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Oliver Heaviside

A first-rate oddity

Bruce J. Hunt

Prickly, reclusive, and unemployed for most of his career, Heaviside nonetheless strongly influenced the evolution of 19th century electromagnetics.

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Oliver Heaviside (1850–1925) was a self-educated English mathematical physicist who spent most of his life on the far fringes of the scientific community. Yet he did more than anyone else to shape how James Clerk Maxwell's electromagnetic theory was understood and applied in the 50 years after Maxwell's death. Indeed, Maxwell's equations in their most familiar vector form come from Heaviside. (Photo courtesy of the IET Archives.)

When physicists today write down Maxwell's equations in their standard vector form or simply set up a problem using vector analysis, they are drawing, usually without realizing it, on the work of Oliver Heaviside. When they analyze how electromagnetic waves move along a wire or across space, or when they use such words as "impedance" or "inductance," they are following in Heaviside's footsteps. And when at the climax of the musical *Cats*, chorus members sing about how Grizabella is about to rise "Up, up, up past the Russell Hotel/ Up, up, up, up to the Heaviside Layer," they are alluding to Heaviside's idea that there must be a conducting layer in the upper atmosphere—though few in the audience probably catch the reference.

Heaviside was a self-trained English mathematical physicist and a pioneer of electromagnetic theory. He was also a very unusual personality; Cambridge physicist G. F. C. Searle, Heaviside's closest scientific friend in his later years, described him as "a first-rate oddity," though he felt compelled to add, "never, at any time, a mental invalid."[1] Heaviside spent his career on the far fringes of the scientific community, but he became a central figure in the consolidation of Maxwell's electromagnetic theory and its application to practical problems.

Humble origins

Heaviside was born 18 May 1850 in a decaying part of Camden Town in north London. His father, Thomas, was a skilled wood engraver whose craft was being undercut by advances in technology; his mother, Rachel, was a former governess who ran a small school for neighborhood children. The family lived for years on the ragged edge of poverty in a setting that was almost literally Dickensian—their home was just around the corner from where Charles Dickens had lived during the most miserable part of his own childhood. An early bout with scarlet fever left Oliver nearly deaf, though he recovered most of his hearing by his teens. He later described his childhood in a letter to Irish physicist George Francis FitzGerald:

> I was born and lived 13 years in a very mean street in London, with the beer shop and bakers and grocers and coffee shop right opposite, and the ragged school and the sweeps just round the corner. Though born and bred up in it, I never took to it, and was very miserable there, all the more so because I was so exceedingly deaf that I couldn't go

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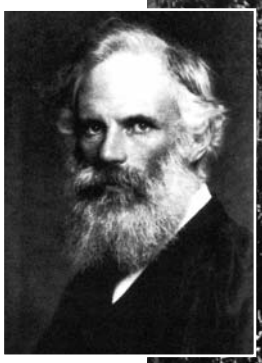
> and make friends with the other boys and play about and enjoy myself. And I got to hate the ways of tradespeople, having to fetch the things, and seeing all their tricks. The sight of the boozing in the pub made me a teetotaller for life. And it was equally bad indoors. [Father was] a naturally passionate man, soured by disappointment, always whacking us, so it seemed. Mother similarly soured, by the worry of keeping a school.[2]

After a small inheritance enabled the family to move to a better part of Camden Town, Oliver's life improved a bit. He did well at the local grammar school, but there was no money to go further, and his formal education ended when he was 16.

Heaviside had one great advantage in life, beyond his native abilities: His mother's sister had married Charles Wheatstone, professor of physics at Kings College London and one of the inventors of the electric telegraph. The Heaviside boys looked to Wheatstone for help in finding careers, and he obliged: Oliver's older brother Charles became an expert on the concertina (another of Wheatstone's inventions) and later opened music shops in Torquay and Paignton in Devonshire, while his other brother, Arthur, joined Wheatstone's telegraph business in Newcastle and later became an engineer in the British Post Office telegraph system. After leaving school, Oliver was sent north to assist Arthur, and then in 1868 he landed a job on the Anglo-Danish telegraph cable, newly laid across the North Sea from Newcastle to Denmark.

