Twenty Three Years: The Acceptance of Maxwell's Equations

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Abstract **─** Maxwell first published what came to be called "Maxwell's equations" in 1865. However, it was not until 1888, and Heinrich Hertz's experimental validation, that Maxwell's equations were widely accepted as correct. The story of the intervening 23 years is little known. Maxwell, who died in 1879, was exceptionally modest and did not promote his own results at any time. The survival of Maxwell's equations was up to the only three researchers in the entire world who paid serious attention to Maxwell's paper in 1865, and his seminal *Treatise* in 1873: Oliver Heaviside, Oliver Lodge, and George Francis FitzGerald. Later, Hertz joined the group forming "The Four Maxwellians". In this paper, we describe the torturous 23 year path Maxwell's equations took from their creation to their initial acceptance.

Index Terms **─** Fitzgerald, Heaviside, Hertz, history, Lodge, Maxwell's equations.

I. PROLOGUE

Flying splinters of wood from cannon balls exploding through the sides of the ships wreak the most carnage in the battle of Trafalgar, Fig. 1. One hundred fifty five years ago on October 21, 1805, the final and the greatest sailing ship battle of all time is fought to its gory end. Lord Nelson's 27 British battle ships and 2,150 cannons face 33 French and Spanish ships of Napoleon's navy carrying 2,640 cannons. Lord Nelson's flag ship, the HMS Victory becomes locked, rigging entangled, side-by-side with the French ship Redoubtable. The British reduce the gun powder in each charge, so the cannon balls penetrate only the near side of the Redoubtable and then bounce around inside, wreaking even more carnage. The crew of the Redoubtable valiantly return fire…

Every man does his duty and Britain wins the battle, however Lord Nelson does not survive. All

Fig. 1. The death of Lord Nelson on his flagship, the HMS Victory, in the battle of Trafalgar, image from a philatelic souvenir sheet issued by the Island of Jersey.

ships receive extensive damage and soon a major storm scatters survivors. Today, you can view a statue of Nelson on a hundred foot column in the exact center of London in Trafalgar Square. Little known, the radical battle-winning strategy Nelson used (which is detailed in any book on the battle) was first suggested by John Clerk of Eldin, great-great uncle of James Clerk Maxwell [1].

Britain's victory assures British dominance of the oceans for the remainder of the 19th century. As part of this dominance, Britain secures a monopoly on the production of "gutta percha", a natural plastic made from the sap of a tropical tree. Gutta percha will become the perfect, and for many years, the only practical insulator for the undersea cables linking far-flung dominions of the Empire. Dominance on the ocean and in undersea cables, these two factors are critical in Britain's leading role in science and technology for the 19th century…all tracing back to a naval strategy suggested by Maxwell's great-great uncle.

Flash forward 60 years to 1865. The American Civil War is ending. Maxwell, Fig. 2, [2], working at home [3], Fig. 3, publishes, "A Dynamical Theory of the Electromagnetic Field," in the Royal

Fig. 2. Unveiling of a statue in honor of Maxwell in Edinburgh [2]. Sandy Stoddart, the sculptor, watches to the left.

Society Transactions, Vol. CLV (he actually presented the paper orally in December 1864). Comparing several measurements of the speed of light to that calculated by his new electromagnetic theory, he notes, “The agreement of the results seems to shew[1] that light and magnetism are affections of the same substance, and that light is an electromagnetic disturbance propagated through the field according to electromagnetic laws.”

The directly measured values for the speed of light that Maxwell quotes are 314,858,000 m/s (M. Fizeau), 298,000,000 m/s (M. Foucault), and 308,000,000 m/s (by stellar aberration). Measurements of a capacitor discharge applied to Maxwell’s theory yields 310,740,000 m/s (MM. Weber, and Kohlrausch). Given the modern knowledge of the speed of light, we know which results are presented to appropriate precision and with minimum error (Foucault eventually refined his result to within 4 km/s of the correct answer),

Fig. 3. Maxwell’s home in Scotland [3], recently and partially restored, where Maxwell wrote his *Treatise* and the field of electromagnetic theory began.

and even with that knowledge, Maxwell’s conclusion is strong.

