Imperial Science: Victorian Cable Telegraphy and the Making of "Maxwell's Equations"

By Bruce J. Hunt

Maxwell's equations of the electromagnetic field are generally, and quite rightly, regarded as among the great achievements of 19th century science. They govern everything from the behavior of light and radio waves to the workings of matter and the operation of the electric power system; their technological uses underlie much of our modern way of life. The physicist Richard Feynman once said, with perhaps excusable hyperbole, that "from a long view of history, there can be little doubt" that the formulation of these equations "will be judged as the most significant event of the 19th century."[1] The electrical engineer John R. Pierce saw a deeper value in them as well, declaring that "To anyone who is motivated by anything beyond the most narrowly practical, it is worth while to understand Maxwell's equations simply for the good of his soul."[2] The four vector equations we now know as "Maxwell's" hold an honored place in textbooks and on T-shirts, and adorn the base of the statue of James Clerk Maxwell that was recently erected in his native Edinburgh (Fig. 1). They have become icons of electrical science and engineering.

In this month's history article, the author traces how Oliver Heaviside's work on telegraphic propagation and energy flow led to his now popularly used representation of Maxwell's equations.

All of this raises the question of just where Maxwell's equations came from. How and why they did they come to look the way they do? Why were they were formulated in Britain, rather than, say, Germany, and why in the second half of the 19th century? In particular, why was it Oliver Heaviside, rather than James Clerk Maxwell, who in fact first cast these equations into their most familiar and now canonical form?

To answer these questions we will need to look beyond the strictly scientific context of 19th century electrodynamics and consider the broader material and technological circumstances of the time. We will need to look to the workings of the global economy and the rising electrical industries of the 19th century, particularly the first of them to become important: telegraphy. Once we do so, we will see that Maxwell's equations were cast into their definitive and most widely used form–the set of four vector equations connecting the electric and magnetic intensities and fluxes–largely in response to the demands and opportunities presented by submarine cable telegraphy, one of the characteristic technologies of the British Empire in the Victorian era.

I. CABLES

Not long after Heinrich Hertz first demonstrated the existence of electromagnetic waves experimentally in 1888,

[1] R. Feynman, *The Feynman Lectures on Physics*. Reading, MA, USA: Addison-Wesley, 1964, vol. 2, p. 1.11.

[2] J. R. Pierce, *Electrons, Waves and Messages*: *The Art and Science of Modern Electronics*. Garden City, NY, USA: Hanover House, 1956, p. 105. When this passage was reprinted in Pierce, *Electrons and Waves* (Garden City, NY, USA: Doubleday, 1964, p. 126), the closing words were changed, in perhaps a glimmer of gender awareness, to "good of the soul."

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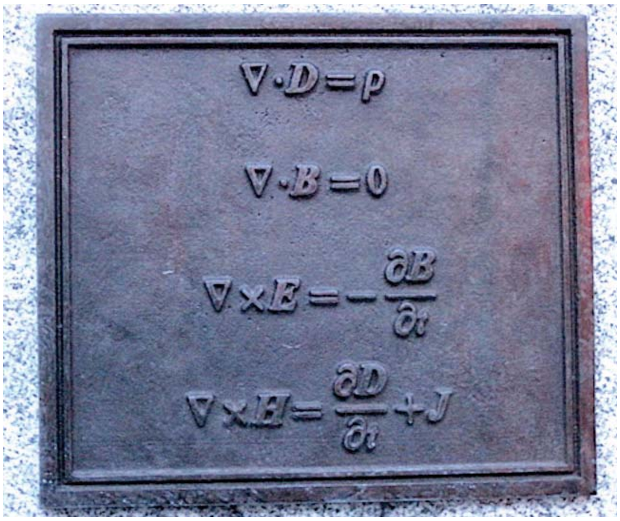

Fig. 1. ***"Maxwell's equations," from a plaque on the base of Alexander Stoddart's statue of James Clerk Maxwell, George Street, Edinburgh (photograph by Angela Smith).***

Oliver Lodge, one of Maxwell's main British followers, declared that with this confirmation of the electromagnetic theory of light, "the whole domain of Optics is now annexed to Electricity, which has thus become an imperial science."[3] Electricity was an "imperial science" in the late 19th century in a more literal sense as well: it was the foundation of the global cable network that sustained Britain's imperial power. A glance at a 1901 map of the world's cable routes shows how pervasive that network was (Fig. 2). Most of the cables that spanned the world's oceans were owned by British companies, and almost all of them were manufactured and laid by British firms.[4] The global cable network was overwhelmingly British from the time the first undersea line was laid across the English Channel in 1851 until the industry began to go into decline after World War I. (Today, with fiber optic lines, the submarine cable industry is bigger than ever.) There is no great mystery behind Britain's dominance of the world's telegraph cable industry in the 19th century: Britannia ruled the waves, and it was only natural that she should seek to extend that rule beneath the waves as well. As a maritime trading nation and as easily the leading commercial, industrial, and imperial power of the day, Britain had both the greatest need for cables and the greatest capacity for making, laying, and operating them.