Cable telegraphy was booming in the late 1860s. After some early stumbles, the industry had found its feet with the successful spanning of the Atlantic Ocean in 1866, and the undersea network quickly spread to India, South America, Australia, and China. Almost all of those cables were built, laid, owned, and operated by British firms, and as the leading high-tech industry of the day, cable telegraphy deeply shaped British work in electrical science in the second half of the 19th century. Even the Anglo-Danish cable, though owned by a Danish firm, was built, laid, and initially operated by British engineers and technicians like Heaviside.



Cable testing rooms were among the most advanced electrical laboratories in the world in the 1860s and 1870s, and Heaviside soon became fascinated by problems of electrical measurement and signal transmission. In 1873 he published a paper in the *Philosophical Magazine* on the most sensitive arrangement of a Wheatstone bridge; the paper attracted the attention of William Thomson (later Lord Kelvin), the most famous electrical scientist of the day. When Thomson passed through Newcastle not long after the paper appeared, he sought out Heaviside to congratulate him on it, which no doubt boosted the young telegrapher's already healthy self-regard. Heaviside also sent a copy of his paper to James Clerk Maxwell, who cited it in the second edition of his great *Treatise on Electricity and Magnetism*.

Heaviside was a valued worker on the Anglo-Danish cable, but he was prickly and refused to do tasks he thought were beneath him. He also suffered health problems. All his life, he was subject to what he called "hot and cold disease," which led to nervous disturbances that he feared might culminate in epilepsy. Whether because of ill health, dissatisfaction with the increasingly routine work on the cable, or simply a desire to focus on his own research, Heaviside quit the cable company in May 1874, at age 24, and returned to London to live with his parents. He never again held a regular job, but instead worked full-time on electrical problems. His brother Arthur provided financial support and collaborated on projects related to his engineering work, but for the next decade or more Heaviside worked in almost complete isolation in his parents' spare room, pushing back the frontiers of electrical knowledge on his own.

While still at Newcastle, Heaviside had taken up Thomson's 1855 theory of telegraphic transmission. Focusing on resistance and capacitance, whose effects predominated on long cables, Thomson had derived equations that treated the passage of voltage and current along a cable as a case of simple diffusion. In a series of papers published between 1874 and 1881 in the *Philosophical Magazine* and the *Journal of the Society of Telegraph Engineers*, Heaviside extended Thomson's theory to take into account current leakage and self-induction. He showed that depending on the relative values of the resistance, capacitance, leakance, and inductance, signals did

Oliver Heaviside became an avid bicyclist in the 1890s. When physicist G. F. FitzGerald (inset) visited him in 1898, they rode together along steep and twisting Devonshire lanes. Heaviside later wrote to FitzGerald, "Idiots consider me a madman about the bike; I ride every day" (in ref. 2, p. 235). (Photo courtesy of the IET Archives.)

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not simply diffuse smoothly along a cable but oscillated, skittering back and forth as waves.

Following Maxwell

Around 1882 Heaviside turned from the equations of linear circuit theory to the physics of electromagnetic waves. He had read Maxwell's *Treatise* when it first came out in 1873, but said later that he did not really understand Maxwell's theory until he rewrote it. Maxwell had written most of his equations in Cartesian coordinates, which yielded long and complicated expressions for such things as the curl of a flux. He gave some results, however, in the compact form of quaternions, a number system that Irish mathematician William Rowan Hamilton had devised in 1843. A quaternion has four parts: three components that form a vector, plus a scalar. Hamilton had focused on the algebraic properties of quaternions, but his disciple Peter Guthrie Tait emphasized how they could be used to represent motions and forces in space, and it was at Tait's urging that Maxwell introduced them into his *Treatise*.

After encountering quaternions there, Heaviside tried to use them himself, but he soon found them to be "antiphysical and unnatural." In the end, he later said, "I dropped out the quaternion altogether, and kept to pure scalars and vectors, using a very simple vectorial algebra in my papers from 1883 onward."[3] With the scalar and vector products and the operators grad, div, and curl, he assembled a simple and powerful set of mathematical tools that he could bring to bear on electromagnetic problems. American physicist J. Willard Gibbs had followed a similar path a few years earlier, though he did not publish an account of his vector system until after Heaviside. Their notations differed slightly (it was Gibbs who introduced "dot" and "cross" for the scalar and vector products), but their underlying ideas were essentially the same, and Gibbs and Heaviside became strong allies in the battles that raged in the early 1890s between "vectorists" and "quaternionists."