Thus, one of the greatest problems of physics is now solved! Break out the champagne, wild celebration, Maxwell is our hero! Hold on, not quite yet. We must patiently wait 23 years. One problem, Maxwell offers no mechanical model for the “luminiferous ether”, the medium in which this supposed wave travels. Maxwell and friends all know that light is a transverse wave (assuming that it is actually a wave, not a particle as Newton had insisted). So whatever medium you propose, it must not allow a longitudinal wave. Further, the earth plows through this medium without spiraling into the sun, so either it has no mechanical effect on matter or it has no shear strength. But without shear strength, it cannot support a transverse wave. And if there is no interaction with matter, how could any wave ever get started? Maxwell’s theory is just a bunch of equations, no model what-so-ever.

[1] Modern spelling is “show”.

And what a bunch of equations. There are 20 of them, simultaneous differential equations, not the four equations we know today. Maxwell has the concepts of divergence (he uses the opposite sign and calls it convergence), and curl. But vector calculus is not yet formalized, so he just writes out all 20 equations. Sometimes he uses "quaternions", encouraged by quaternion champion and very good lifelong friend P. G. Tait. Quaternions are a combination of a scalar and a vector, which have the not so nice requirement of a squared magnitude of -1, and of complicating situations better dealt with by vectors.

Wait, there's more. Those twenty equations are not easily recognized today. Maxwell places as primary something he calls "electromagnetic momentum" (because its time derivative is force). Electric and magnetic fields are secondary. His friend, Michael Faraday, who originated the field concept as an alternative to the then popular "action at a distance", called it the "electrotonic state". It is, Faraday said, changes in the electrotonic state surrounding magnets that cause magnetic induction. Maxwell formalized Faraday's field concept. The electrotonic state is today called the magnetic vector potential, usually introduced only in graduate level EM courses as a side-effect of a cute little vector identity. (Primacy of the vector potential is returning to popularity in physics.)

Maxwell viewed magnetic vector potential as primary (presumably why he gave it the symbol A) and magnetic field as secondary (presumably why he gave it the symbol B). However, by making the vector (and scalar) potentials primary, Maxwell's equations become complicated. Very few take the time to learn them.

Finally, unlike Newton, Maxwell was not a self-promoter. For example, while president of Section A of the British Association, he gave a presidential address (published in Vol. 2 of the new British journal Nature) at the 1870 annual meeting with high praise for a vortex theory of molecules due to his good friend William Thomson (later Lord Kelvin). Rather than wave the flag to the scientific world about his own electromagnetic theory, he only briefly mentions at the end, "Another theory of electricity which I prefer…," not even taking credit for his own work [4].