The network of undersea cables was often called the "nervous system" of the British Empire; information flowed in along the cables and commands flowed out. By the last third of the 19th century, cables had become the favored channel for rapid overseas diplomatic, military, and commercial communications; they bound the Empire more closely together and helped Britain secure her continued

[3]O. Lodge, *Modern Views of Electricity*. London, U.K.: Macmillan, 1889, p. 307; first published in *Nature* (Jan. 31, 1889), vol. 39, p. 322. On Maxwell's British followers, see B. J. Hunt, The *Maxwellians*. Ithaca, NY, USA: Cornell Univ. Press, 1991.

[4]On the cable industry, see C. Bright, *Submarine Telegraphs*. London, U.K.: Crosby Lockwood, 1898; and S. M. Müller, *Wiring the World: The Social and Cultural Creation of Global Telegraph Networks.* New York, NY, USA: Columbia Univ. Press, 2016.

Fig. 2. ***Cable map of the world, 1901, from W. Clauson-Thune, A.B.C. Telegraphic Code, 5th ed. London, U.K.: Eden Fisher & Co., 1901, courtesy of Bill Burns. The dashed lines in the Pacific represent cables then in the planning stages; the one from Canada to Australia and New Zealand was completed in 1902, while the one from California to Hawaii was laid at the end of that year and extended to the Philippines in 1903.***

political and commercial preeminence.[5] In return, Britain's imperial and commercial power helped reinforce its dominance of the cable industry in some quite direct ways. For instance, Britain's control of Malaya and Singapore gave it an effective monopoly on the trade in gutta-percha, a natural plastic derived from the latex of certain tropical trees that was the favored material for insulating cables. Hundreds of tons of gutta-percha went into a long cable, and since foreign companies were unable to obtain such large quantities, they were effectively shut out of competition.[6]

How did Britain's virtual monopoly on cable telegraphy affect the science that was done in Victorian Britain? Submarine telegraphy was one of the top high-tech industries of the day; it required specialized expertise, and in this the dominance of British engineers and scientists was almost total. They were the ones who designed and manufactured the cables, who found ways to lay them safely at the bottom of the sea, and who devised techniques and apparatus for signalling effectively through them. All of this, especially the signalling, exposed British physicists and engineers to effects that no one else had ever encountered and strongly affected the way they conceived of electrical phenomena. In particular, this experience with cables led British physicists to pay special attention to electrical propagation and electromagnetic waves, phenomena that were leading features of Maxwell's theory, especially in the definitive form it took in the 1880s.

The ties between cables and British field theory can be seen in several key episodes: Michael Faraday's participation in early cable tests in 1853 and their role in drawing attention to his theories; the deep involvement of William Thomson (later Lord Kelvin) in the first (failed) Atlantic cable of 1858, in the successful ones of 1866, and in a string of other cable projects over the next 40 years; and Maxwell's own work for the British Association for the Advancement of Science in establishing the value of the ohm, a project that was launched to serve the needs of cable engineers and went on to have enormous effects on telegraphy, on the rise of laboratory physics, and on Maxwell's own work on his electromagnetic theory of light.[7] Here we will focus on a slightly later case: Oliver Heaviside's recasting of Maxwell's theory in the 1880s into the "Maxwell's equations" we know today:

$$\begin{aligned} \mathrm{div}\,\mathbf{D} &= \rho \quad \mathrm{curl}\,\mathbf{H} = \partial\mathbf{D}/\partial t + \mathbf{J} \\ \mathrm{div}\,\mathbf{B} &= 0 \quad \mathrm{curl}\,\mathbf{E} = -\partial\mathbf{B}/\partial t. \end{aligned}$$

[5]D. R. Headrick, *The Invisible Weapon: Telecommunications and International Politics, 1851-1945.* Oxford, U.K.: Oxford Univ. Press, 1991.

[6]Bright, *Submarine Telegraphs*, p. 253; W. von Siemens, *Inventor and Entrepreneur: Recollections of Werner von Siemens*, 2nd ed. Munich, Germany: Prestel-Verlag, 1966, pp. 119, 241.