At the same time that Heaviside was taking up Maxwell's theory, he was finding a new place to publish. The *Electrician* was a weekly trade journal owned by cable interests, and though its pages were crowded with advertisements and commercial notices, it also carried quite advanced articles on electrical theory and practice. (In the usage of the time, an electrician was any expert on electrical science or technology, rather than a tradesman who wired up buildings.) Heaviside had written a few short pieces for it, and in 1882 its editor, Charles H. W. Biggs, invited him to become a regular contributor. Over the next 20 years, apart from a gap of about 3 years, the *Electrician* carried something from Heaviside's pen every few weeks, altogether enough to fill 1700 pages in his collected works. The *Electrician* paid Heaviside about £40 a year for his articles. It was not much—Heaviside later said for years he had "earned less than a hodman"—but his needs were modest, and the money, while welcome, was less important to him than having a steady outlet for his writings.[4]

Heaviside made his greatest advance in the summer of 1884, while exploring how energy moves through the electromagnetic field. Maxwell had given formulas based on the electric and magnetic fields **E** and **H** for how energy is distributed in the field, but he never explained how it got from one place to another. As Heaviside saw it, telegraphy was ultimately about sending energy cleanly—without distortion—along a wire, and he dug into the equations in the *Treatise* to find how electromagnetic energy would move. After laborious transformations, he extracted a remarkably simple result: $\mathbf{S} = \mathbf{E} \times \mathbf{H}$—the flow of energy at a point in space is simply the vector product of the electric and magnetic fields there. The equation had some surprising consequences; in particular, it implied that the energy of an electric current does not flow within the wire like water in a pipe but instead passes through the surrounding field and enters the wire through its sides. Heaviside took the idea in stride, however, having long been convinced that the real action lay not within a conducting wire but in the field around it.

Heaviside saw his energy-flow formula as the keystone of Maxwell's theory. As such, he said, it should be possible to derive it not via the roundabout route he had initially followed but directly from the basic equations of the field—if one started with the right basic equations. In his *Treatise*, Maxwell had built his theory around the vector and scalar potentials **A** and Ψ. They did not locate the energy correctly, however, and Heaviside regarded them as quite distant from the real workings of the field. He proceeded to work back from his energy-flow formula to find a new set of basic equations, equivalent to those in Maxwell's *Treatise* but based directly on **E** and **H** and so better suited to treating energy flow. By combining two of Maxwell's expressions relating the vector potential **A** to the fields **E** and **H**, Heaviside derived what he called the "second circuital law," which related the curl of **E** directly to the rate of change of **H**—a fitting partner, he said, for Maxwell's "first circuital law" relating the curl of **H** to **E** and its rate of change (see the box on page 53). By combining them with Maxwell's expressions for the divergence of the electric displacement **D** and the magnetic induction **B**, Heaviside arrived at the compact set of four vector relations we now know as Maxwell's equations.

Once he had recast the equations of Maxwell's theory, Heaviside found that many things fell neatly into place; indeed, he later declared, "After that I did more work in a week than in all the previous years, in fact, I sketched out all my later work."[5] He gave a first brief account of his energy-flow theorem in the *Electrician* in June 1884 and made it the centerpiece of a long series on electromagnetic induction that began there in January 1885. Besides discussing how energy enters a wire, Heaviside used his theorem and his new set of equations to clarify various propagation problems and to explain such phenomena as the skin effect, in which high-frequency alternating currents are confined to the outer layers of a conductor.