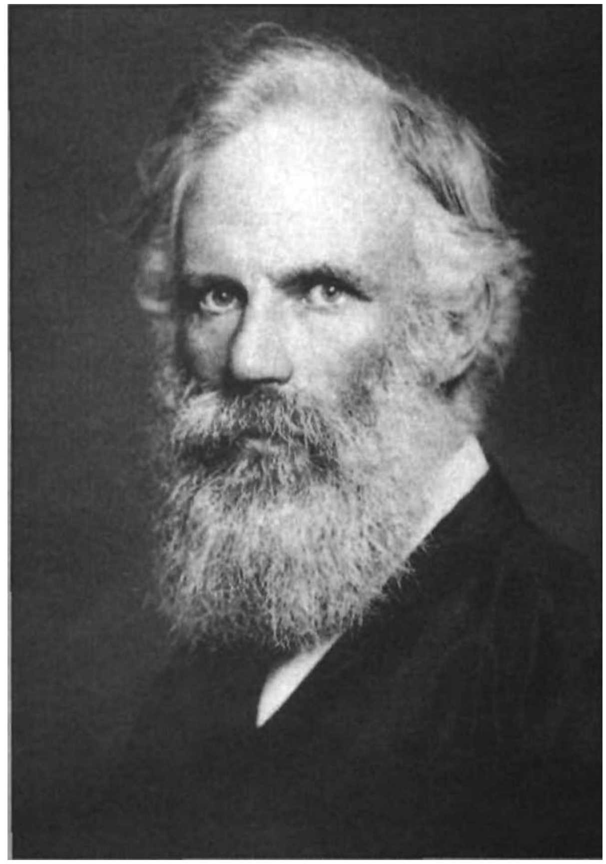

Fig. 4. George Francis FitzGerald found a connection to an earlier theory of the ether, and thus, introduced reflection, refraction, and diffraction to Maxwell's work, image from [7].

Those with further interest in Maxwell's life with respect to the origin of electromagnetics will find more information in [2-5].

II. MAXWELLIAN FITZGERALD

Maxwell dies in 1879. There is no one, no students, no colleagues, to carry on his work in electromagnetics. Well, almost no one. Two days after Maxwell's death, the Royal Society mails a paper review written by Maxwell some months earlier back to George Francis FitzGerald, Fig. 4, Fellow and soon to be professor of Trinity College Dublin [6-7]. The future of electromagnetics now lies in FitzGerald's hands.

FitzGerald is a brilliant idea man. However, he describes himself as "lazy" when it comes to follow up experimental work. More typically, he does the initial work, and then hopes others (usually friends or students) will be inspired to continue. In the paper that Maxwell reviewed, FitzGerald links Maxwell's electrodynamic theory to an earlier theory of Prof. James MacCullagh, also, of Trinity College. This theory models the luminiferous ether required by Fresnel's wave theory of light and requires a purely rotational elasticity, i.e., no translational stress can be allowed to form. MacCullagh had shown that given this form for the ether, one can model refraction, reflection, and polarization perfectly. Quite the coincidence! However, there are a couple of problems. First, MacCullagh does not suggest a physical form for this mysterious ether; it is certainly unknown in normal matter. Second, in 1862, G. G. Stokes, in reviewing a number of proposed ethereal models, points out that MacCullagh's ether violates conservation of angular momentum. Nice idea, while it lasted.

Maxwell published his *Treatise* on electromagnetics (the founding document of our field) in 1873. However, in this, and in all of Maxwell's EM theory publications, there is no electromagnetic treatment of reflection or refraction. FitzGerald is one of the very few people who read and learn the *Treatise* in detail. FitzGerald also extensively studied MacCullagh's ether model while preparing for his fellowship exam. His well annotated copy of Maxwell's *Treatise* includes a long note dated 7 September 1878 where he first mentions that it might be possible to connect Maxwell's theory to MacCullagh's. Over-simplifying just a bit, FitzGerald found a mapping of variables from Maxwell's theory to MacCullagh's. In his paper, he describes the mapping and points out that MacCullagh's work now brings reflection and refraction to Maxwell's theory.

However, Stokes' objections still hold; MacCullagh's ether does not conserve angular momentum. If MacCullagh's ether is the same as Maxwell's, then Maxwell cannot be correct either. FitzGerald, a lifelong believer in some kind of ether, optimistically announces that perhaps we should "emancipate our minds from the thraldom of a material ether."

III. MAXWELLIAN LODGE

Oliver Lodge [6], Fig. 5, is a son of a pottery clay merchant. He takes a higher road when he wins a scholarship and completes a University of London external degree. He completes a doctorate at University College in London, later becoming