[7]B. J. Hunt, "Michael Faraday, cable telegraphy, and the rise of field theory," *History of Technology*, vol. 13, pp. 1–19, 1991; C. Smith and M. Norton Wise, *Energy and Empire: A Biographical Study of Lord Kelvin.* Cambridge, U.K.: Cambridge Univ. Press, 1989; B. J. Hunt, "The Ohm is where the art is: British telegraph engineers and the development of electrical standards," *Osiris*, vol. 9, pp. 48–63, 1994; and B. J. Hunt, "Maxwell, measurement, and the modes of electromagnetic theory," *Historical Studies in the Natural Sciences*, vol. 45, pp. 303–339, 2015.

When people speak of "Maxwell's theory" today, these equations are generally what they mean. But you will not find them in Maxwell's great *Treatise on Electricity and Magnetism* of 1873. Maxwell's chapter on the "Fundamental Equations of the Electromagnetic Field" instead contains a list of 13 main equations involving the vector and scalar potentials and other quantities that do not appear at all in the famous four equations. The compact set of four vector equations we know as "Maxwell's" has in fact been drawn from papers Heaviside published in the mid-1880s.[8] Moreover, Heaviside cast Maxwell's equations into this particular form as a result of his long experience wrestling with telegraph problems.

II. HEAVISIDE

Heaviside was an unusual man; his best friend once described him as "a first-rate oddity" but "never a mental invalid"[9] (Fig. 3). Born in 1850 in what he later described as "a very mean street in London," his early life was almost literally Dickensian: Charles Dickens, in the unhappiest part of his own childhood, had lived in lodgings just around the corner from the house in Camden Town where the Heavisides later settled. "Though born and bred up in it," Heaviside later said, "I never took to it, and was very miserable there, all the more so because I was so exceedingly deaf that I could not go and make friends with the other boys and play about and enjoy myself."[10] A bout with scarlet fever had damaged his hearing when Oliver was very young, and though he recovered from most of his deafness by early manhood, it left a permanent

[8]Heaviside first published his form of "Maxwell's equations" in the opening installments of a long series of articles on "Electromagnetic induction and its propagation," which appeared in the *Electrician* between January and June 1885; these were reprinted in his *Electrical Papers*, 2 vols. (London, U.K.: Macmillan, 1892), with the equations first appearing in vol. 1, pp. 447, 452, and 475. Heaviside also developed the vector algebra he used to express these equations, and which in slightly modified form is still used today.

[9]G. F. C. Searle, "Oliver Heaviside: A Personal Sketch," in *Heaviside Centenary Volume.* London, U.K.: IEE, 1950, p. 96. On Heaviside's life and personality, see P. J. Nahin, *Oliver Heaviside: The Life, Work, and Times of an Electrical Genius of the Victorian Era.* Baltimore, MD, USA: Johns Hopkins Univ. Press, 2002; and B. Mahon, *The Forgotten Genius of Oliver Heaviside: A Maverick of Electrical Science.* Amherst, NY, USA: Prometheus Books, 2017.

[10]Oliver Heaviside to G. F. FitzGerald, June 3, 1897, quoted in Nahin, *Heaviside*, p. 13.

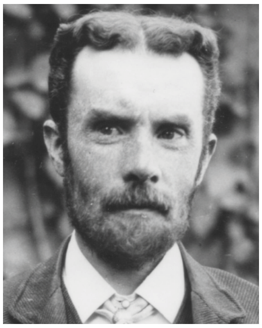

Fig. 3. ***Oliver Heaviside in the early 1890s, courtesy of IET Archives.***

mark on his personality. He was always a loner and spent most of his time reading and studying. He had few social skills, and though in later years he maintained a wide correspondence with other scientists, he had little direct contact with people outside his family after he was about 25. He had a sharp wit, which showed itself even in his mathematical writings, but his gift for sarcasm helped land him in several bitter disputes.

Heaviside attended the local grammar school in Camden Town and showed early talent in science. There was no money to send him to a university, however, so at age 16 he left school and set out to find a job. He was soon sent north to Newcastle to become a telegrapher, a move that would set the course for all of his later work. That Heaviside went into telegraphy was the result of a fortunate family connection: his mother's sister had married Sir Charles Wheatstone, one of the inventors of the telegraph. As Wheatstone's "poor relations," the Heavisides looked to Sir Charles for help in finding careers for their sons, and he obliged: Oliver's brother Charles became an expert on the concertina (another of Wheatstone's inventions) and went into the music business, while another brother, Arthur West Heaviside, became Wheatstone's telegraphic assistant and later ran one of his local telegraph companies in Newcastle. After the British inland telegraph companies were nationalized in 1870, Arthur became a leading engineer in the Post Office telegraph system, and he continued to play an important part in Oliver's career.[11] Oliver started in 1867 as Arthur's assistant, and the next year was hired to help with testing the Anglo-Danish cable, then newly laid across the North Sea.