Heaviside did not have much access to scientific journals and so did not learn until late in 1885

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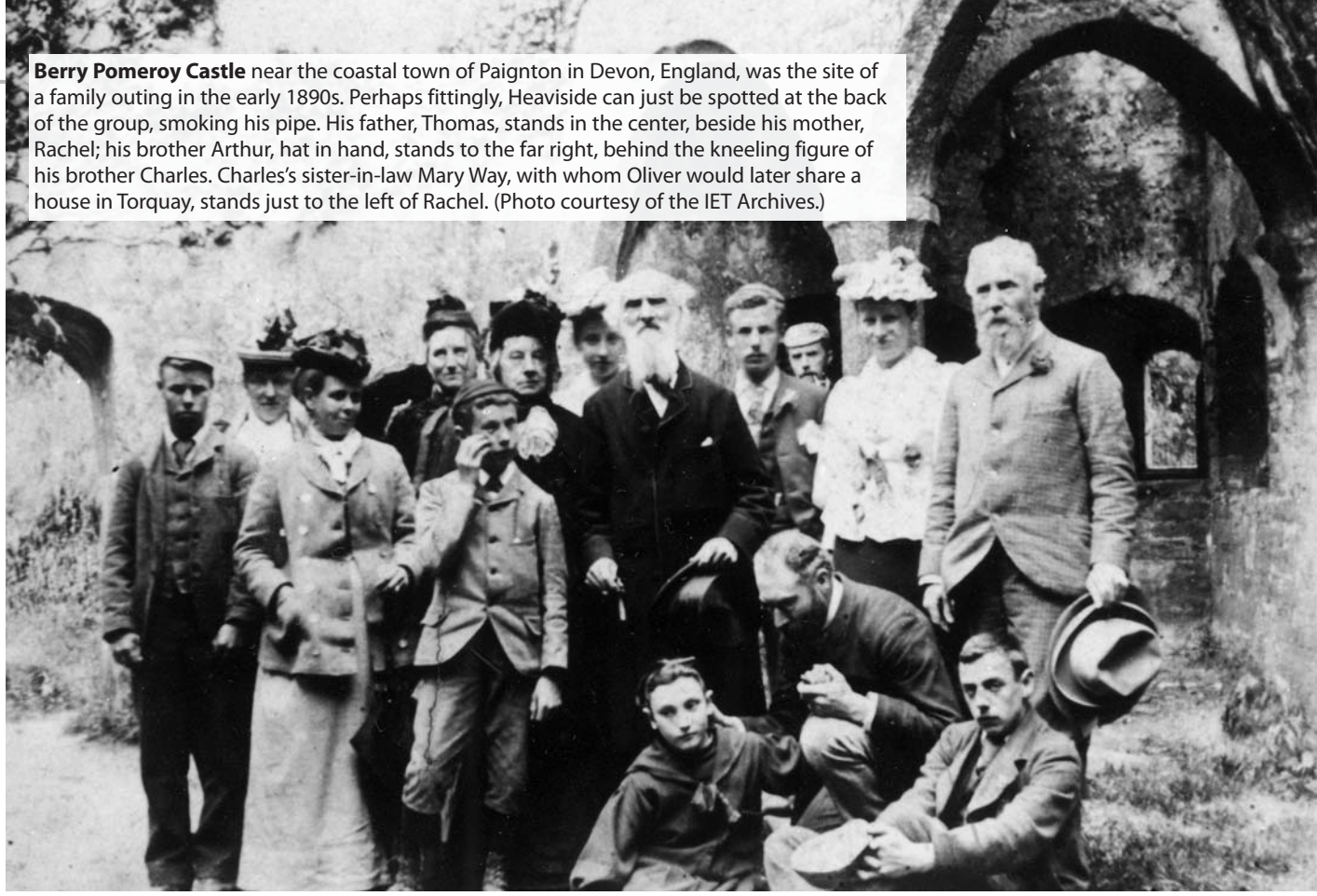

Berry Pomeroy Castle near the coastal town of Paignton in Devon, England, was the site of a family outing in the early 1890s. Perhaps fittingly, Heaviside can just be spotted at the back of the group, smoking his pipe. His father, Thomas, stands in the center, beside his mother, Rachel; his brother Arthur, hat in hand, stands to the far right, behind the kneeling figure of his brother Charles. Charles's sister-in-law Mary Way, with whom Oliver would later share a house in Torquay, stands just to the left of Rachel. (Photo courtesy of the IET Archives.)

that a Cambridge-trained physicist, John Henry Poynting, had hit on the energy-flow theorem shortly before him. The Royal Society published an abstract of Poynting's result in January 1884 and the full paper later that year, which is why today we call the energy-flow vector by Poynting's name rather than Heaviside's.