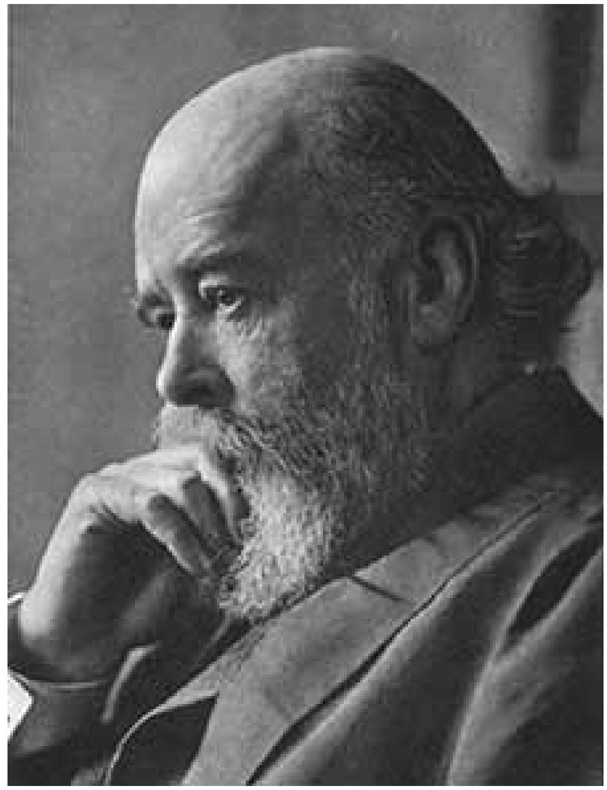

Fig. 5. Oliver Lodge worked extensively with mechanical models of the ether inspired by Maxwell's *Treatise* and his association with Fitzgerald.

the first professor of physics at the new University College in Liverpool in 1881. Lodge had acquired a copy of Maxwell's *Treatise* in 1873, right after it was published. The bookseller grumbled that it was, "a product of the over educated." He started studying it in 1876. He first meets FitzGerald at the August 1878 Dublin meeting of the British Association. Sharing a strong interest in Maxwell's *Treatise*, they quickly become good friends.

A great unsolved mystery is why Maxwell never tried to produce electromagnetic waves. Historians suggest that it is most likely Maxwell simply missed that implication of his theory. The possibility that changing currents could make light just did not occur to Maxwell and that radiation could be generated by electricity is not obvious from Maxwell's equations, especially in the form Maxwell used. Maxwell appears to have believed that light was made by mechanically vibrating molecules somehow coupling to and vibrating the ether. And EM waves of long wavelength? At that time, such "dark light" was outside human experience.

Lodge is more comfortable working with mechanical models, rather than directly with equations. In 1879, one of his models suggests that it might be possible to create light electrically. But how? He suggests applying a voltage source through a switch that switches ("breaks") 400 times a second. The square wave is applied to a coil which somehow doubles the frequency. A cascade of 40 such coils should yield light. FitzGerald gently points out that the square wave would be smoothed into a sine wave after only several coils and thus would not work.

Lodge, not one to give up easily, suggests that a discharging condenser (i.e., capacitor, in the form of a Leyden jar) is oscillatory. FitzGerald's response is not preserved, but he likely told Lodge that the frequency would be too low for light. So close…they missed the idea that it would be just fine to generate long wavelengths, "dark light", if only they could find a way to "see" such wavelengths.

FitzGerald then pursues the problem mathematically, using Maxwell's *Treatise*. He makes several errors. First, he reads Maxwell too literally, as though the *Treatise* is an electromagnetic bible. For example, Maxwell states repeatedly that his theory gives results equivalent to the old "action at a distance" concept. In this case, there can be no radiation. However, it appears that Maxwell's comment was limited to the non-time varying situation, something FitzGerald did not realize. A second very serious error concerns what is now called the gauge condition. Maxwell selected what we call the Coulomb gauge (divergence of *A* is zero) and then incorrectly specified the scalar potential to be independent of time, yielding a static solution. Eventually FitzGerald realizes the problem, in part by toying with mechanical models of the ether that he had built. Then likely inspired by Lord Rayleigh's Theory of Sound, and by electromagnetic research published by Lorenz, he introduces retarded potentials to Maxwell's theory.

