemical reaction and to account for any "missing" matter.