The articles Heaviside wrote on Maxwell's theory in the mid 1880s drew little attention at the time; no doubt most readers of the *Electrician* simply skipped over their dense thickets of unfamiliar symbols. Heaviside seemed untroubled, however. As he wrote to Irish physicist Joseph Larmor many years later,

> There was a time indeed in my life when I was something like old Teufelsdröckh in his garret [a reference to the German "philosopher of clothes" in Thomas Carlyle's *Sartor Resartus*], and was in some measure satisfied or contented with a mere subsistence. But that was when I was making discoveries. It matters not what others may think of their importance. They were meat and drink and company to me.[6]

Inductive loading

In 1886 Heaviside's brother Arthur, by then a leading post office engineer, was experimenting with telephone lines in which the receivers were arranged in "bridge" or parallel circuits. To his surprise, he found that adding more telephones to a circuit actually improved the clarity of transmission. He turned for an explanation to Oliver, who soon showed that the leakage of current through each telephone reduced the distortion, though it also weakened the signal.

Looking more deeply into circuit theory, Heaviside also found that adding more inductance to the circuit—for instance, by inserting coils at regular intervals along the transmission cable—would reduce the distortion even further. The extra inductance, he explained, would help carry the waves along in much the same way that loading a clothesline with birdshot makes it better able to convey transverse waves. He later joked that his name and inductive loading were "naturally and providentially connected. You heavify a line by the process of heavification."[7] Whatever one called it, inductive loading offered a relatively cheap and easy way to improve telephone transmission, and AT&T and other companies later used it with great success.

Heaviside never patented his idea, so he never made a penny from it; the money instead went to Serbian-born American physicist Michael Pupin, who secured a patent on inductive loading in 1899 and sold the rights, under somewhat shady circumstances, to AT&T for $500 000. Heaviside came to despise Pupin and AT&T, but he had little legal recourse. Mathematician Norbert Wiener of MIT later took up Heaviside's cause; he denounced AT&T and Pupin as thieves and cast Heaviside (thinly disguised) as the hero of a rather turgid novel, *The Tempter*, in 1959. Wiener even tried to interest Orson Welles in making a movie about Heaviside, but nothing came of it.[8]

Whatever its later success, the idea of inductive loading initially faced an uphill fight. Inserting a

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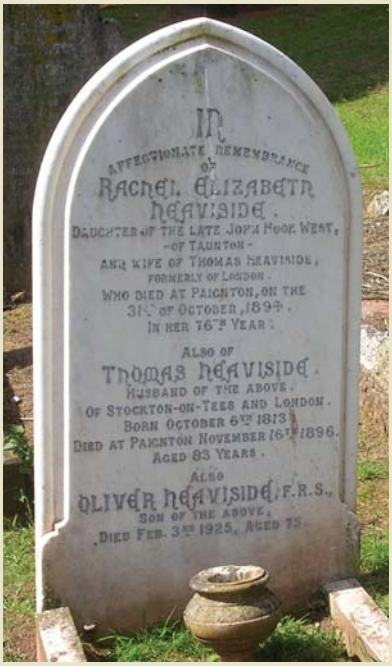

When Oliver Heaviside died in February 1925, he was buried in the Paignton Cemetery in the same plot as his parents. His name was simply added beneath theirs on the gravestone, the appended "F.R.S." (for "Fellow of the Royal Society") giving the only hint of his achievements. Though the inscription says he was "aged 75," he was in fact 74 when he died. The grave later fell into disrepair and Heaviside's name was often obscured by weeds until 2005, when an anonymous benefactor had the stone cleaned and set upright.

single high-induction coil into a circuit was known to be fatal to clear signaling, a notion that led William Preece, the head of the post office telegraph engineers, to declare self-induction to be a "bête noire" that ought to be hunted down and eliminated from all telephone circuits. Preece had called for the post office to shift from iron to copper wires, an expensive move that he justified in public statements in 1886 and early 1887 by citing the need to reduce inductance.