In the late 1860s, when Heaviside got his start in it, the cable industry was booming. The completion of the first successful Atlantic cable in 1866 was followed by a series of big cable projects, especially lines connecting Britain to India, Australia, and the Far East. The Anglo-Danish cable was an important link in the Great Northern network, which ran from England across the North Sea and Russia to China and Japan. It was one of the relatively few cables that was not British owned (the Great Northern Company was Danish) but, significantly, the cable was manufactured, laid, and tested by British contractors.[12]

It was while testing the newly laid cable, checking it for faults, and adjusting the sending and receiving apparatus that Heaviside was exposed to the practical problems of telegraphy and the peculiarities of working a submarine cable. Cable testing rooms were among the most advanced and best equipped electrical labs in the world in the 1860s; many instruments and measuring techniques–even the basic units of ohms, amps, and volts–were first developed by and for British cable engineers and only later made their way into academic physics laboratories.[13] Heaviside was thus exposed to the leading edge of electrical technology and science in the 1860s, and he learned far more about the actual behavior of magnets, currents, and coils while working on the cable than he would have had he been sent to Cambridge or most other universities of the day.[14]

The most important phenomenon Heaviside encountered in the testing room was distortion–the stretching and blurring signals suffered as they passed down a cable. This was a serious difficulty, since it put a limit on how rapidly a cable could be operated and so on the amount of business it could handle. British engineers first noticed distortion in the early 1850s, and it became a major problem for them as they laid longer cables over the next few years. The electrical characteristics of the cables, mainly their high capacitance, caused initially sharply defined pulses of current to blur and run together during transmission; signalling thus had to be done relatively slowly to keep messages from becoming indecipherable at the receiving end. The problem was especially acute on long cables, since the distortion increased with the *square* of the cable's length. Some early cables could be worked at only a few words per minute, though the Atlantic cables could handle about 15. The Anglo-Danish cable was better; depending on the instruments used, it could handle up to 70 words per minute on test runs, and had little trouble with the usual commercial rate of 20 or 30 words per minute. Still, this was much less than overhead land lines could handle, especially compared to the hundreds of words per minute being achieved by the Wheatstone automatic telegraph transmitters that became standard on the main British land lines in the 1870s.[15]

Heaviside was familiar with these automatic telegraphs and was frustrated by the impossibility of using them to their full advantage on the Anglo-Danish cable. Engineers could improve their transmission rates to some extent by using more ingenious sending and receiving instruments, but by the time Heaviside started it was clear that the electrical characteristics of the cable itself set fundamental limits on the speed of signalling. As the pace of world communications increased in the last third of the century, that limit became less and less acceptable. As British engineers tried hard to find ways to make their cables handle faster signalling rates, they were pushed into making a close study of the causes of distortion and of the fundamental question of just how electrical signals travel along a cable.

Note that this was a specifically British problem, since it was the British who built and ran the world cable system. British engineers had to deal with distortion problems on submarine cables that their German, French, and American

[11] Mahon, *Forgotten Genius*, pp. 53–54.

[12] N. J. Holmes, "Submarine telegraphs," *Nature*, vol. 4, pp. 8–10, May 4, 1871; Holmes had supervised the laying and testing of the Anglo-Danish cable.

[13] Hunt, "Ohm," p. 48.

[14] G. Gooday, "Precision measurement and the genesis of physics teaching laboratories in Victorian Britain," *British J. History Sci.*, vol. 23, pp. 25–51, 1990.

[15] Holmes, "Submarine telegraphs," p. 10.

counterparts simply did not face. The telegraph lines in those continental countries ran overland; most were little more than bare wires strung from poles. Such overhead lines are much simpler electrically than are submarine cables; their capacitance is quite low, and consequently they show little distortion, even on quite long lines. In practice, the limits to speed on overhead lines were generally set by the rate at which clerks or machines could send and receive; a suspended wire could handle even very high rates of signalling without much trouble. Telegraph engineers in America, France, and Germany thus did not have to pay much attention to propagation problems or to whatever might be going on in the space around a telegraph wire; they could generally treat an electric current much like water flowing in a pipe and ignore any complicated field effects.

An incident in Thomas Edison's career gives a good idea of the difference between the problems of submarine telegraphy and those of landlines. In 1873, Edison visited England to try to sell an automatic telegraph system he had developed. He demonstrated it running at a thousand words per minute on overhead lines between Liverpool and London, and then was asked to try it on a 2000-mile coil of submarine cable that was being readied for shipment from a London factory. When he sent a dot through the cable, he found that instead of getting a mark on the paper tape a tiny fraction of an inch long, as he did through land lines, he got "a smear 27 feet long! If I ever had any conceit," he said later, "it vanished from my boots up." Despite intensive tinkering, he could never get more than two words per minute through the cable.[16] The problems of cable propagation forced British physicists and engineers to pay far more attention to field phenomena than was required of their American, German, and French counterparts, and their theories reflected that difference.