FitzGerald, with considerable effort, does find a solution to Maxwell's equations for a time varying current, but it is a non-radiating solution, "like the nodes and loops in an organ pipe". He, thus, concludes that generating EM waves electrically is impossible. What FitzGerald did not realize is he had unwittingly found the solution assuming a conducting wall boundary condition. This illustrates a problem of the vector potential; boundary conditions are difficult to see. Years later, FitzGerald realizes that an alternative solution (assuming a different boundary condition) takes the form of the sought after traveling waves. Regardless, the damage is done. FitzGerald and Lodge continue enthusiastically working with Maxwell's theory, but the search for an EM wave generation is terminated…until 1888.

IV. MAXWELLIAN HEAVISIDE

"The following story is true. There was a little boy, and his father said, 'Do try to be like the other people. Don't frown.' And he tried and tried, but could not. So his father beat him with a strap; and then he was eaten up by lions."

This is the first paragraph in Vol. III of Oliver Heaviside's *Electromagnetic Theory*. Heaviside is a "first rate oddity" as described by a friend [8]. He is, also, an exceptionally prolific writer, difficult to read, and an absolute mathematical genius, Fig. 6. He was raised in Dickensian poverty in Camden Town, London, in fact just around the corner from where Dickens himself had lived and worked as a boy in a blacking factory. In addition to the harsh treatment, he was often ill. A bout with scarlet fever left him deaf until young manhood and unable to interact normally with other children. He never attended a university. Beyond a reasonable early education (partially provided by his mother), he was self taught in science and mathematics. He learned by reading books from the library. It appears he passionately avoided books on theology and metaphysics (unlike Maxwell), but he adored books dealing with Newton, and Laplace, to name a few.

He started his first and only job in 1867 as a telegraph clerk. His uncle by marriage, Charles Whetstone (of bridge fame), helped him obtain the position. The first undersea cable (Dover to Calais) was laid in 1851. By 1885, there are nearly 100,000 miles of cable under the ocean, mostly laid by Britain due to their dominance on the ocean and monopoly of the only viable undersea cable insulator, gutta percha. Because of its importance to the Empire, much of British science is now focused on problems relating to undersea cables.

Heaviside obtained a copy of Maxwell's *Treatise* in 1873. "I browsed through it and I was astonished! I read the preface and the last chapter, and several bits here and there; I saw that it was great, greater, and greatest…I was determined to master the book and set to work." Heaviside left his job the next year and moved in with his parents to pursue the mathematics of Maxwell, especially with regard to telegraphic (and soon, telephonic) cable problems.

Heaviside has no patience with stupidity. One person in particular, William Henry Preece, later the Engineer-in-Chief of the British General Post Office (which controls all British telegraph and telephone lines), considers himself to be an especially intelligent "Practical Man" who has no need for theoretical mathematicians. In reality, Preece's high self-esteem is undeserved, as Heaviside often bluntly points out. Preece takes offense.

In one case, Heaviside discovers the transmission line "telegraphers" equation, deriving it from Maxwell's theory. William Thomson (Lord Kelvin) had successfully analyzed undersea cables based on the diffusion equation, i.e., just resistance and capacitance, no inductance. In this case, a pulse effectively diffuses into the cable. This actually provides reasonable results for most undersea cables but fails miserably for overhead lines.

When Heaviside derives the full telegrapher's equation, he determines that if the ratio of L/R is equal to C/G, distortion (i.e., pulse spreading) is eliminated. G is very small, thanks to gutta percha. R is expensive to decrease. So, simply increase L. His work is effectively suppressed over a long period by Preece. Preece is vehement that the inductance of a transmission line is zero and increasing it only leads to disaster. As a "practical man", he cannot be convinced otherwise by these silly mathematicians. Later, engineers in the United States successfully make, apply, and patent the same discovery. Heaviside receives no credit.

In the summer of 1884, Heaviside starts working on energy flow in the electromagnetic field. The derivation is complicated, but the result is simple, $S = E \times H$. Heaviside, being reclusive and not well connected with the rest of the scientific community, is later only a little disappointed to find that Prof. Poynting of the new Mason College of Science in Birmingham had published the same result a few months earlier.