The Heaviside brothers thus could hardly have chosen a less opportune moment to call for adding inductance to telephone lines. In April 1887 they completed their joint paper on the subject and prepared to send it off to the *Journal of the Society of Telegraph Engineers and of Electricians*. As a post office employee, however, Arthur first had to secure clearance from his superior in the engineering ranks—none other than Preece, who promptly declared the paper worthless and blocked it. Arthur soon acquiesced, but Oliver emphatically did not. Through the summer of 1887 he sent the *Electrician* caustic letters attacking "the eminent scienticulist," as he called Preece, but Biggs, though sympathetic, feared a libel suit and declined to publish them. Then in October, Biggs was abruptly removed as editor of the *Electrician*, a move he later hinted was prompted by his support for Heaviside. The new editor soon cancelled Heaviside's long-running series of articles, saying he had asked around and found no one who read them.[9]

Heaviside was furious. He considered inductive loading to be one of his best ideas, and certainly the most practically important; to be blocked from publishing on it was simply unacceptable. This "was a serious matter to me last October," he wrote in 1888, and had he not been able to find an outlet for his work, "I should have been obliged to take some very decisive measures, and I am a determined character in my way."[10]

Gaining recognition

Fortunately, no "decisive measures" were needed. In November 1887, with help from Thomson, Heaviside persuaded the *Philosophical Magazine* to accept a series of articles on electromagnetic waves; the series ran throughout 1888. That March, physicist Oliver Lodge delivered a highly publicized series of lectures on lightning protection in which he showed that discharging a large Leyden jar into a long wire produced oscillating surges of current. In searching for the theory of such waves, he came across the first of Heaviside's *Philosophical Magazine* articles, and in his second lecture, Lodge went out of his way to remark on "what a singular insight into the intricacies of the subject, and what a masterly grasp of a most difficult theory, are to be found among the eccentric, and in some respects repellant, writings of Mr. Oliver Heaviside."[11] Heaviside was by that time hungry for public notice, and, the remark about his "repellant" style aside, he was overjoyed. He later told Lodge, "I looked upon your 2nd lecture when I read it as a sort of special Providence!"[12] Heaviside wrote to thank Lodge (and to fill him in on Preece's iniquities), and they soon became friends and allies.

Lodge hoped his experiments on waves on wires would be the hit of the 1888 meeting of the British Association for the Advancement of Science, held that September in Bath. But they were overshadowed by reports from Germany of Heinrich Hertz's even more dramatic experiments on electromagnetic waves in air. FitzGerald used his presidential address to hail Hertz's experiments as the long-sought confirmation of Maxwell's field theory. A debate at the meeting between Lodge and Preece on methods of lightning protection also focused on points of electromagnetic theory, particularly self-induction and the skin effect. On reading an account of the meeting—he never attended such things himself—Heaviside was moved to burst into verse, with Preece obviously in mind:

> Self-induction's "in the air,"
> Everywhere, everywhere;
> Waves are running to and fro,
> Here they are, there they go.
> Try to stop 'em if you can
> You British Engineering man![13]

The Bath meeting was also the scene of what came to be called the "murder of Ψ" debate over what place, if any, the potentials ought to hold in Maxwell's theory. FitzGerald, Lodge, Thomson, and American physicist Henry Rowland led the discussions, with Heaviside an important offstage presence. At one point during the meeting FitzGerald wrote a crucial new equation—essentially a gauge condition—in his notebook and scrawled beside it, "Very important. . . . Must be all in O. Heaviside."[14] The discussions were lively but not altogether conclusive, and a published account said that "everyone expressed regret at the absence of

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Mr. Heaviside, and kept on his guard."[15]

In the space of a few months in 1888, Heaviside had gone from being a nobody, easily silenced by a minor official who did not like what he had to say, to being a scientific authority treated with respect and deference by the top physicists of the day. In January 1889 Thomson devoted much of his presidential address at the newly renamed Institution of Electrical Engineers to praise for Heaviside's propagation theory. FitzGerald visited Heaviside in his Camden Town home the following month, and Lodge did so in March. Heaviside began to correspond regularly not just with Lodge but with FitzGerald, Hertz, and many others. He was elected a fellow of the Royal Society of London in 1891, and in January that year the *Electrician*, finally carrying his writings again, launched a series on electromagnetic theory that would run until 1902 and be reprinted in three volumes. Heaviside's work also began to find its way into textbooks, notably August Föppl's 1894 *Einführung in die Maxwellsche Theorie der Electricität* (*Introduction to Maxwell's theory of electricity*), from which Albert Einstein, among others, would learn electromagnetic theory.