The connection between cables and field theory can be traced in some detail in Heaviside's career. He continued to work for the Great Northern Company for about six years, but in 1874 he left Newcastle and returned to London to live with his parents, partly because of health problems and partly to free himself to devote all of his time and considerable talents to theoretical investigations of the cable problems that had come to fascinate him. To equip himself for this task, in the 1870s, he essentially turned himself, through private study, into a mathematical physicist. Heaviside never again held a regular job after leaving Newcastle and really had almost no income; his brother Arthur apparently sent him a little money and he later got about £40 a year for articles he sold to *The Electrician*, a London trade journal owned by cable interests.[17] It was a bare subsistence, but it was enough to enable him to carry on his work, and he seemed to be happy with it.

Heaviside's great ambition was to design a perfect cable that could be worked arbitrarily fast with no distortion. The standard theory of cable signalling had been worked out by William Thomson in 1854; it treated electrical propagation as a kind of diffusion of current along the cable, on analogy to Fourier's theory of the diffusion of heat, and gave equations describing how the current and voltage would gradually rise at the far end of the cable.[18] Thomson's theory was put to good use for many years, and it allowed cables and apparatus to be designed much more efficiently than before. But while Thomson had explained why distortion occurred and had suggested ways to work around some of its effects, he could not point to any practical way to lessen or eliminate the distortion itself beyond the expensive expedient of using much fatter cables. In Thomson's theory, and in the experience of cable engineers, distortion seemed inescapable.

But Thomson's theory was incomplete, as Heaviside pointed out in 1876. Thomson had ignored self-induction, a sort of electromagnetic inertia that opposes changes in a current.[19] For the slowly varying currents Thomson had considered in 1854, self-induction had relatively little effect, but for the faster rates Heaviside was interested in, it had to be taken into account. One then found that the current did not simply diffuse along the wire, as Thomson had said; instead, its inductive "momentum" caused the current to oscillate, sending waves of voltage and current surging up and down the cable. Exactly how this worked was not entirely clear to Heaviside in the 1870s, but his telegraphic investigations were already pushing him into paying more attention to electromagnetic waves and the electromagnetic field.

III. HEAVISIDE AND MAXWELL'S THEORY

Hoping to gain a clearer grasp of what was going on in and around a telegraph wire, Heaviside turned to Maxwell's *Treatise* soon after it appeared in 1873. The book was full of ideas, but they were not always clearly expressed. Many of Maxwell's most important ideas–on the distribution of energy in the field, for instance, and on electromagnetic waves–were buried amid long accounts of miscellaneous facts and other people's views. To make matters worse, Maxwell died in 1879, just six years after his book was first published and before he had made much progress on revising it for a second edition. As a result, the main work of cleaning up Maxwell's theory, deciding exactly

[16]M. Josephson, *Edison: A Biography.* New York, NY, USA: McGraw-Hill, 1959, pp. 133–134; see also R. Jenkins (ed.), *The Papers of Thomas A. Edison.* Baltimore, MD, USA: Johns Hopkins Univ. Press, 1989, vol. 1, pp. 591–626, especially p. 604. W. Smith (*The Rise and Extension of Submarine Telegraphy.* London, U.K.: J. S. Virtue, 1891, pp. 317–318) gives the length of the coil Edison used as about 700 miles. Since the wire was coiled, Edison had to deal with magnetic as well as capacitative effects.

[17]On Heaviside's income, see Hunt, *Maxwellians*, p. 184.

[18]On Thomson's cable transmission theory, see Hunt, "Faraday," pp. 6–11.

[19]O. Heaviside, "On the extra current," *Philosoph. Mag.*, vol. 2, pp. 135–145, 1876; reprinted in Heaviside, *Electrical Papers*, vol. 1, pp. 53–61.

what it meant, extending it and testing it experimentally, was left to be done after his death by others, the so-called "Maxwellians," including Heaviside. In this process of revision and extension the theory acquired many features that, while in some sense implicit in Maxwell's original scheme, had by no means been recognized or stated by Maxwell himself.