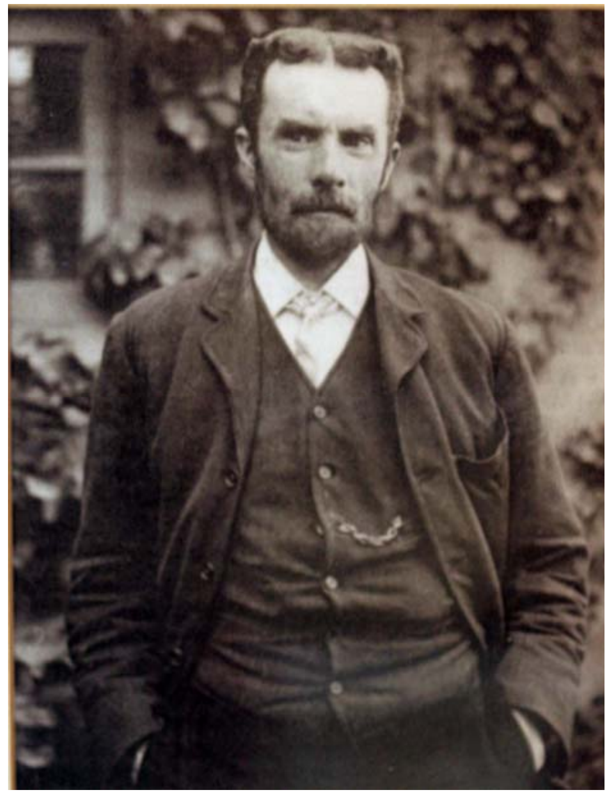

Fig. 6. Oliver Heaviside was the first to put Maxwell's equations in their modern form, image from IEE archives.

As an example of energy flow, take the field around a straight copper wire at DC. $E \times H$ points radially into the wire. Energy does not flow along the wire as had been thought. It flows from the field surrounding the wire and dissipates as heat as it enters the wire. This is the big clue. In sharp contrast to action at a distance, where energy is viewed as flowing along the wire with the current like water in a pipe; Maxwell's equations suggest that energy is in the field and flows from the field into the resistance of the conductor.

In fact, the Maxwellian view at this time is that charge and current are not physical. Rather, they are changes in the stresses and strains of the ether. The conductor of the wire relieves the stress of the field and dissipates the energy as heat. This view fades with the advent of a new discovery a few years later, the electron. As for the modern view, electromagnetic energy is calculated in terms of either the field or the current. It's hard to say precisely "where" it is.

Heaviside went further than Poynting. As Heaviside was working with his energy concept, he came upon a new form for Maxwell's equations, the "duplex" form, the four equations with which we are familiar today. These differential curl equations involve *E*, *H*, *D*, and *B*. The potentials are gleefully "murdered" according to Heaviside, "I never made any progress until I threw all the potentials overboard," he later wrote to FitzGerald. With the duplex form, the symmetries in Maxwell's equations are beautifully seen, but something is missing. Heaviside adds the fictitious magnetic current to complete the symmetry.

If Heaviside modified Maxwell's equations to this degree, why don't we call them Heaviside's equations? Heaviside answered this question in the preface to Vol. 1 of his over 1500 page, three volume, lifetime culminating work, *Electromagnetic Theory* stating that if we have good reason, "to believe that he [Maxwell] would have admitted the necessity of change when pointed out to him, then I think the resulting modified theory may well be called Maxwell's."

In 1888, Lodge is requested to give two lectures on lightning protection and he conducts experiments by discharging condensers in the vicinity of models of various structures. The lectures stimulate major controversy with Preece as Lodge's results contradict standard practice (in this case, Preece actually turned out to be correct). But all that is minor. In the course of his experiments, Lodge notices arcs being induced in nearby circuits. In one experiment, he sees an arc at the end of two parallel wires. In the dark, he can even see a distinct standing wave glowing in the air around the wires. Lodge has generated and detected electromagnetic waves! The British Association is meeting in Bath in September. Lodge plans to report his astounding results at that meeting, right after he returns from vacation in the Alps.