In the fall of 1889 Heaviside and his aging parents moved from London to the seaside town of Paignton in Devonshire, where they lived above one of his brother Charles's music shops. One of his few scientific visitors there was Searle, who first came in 1892 to discuss Heaviside's work on moving charges and visited many times thereafter. Heaviside worked along steadily during his early years in Devonshire, publishing not just on electromagnetic theory but on vector analysis and his "operator" methods for solving differential equations.

In those days the Royal Society would publish in its proceedings virtually anything one of its fellows submitted, and in 1893 Heaviside sent in the first two installments of a paper "On operators in physical mathematics." But pure mathematicians objected to the cavalier way he handled divergent series, and when he submitted a third installment, it was sent to a referee and rejected. Heaviside was incensed; if handled properly, he said, his methods gave demonstrably right answers, and that ought to be justification enough. "Shall I refuse my dinner," he said, "because I do not fully understand the process of digestion?"[16] Despite the objections of "rigorists," Heaviside's operator methods later came into wide use, especially among engineers, and probably influenced the thinking of Paul Dirac, who learned them during his initial training as an electrical engineer.

In 1894 a group of Heaviside's scientific friends tried to arrange a grant for him from the Royal Society Relief Fund, but Heaviside smelled charity and turned it down. Two years later they persuaded the government to offer him a pension of £120 a year (later raised to £220) and, by framing it as an honor rather than charity, managed to get Heaviside to accept it; it was his main source of income for the rest of his life. After his mother died in 1894, and his father in 1896, Heaviside stayed on in Paignton for a few months before renting a house near Newton Abbot, a few miles inland. "Behold a transformation!" he wrote to FitzGerald. "The man 'Ollie' of Paignton, who lives in the garret at the music shop, is transformed into Mr. Heaviside, the gentleman who has taken Bradley View."[17] The situation soon soured, however. Heaviside complained that local boys were calling him names, stopping up his sewer line, and even throwing rocks through his windows. Some of that harassment was no doubt real, but some was probably just in his head. In September 1898 Heaviside wrote to Lodge about "devilish hanky panky" at Newton Abbot, with people being stirred up against him.

Heaviside was certainly subject to periods of at least mild paranoia and had complained of being spied on. He also suffered from serious physical ills at Newton Abbot—mostly bouts of his "hot and cold disease"—that by 1905 had brought his scientific work to an almost complete stop. Three years later, after an especially bad winter, his brother Charles arranged for Oliver to move to Torquay, where from 1908 he shared a large house with Mary Way, the unmarried sister of Charles's wife, and helped with her mortgage payments. (Heaviside, in fact, took over ownership of the house, "Homefield," in 1911.) His health improved, but he bossed Way around so mercilessly that she moved out in 1916, leaving Heaviside to spend his final years in increasing isolation and eccentricity.

Heaviside's health collapsed completely at the beginning of 1925, and Searle helped move him to a nursing home, where he died on 3 February. He was buried in the Paignton Cemetery, in the same plot as his parents. His name was added below theirs on the tombstone, where it was often obscured by weeds—until 2005, when an anonymous benefactor had the tombstone cleaned and set upright. After Heaviside's death, Homefield was turned into a

"Maxwell's equations"

In 1884–85 Oliver Heaviside rewrote the 20 fundamental equations of Maxwell's *Treatise on Electricity and Magnetism* into a new and more compact form that by the late 1890s had become standard. He eliminated the vector and scalar potentials **A** and Ψ from the equations and expressed the electromagnetic relations purely in terms of the electric and magnetic fields, **E** and **H**.