The most important of these new ideas was that of energy flow. Maxwell had said quite clearly that energy is stored in the field around a charge or current and had even given formulas for how it is distributed, but he had not addressed how the energy in the field might move around when the charges or currents changed. Heaviside looked into this question in summer 1884 in hopes of learning more about how energy gets into and out of a telegraph line, or into the core of an electromagnet. Using Maxwell's own cumbersome formulas and going through a series of roundabout mathematical transformations, Heaviside hit upon a strikingly simple result: the flow of energy at a point depends only on the vector product of the electric and magnetic intensities there: $\mathbf{S} = \mathbf{E} \times \mathbf{H}$.[20] He immediately saw the importance of this result and began to draw surprising consequences from it–for instance, that the energy conveyed by an electric current does not flow along within the wire, as everyone had always assumed, but instead flows through the space outside it, the wire serving as a guide rather than a pipeline. Most physicists and engineers found this idea hard to swallow, and few accepted it at first. Heaviside, however, saw it as the key to understanding and improving telegraphic propagation. It is, after all, the energy that is sent along a wire that counts–the energy to deflect a needle or tap a key. A clear grasp of how that energy gets from one place to another was the central problem of effective telegraphy, and Heaviside was determined to follow up the clue his energy flow idea seemed to offer.

Heaviside's discovery of the paths of energy flow revolutionized the way he understood Maxwell's theory, and also the way he expressed it. Taking energy flow as the central fact of electromagnetism, Heaviside insisted that his simple result ought to follow directly from the basic equations of the theory, without requiring the roundabout derivation he had originally used. Following this clue, he worked back from the flow formula and recast the complicated equations Maxwell had given into an equivalent but much simpler form–the four symmetrical vector equations we now know as "Maxwell's," which Heaviside first published in *The Electrician* in the first half of 1885.[21]

Heaviside called these equations "Maxwell redressed" and used them almost exclusively in his own work from 1885 on.[22] They are better suited to dealing with many problems involving propagation and electromagnetic waves than are Maxwell's original equations–which is not surprising, since Heaviside had deliberately tailored his set of equations to handle energy propagation. This is a key point: Heaviside's form of "Maxwell's equations" is just one of a number of formally equivalent ways in which the laws of electromagnetism can be expressed, but it is the one best suited to treating the kinds of propagation phenomena that were Heaviside's main concern. When the announcement of Heinrich Hertz's experiments in 1888 suddenly put electromagnetic waves in the scientific spotlight, physicists quickly took up Heaviside's work and put it to use. By the mid-1890s his equations had become the standard textbook form of electromagnetic theory. Einstein learned Maxwell's theory from a textbook based quite directly on Heaviside's work, and physics and electrical engineering students ever since have studied essentially the equations Heaviside laid down.[23]

Unbeknownst to Heaviside, the energy flow formula had in fact been discovered by the Cambridge-trained physicist J. H. Poynting at the end of 1883, a few months before Heaviside hit on it; that is why it is now called the "Poynting flux" rather than the "Heaviside flux."[24] But Poynting was not nearly as close as Heaviside to the problems of telegraphy and electromagnetic waves, and he did not see the full strategic importance of his discovery. He was satisfied with having proved a nice mathematical theorem, even if his derivation was rather roundabout. He did not see the flow idea as a clue to the kind of deep restructuring of electrical theory that Heaviside undertook, and he made no move to follow up his discovery and recast Maxwell's equations into a simpler form. That was left to Heaviside, whose struggles with cable problems had made him sensitive to anything touching on electromagnetic waves and the relationship between wires and fields.

Heaviside was not slow to follow up the implications his energy flow theorem had for telegraphy. It led him to radically reconceptualize the function of telegraph lines, away from the old view of them as electrical pipelines and toward a new view of wires as waveguides. A wire, Heaviside said, is just the comparatively passive core of actions that really go on mostly in the space outside it. This reconceptualization completed the process, begun by Faraday and Maxwell, of shifting attention away from charges and currents and toward the surrounding field.

[20] O. Heaviside, "The induction of currents in cores," *Electrician*, vol. 13, pp. 133–134, Jun. 21, 1884; reprinted in Heaviside, *Electrical Papers*, vol. 1, pp. 377–378; see also Hunt, *Maxwellians*, pp. 119–122.

[21] Heaviside first published his two most important equations, involving curl $\mathbf{H}$ and curl $\mathbf{E}$, in the *Electrician* on Feb. 21, 1885; the equation for div $\mathbf{B}$ followed on Mar. 14 and that for div $\mathbf{D}$ on Jun. 12; see his *Electrical Papers*, vol. 1, pp. 447, 452, and 475. Note that Heaviside generally treated the electric and magnetic fluxes $\mathbf{D}$ and $\mathbf{B}$ as simply $\epsilon\mathbf{E}$ and $\mu\mathbf{H}$ and the electric current $\mathbf{J}$ as $k\mathbf{E}$, so that his set of equations involved only the electric and magnetic intensities $\mathbf{E}$ and $\mathbf{H}$, the quantities that determine the flow of energy in the field.