On the train out of Liverpool, he picks up the July issue of *Annalen der Physik*. He immediately notices an article, "Ueber elektrodynamische Wellen in Luftraume und deren Reflexion" ("On Electromagnetic Waves in Air and Their Reflection").

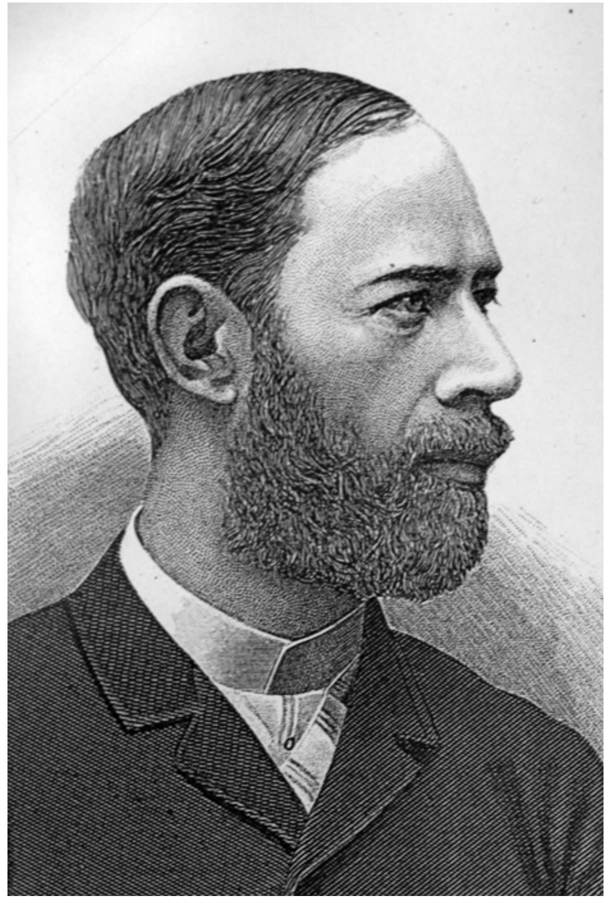

Fig. 7. Heinrich Hertz independently put Maxwell's equations into their modern form and went on to achieve experimental validation.

IV. MAXWELLIAN HERTZ

Six years of Heinrich Hertz's education was in Berlin under Hermann von Helmholtz. Helmholtz had incorporated the electromagnetic theories of Maxwell, Weber, and Neumann into a single theory with a parameter (k), whose value selected the theory to be used. It was not realized until later that Maxwell's theory was not fully correctly incorporated, but Hertz, Fig. 7, was able to study much of Maxwell's theory under Helmoholtz's guidance in this manner.

Helmholtz had encouraged Hertz to perform experiments to test and differentiate the theories. Hertz at first declined, having determined that the experiments would be difficult to perform. However, he kept the possibility in mind. A few years later, while teaching at Technische Hochschule in Karlsruhe, he notices while discharging a condenser through a loop, that an identical loop some distance away develops arcs.

He instantly recognizes a resonance condition and suspects electromagnetic waves. The experiments he subsequently conducts verify reflection, refraction, diffraction, and polarization for both free space waves and wire guided waves. It is Hertz's experimental results that Lodge is reading in *Annalen der Physik* as he leaves for vacation.

As Lodge reads the paper, he realizes that his own results are now superfluous. However, his disappointment is more than compensated by the beauty and completeness of Hertz's work. Fitzgerald (who had actually heard about one of Hertz's papers a month before Lodge, and had requested a copy from Hertz) presents Hertz's results at the September 1888 British Association meeting in Bath and is Hertz is hailed as a hero. His results provide full confirmation of Maxwell's electromagnetic theory. The British Maxwellians, after 15 years of careful theoretical investigation of Maxwell's theory, are catapulted to the top of British science thanks to Hertz's timely experimental validation. Hertz is warmly welcomed into the small Maxwellian group and takes an active role, but, unfortunately, for far too short a time.