His most important step was to derive what he called the second circuital law, which relates the curl of **E** to the rate of change of **H**. Starting with Maxwell's relation $\mathbf{E} = -\partial\mathbf{A}/\partial t - \nabla\Psi$, Heaviside took the curl of both sides: $\nabla \times \mathbf{E} = \nabla(-\partial\mathbf{A}/\partial t) - \nabla \times \nabla\Psi$. Since the curl of any gradient is zero, the last term vanishes. By switching the order of the space and time differentiations, Heaviside obtained $\nabla \times \mathbf{E} = -\partial(\nabla \times \mathbf{A})/\partial t$. Since $\nabla \times \mathbf{A} = \mu\mathbf{H}$, this yielded the second circuital law, $\nabla \times \mathbf{E} = -\mu\partial\mathbf{H}/\partial t$.

Heaviside then combined this with equations drawn from Maxwell's *Treatise* to obtain his new set of four "Maxwell's equations":

$$\nabla \cdot \varepsilon\mathbf{E} = \rho \qquad \nabla \times \mathbf{E} = -\mu\,\partial\mathbf{H}/\partial t$$

$$\nabla \cdot \mu\mathbf{H} = 0 \qquad \nabla \times \mathbf{H} = k\,\mathbf{E} + \varepsilon\,\partial\mathbf{E}/\partial t,$$

where ε is the permittivity; μ the permeability; ρ the charge density; and k the conductivity.

Heaviside used what he called rational units, which eliminated the factors of 4π that otherwise appeared in so many electromagnetic equations.

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tourist hotel, and then fell derelict. It was recently demolished, and a cracked blue plaque left on the gate is the only reminder that someone notable once lived there.

In a passage he once wrote about Maxwell but that might equally apply to himself, Heaviside reflected on what he called the true doctrine of the immortality of the soul—not in its religious sense, which he thought quite mistaken, but in the "far nobler sense" of the lasting effect that each person exerts on the world and that continues after his or her death. Some souls, he said, are in this sense very great:

> That of a Shakespeare or a Newton is stupendous. Such men live the best parts of their lives after they shuffle off the mortal coil and fall into the grave. Maxwell was one of those men. His soul will live and grow for long to come, and, thousands of years hence, it will shine as one of the bright stars of the past, whose light takes ages to reach us, amongst the crowd of others, not the least bright.[18]

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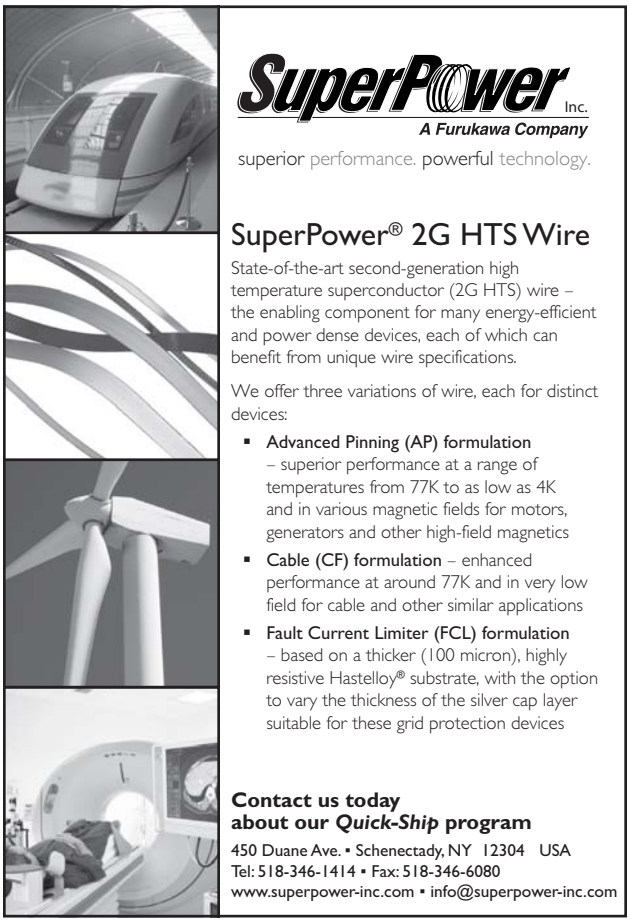

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