[22] On Heaviside's use of the phrase "Maxwell redressed," see Hunt, *Maxwellians*, p. 108.

[23] Albert Einstein learned Maxwell's theory largely by studying A. Föppl, *Einfuhrung in die Maxwell'sche Theorie der Elektricität*. Leipzig, Germany: Teubner, 1894; see G. Holton, "Influences on Einstein's early work in relativity theory," *Amer. Scholar*, vol. 37, pp. 59–79, 1967. As Föppl noted in his introduction, he drew heavily from Heaviside's writings, including his use of vectors.

[24] J. H. Poynting, "On the transfer of energy in the electromagnetic field," *Philosoph. Trans. Roy. Soc. Lond.*, vol. 175, pp. 343–361, 1884.

Heaviside now saw telegraph signals as electromagnetic waves *in space*, not within the wire; they were really no different from light waves except that they were of much longer wavelength. Heaviside later emphasized this point by declaring that telegraph wires made "beams of dark light."[25] From this point of view, a modern fiber optic cable is not so different from an old copper and gutta-percha one.

Wires were still important, of course; they steered the waves from one place to another and kept them from spreading out the way ordinary light does. Also, the electrical resistance of the wire pulled energy out of the waves, heating the wire and distorting the waves' shape. But now that he saw the waves as traveling *outside* the wire, Heaviside's focus was firmly on the field, and his approach to dealing with distortion problems shifted in important ways. He soon saw that if he could get the wire to draw energy out of the waves in a balanced way, he could preserve the shape of the waves and eliminate distortion. By about 1886 Heaviside could see that he was coming close to his goal of designing a perfect distortionless cable.

IV. LOADING

Heaviside hit on the solution to the problem of distortionless propagation in winter 1886–1887 while helping his brother Arthur with a joint paper for the Society of Telegraph Engineers and Electricians. Arthur Heaviside was a leading figure in the early history of telephones in England; among other things, he devised the bridge, or parallel, telephone circuit, which made party lines practical.[26] He wanted to publish a paper on this, and Oliver agreed to write the theoretical part.

Distortion was even more of a problem with telephones than with telegraphs. The human voice includes frequencies up to several thousand cycles per second, and on a telephone line, unlike a telegraph, you cannot work around distortion by just talking slower. The attenuation and jumbling of voice frequencies, and the absence in this period of any kind of electronic amplifier, put severe limits on long-distance telephony even on overhead land lines and virtually ruled out working telephones through underground or submarine cables of any appreciable length.

When Heaviside looked into the theory of how one of his brother's bridge circuits would affect a signal sent along it, he was surprised to find that the self-induction of the telephones along the line had a *beneficial* effect.[27] This seemed odd, since it was known that a single source of self-induction on a line (a coil, for instance) affected signals very badly; in fact, such coils were called "choke coils." But Heaviside's mathematical theory showed that if he spread the extra inductance out along the line, it in effect gave the waves extra momentum that helped carry them along. The waves still died out as they passed along the wire, but they did so more slowly and smoothly than before, and with much less distortion. Heaviside showed theoretically that by inserting coils at proper intervals along a wire, or by adding finely divided iron to its insulation, one could load it with just enough self-induction to completely eliminate distortion. Adding even a little extra inductance could greatly improve the clarity of the signals and make it possible to telephone to much greater distances or to work a cable at much higher speeds than would otherwise be possible, and at relatively small additional cost. Heaviside was excited by this discovery; he saw that it could revolutionize both cable and telephone communications, and later said that he considered it his best work.[28]

By this point—spring 1887—Heaviside had completed his main creative contributions to electromagnetism, but they had not yet had much real effect. His theoretical work had attracted almost no notice from physicists and his practical proposals, notably loading, had not yet drawn the attention of engineers. All of that would change rapidly over the next few years.

Heaviside's main problem was William Henry Preece (later Sir William), the head of the Post Office telegraph and telephone system and a powerful figure in British electrical engineering. Preece knew from experience how badly a single lump of self-induction could distort telephone signals, and he found it ridiculous to think that spreading this evil inductance out along a line would somehow give it a beneficial effect. Like most people, he was unable to follow the mathematics of Heaviside's loading theory, but he was sure its conclusions must be wrong. Moreover, Preece was in a position to make this rejection stick: he was Arthur Heaviside's boss and had to approve any papers submitted for publication by his Post Office subordinates. He blocked the Heaviside brothers' paper outright in spring 1887 and was apparently behind the abrupt cancellation that fall of Oliver's regular series of articles in *The Electrician*.[29] This touched off a bitter feud between Preece and Heaviside that was to last the rest of their lives.