In Germany, because of the continental predisposition toward action at a distance, the importance of Hertz's results is not at first fully recognized. In fact some say, only partly in jest, that word of Hertz's experiments reached Germany by way of England. Once recognized, German researchers likewise embrace Maxwell's theory as well.

Hertz had, independently of Heaviside, discarded Maxwell's potentials and developed the modern duplex form of Maxwell's equations. When Hertz becomes aware of Heaviside's work, he graciously yields priority to Heaviside and likewise chooses to call them Maxwell's equations. As a tribute to Hertz, they are for a few years also sometimes called the Hertz-Maxwell equations.

IV. EPILOGUE

Hertz, always refusing travel to conferences, finally agrees to visit England to receive the prestigious Rumford Medal from the Royal Society in November 1890. The year before, Hertz had received a major promotion and moved to the chair of physics at the University of Bonn. However, the move deprived him of experimental facilities. Hertz still makes significant theoretical contributions in close collaboration with the British Maxwellians. Work becomes difficult when he starts suffering from an infection (perhaps autoimmune disease) that spreads to his jaw and sinuses. He writes to his parents in August 1892, "At present my nose is my universe." He dies tragically and painfully at the age of 36 in January 1894, on New Year's Day, from blood poisoning after an operation.

As researchers adopt and study Maxwell's theory, Joseph Larmor of Cambridge proposes the existence of the electron. Larmor and Heaviside don't get along especially well, but Heaviside evaluates the field around a moving electron. The field includes the square root of $1 - (v/c)^2$ in the denominator, hinting of things to come. Heaviside adamantly insists that there is no reason why electrons cannot move faster than the speed of light. Of course, by modern physics, we know he was only partially correct. Electrons cannot move faster than the speed of light in free space.

Michelson and Morley perform their interferometer experiment in 1887, the year before the Bath meeting, casting doubt on the existence of ether. However, FitzGerald later points out that atomic structure might depend in some way on electromagnetic fields. Heaviside had found that the fields of a moving electron contract in the direction of movement; perhaps matter contracts likewise. This concept was also independently developed by Lorentz. A quick calculation shows that the Michelson-Morley interferometer would contract just enough in the direction of the earth's movement to make it appear that the ether is not moving no matter how fast the earth is moving. British researchers continue searching for mechanical models of the ether well into the 20th century before the effort is gradually dropped as pointless.

FitzGerald periodically experienced long bouts of "indigestion". He passes away after an operation on February 22, 1901. He is 49. To Heaviside and Lodge his death is a great shock.

Lodge did not contribute further to Maxwell's theory after 1900. He did spend considerable effort researching communication with the dead. He died on August 22, 1940, promising to make public appearances after his death. No such appearances have been recorded.

In 1896, Heaviside's father dies, leaving Heaviside on his own for the first time in his life. FitzGerald and John Perry arrange a Civil List pension for him of 120 pounds per year. In a more difficult task, they convince Heaviside to accept it, offering it as recognition of service to his country.

Heaviside becomes senile in his old age, "I am as stupid as an owl." He dies on February 3, 1925 after falling off a ladder and landing on his back. He is 74. His ride to the hospital is his first and final ride in an automobile.

I close with a paragraph written on January 30, 1891, in Heaviside's *Electromagnetic Theory*:

"Lastly, from millions of vibrations per second, proceed to billions, and we come to light (and heat) radiation, which are, in Maxwell's theory, identified with electromagnetic disturbances. The great gap between Hertzian waves and waves of light has not yet been bridged, but I do not doubt that it will be done by the discovery of improved methods of generating and observing very short waves."

We truly do stand on the shoulders of giants.

ACKNOWLEDGMENT

This paper is a revised and supplemented version of [5], reprinted with permission.

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