Blocked by Preece, who was then effectively the head of Britain's electrical engineering community, Heaviside sought a new audience, and in 1888 he found a receptive one among physicists. That spring, Lodge had begun to experiment with electromagnetic waves along wires, and in Germany, Hertz was performing his even more dramatic experiments on electromagnetic waves in air.[30]

[25]Oliver Heaviside to Oliver Lodge, Jan. 5, 1899, quoted in Hunt, *Maxwellians*, p. 132.

[26]On A. W. Heaviside and the bridge circuit, see Heaviside, *Electromagnetic Theory*, vol. 1, pp. 433–437; and Mahon, *Forgotten Genius*, p. 124.

[27]Heaviside first noticed the benefits of loading while working with the line equations and then developed his theory of distortionless propagation more fully by shifting to a field view.

[28]Heaviside to Lodge, Sep. 21, 1888, in Hunt, *Maxwellians*, p. 144.

[29]Mahon, *Forgotten Genius*, pp. 132–136.

[30]On Lodge and Hertz's experiments on electromagnetic waves, see O. Darrigol, *Electrodynamics from Ampère to Einstein*. Oxford, U.K.: Oxford Univ. Press, 2000, pp. 202–208, 239–253.

These aroused great interest and drew physicists' attention to Heaviside's previously neglected papers, where they found that the theory of electromagnetic waves had already been very fully worked out–in connection with telegraph problems. Heaviside suddenly became well known and respected, at least among physicists: his earlier papers were collected and reprinted in two fat volumes, he was elected a Fellow of the Royal Society, and by the mid-1890s his form of Maxwell's equations had begun, as we have seen, to take its place in textbooks.[31] The cycle of Heaviside's work, running from its roots in technology to its impact on theoretical physics, had completed its first leg.

The other half of this cycle, running from theory back to technological application, was somewhat delayed. Preece kept Heaviside's loading proposal from being tried onlong-distance telephone lines in Britain in the 1890s and also discouraged the private cable companies from trying it on submarine cables, where in any case mechanical difficulties made it more difficult to apply. But in America a group of engineers at AT&T took up Heaviside's idea and had a loaded telephone line in operation by 1899.[32] Loading proved very successful and allowed workable long-distance phone lines and underground cables to be built for a fraction of their earlier cost. Columbia University Physics Professor Michael Pupin, who held the American patent rights, made a fortune from loading, as did AT&T. Heaviside, however, never got a penny for his work on loading. He was bitter about this in his later years, probably as much at being denied what he thought was his rightful credit and recognition as at being robbed of the money itself. He was in fact quite proud to see how his ideas had won wide acceptance, both in physics and in the electrical technology from which his work had originally sprung.

There is a final irony here: one of the main areas in which Heaviside's theoretical work was put to practical use was radio, and in the 1920s, it was long-distance shortwave radiotelegraphy, bouncing waves off the conductive "Heaviside layer" in the upper atmosphere, that finally broke the British cable companies' monopoly on international telecommunications.[33] Heaviside's work was rooted in cable technology, but its uses and implications went far beyond it.

V. CONCLUSION

This case study of Heaviside, cables, and "Maxwell's equations" illustrates some simple but important general points. One is the value of looking at scientific work in the broadest possible context, not least for the light this can shed on the inner workings and content of the science itself. It might not seem on the surface that to understand why Maxwell's equations look the way they do, or why they were formulated when and where they were, we should first examine the role telegraph cables played in the British Empire, but it is only when we put the equations in this context that we can see how important problems of telegraphic propagation and energy flow were in their evolution. More generally, it is only by looking at this kind of concrete material context that we can hope to understand many points in the history of science that might seem to be "purely internal" or determined by nature alone, and that we can get a better grasp of the reciprocal relationship between science and technology. ■

[31] Heaviside was elected a Fellow of the Royal Society in June 1891 and Macmillan brought out his collected *Electrical Papers* in two volumes in 1892. The incorporation of his form of Maxwell's equations into textbooks can be seen in Föppl, *Maxwell'sche Theorie*, pp. 159, 171, and 379–387; and in T. Preston, *The Theory of Light*, 2nd ed. London, U.K.: Macmillan, 1895, pp. 549–552.

[32] J. E. Brittain, "The introduction of the loading coil: George A. Campbell and Michael Pupin," *Technol. Culture*, vol. 11, pp. 36–57, 1970.

[33] See Headrick, *Invisible Weapon*, pp. 195–217, on how the spread of long distance radio, particularly shortwave, affected the cable industry in the 1920s.

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