CAMERON LAZAROFF-PUCK*

Empire-Laden Theory: The Technological and Colonial Roots of Maxwell's Theories of Electromagnetism

---

ABSTRACT

James Clerk Maxwell's theories of electromagnetism are distinctively Victorian products. Analysis of his often ignored theory of electric absorption and the Maxwellians' "leaky condenser" reveals that critical details of these theories were shaped by Victorian electrical technology, namely capacitors and undersea telegraphy. Between appearances in his "Dynamical Theory" and *Treatise*, Maxwell's theory of electric absorption evolved. It shifted his understanding of electrical action in the dielectric, bolstered central concepts in his broader electromagnetic theories, provided hope for a beleaguered experimental program to confirm his electromagnetic theory of light, and even led him to distort his expression for Ohm's law. Simultaneously, the technological influences behind his theories come with their own histories. Maxwell draws heavily upon the testimony of cable engineer Fleeming Jenkin to the Joint Committee on the Construction of Submarine Telegraphs, formed to rescue the industry after multiple failed attempts to lay an Atlantic cable. Maxwell's reliance on *this* testimony given to *this* committee imprints the financial and imperial ambition that initially spurred these cables' construction onto his electromagnetic theories. A substance discussed in this testimony, gutta-percha, also connects Maxwell's theory to the extractive global trade of this resource. The success of this committee in reforming the telegraph industry links Maxwell's theories to the colonial, economic, and ecological fallout of the rapid global expansion of Britain's undersea telegraph network.

KEY WORDS: James Clerk Maxwell, electric absorption, submarine telegraphy, imperial science, gutta-percha, Fleeming Jenkin, capacitor, electromagnetism

---

*Max-Planck-Institut für Wissenschaftsgeschichte, Boltzmannstraße 22 14195 Berlin, Germany Cameron.LazaroffPuck@gmail.com

Abbreviations: CES, Committee on Electrical Standards; JCCST, Joint Committee on the Construction of Submarine Telegraphs; PTRSL, Philosophical Transactions of the Royal Society of London; Telcon, Telegraph Construction and Maintenance Company; *SLP* 1–3, *The Scientific Letters and Papers of James Clerk Maxwell*, Volumes 1–3

Historical Studies in the Natural Sciences, Vol. 54, Number 1, pps. 42–83. ISSN 1939-1811, electronic ISSN 1939-182X. DOI: https://doi.org/10.1525/hsns.2024.54.1.42.

INTRODUCTION

Classical electrodynamics was born into the heat of the Industrial Revolution and an ascendant British Empire. As with the history of thermodynamics, there is a growing historiography highlighting how the technological context shaped scientific work in electromagnetism. This is most apparent in histories of William Thomson, later ennobled Lord Kelvin. Crosbie Smith and Norton Wise's thematic biography of Thomson, *Energy & Empire*, demonstrates how his work on electromagnetism was deeply influenced by telegraphy. Thomson's 1854 theory was a product of his interest in submarine telegraphy, and even as his theories became increasingly abstract, telegraphy remained a guiding force. Smith and Wise also recognize the economic and political context surrounding Thomson's electrical theorizing and engineering, particularly as his role as a scientific and engineering expert in electricity and telegraphy garnered him considerable wealth and status.[1] Even if we exclude histories of Thomson, this historiography remains substantial. Ronald Kline has demonstrated how the needs of electrical engineers led them to modify Maxwellian theory to better model the induction motors they were designing.[2] Bruce Hunt has shown how Oliver Heaviside's experience as a telegraph engineer led him to expand on Thomson's incomplete telegraph theory and engage with Maxwell's electromagnetic theory.[3] Hunt has also illustrated the impact a healthy submarine cable industry had on reactions to Michael Faraday's field theory in Britain and contrasted it with Prussian disinterest in field theory shortly after they had dismantled their only underground cable (Prussia had no submarine cables).[4] Graeme Gooday has pointed to the need for design theories and engineering knowledge regarding steam technology and stability above and beyond Maxwellian theory to solve AC paralleling problems.[5]

Histories connecting James Clerk Maxwell's electromagnetic work to technology are less common but numerous enough to form their own notable corpus. There is of course the subgenre of papers and books investigating

---

[1] Crosbie Smith and Norton Wise, *Energy and Empire: A Biographical Study of Lord Kelvin* (Cambridge: Cambridge University Press, 1989).

[2] Ronald Kline, "Science and Engineering Theory in the Invention and Development of the Induction Motor, 1880–1900," *Technology and Culture* 28, no. 2 (1987): 283–313.

[3] Bruce Hunt, *The Maxwellians* (Ithaca, NY: Cornell University Press, 2005), 65–72.

[4] Bruce Hunt, "Michael Faraday, Cable Telegraphy and the Rise of Field Theory," *History of Technology* 13 (1991): 1–19.

[5] Graeme Gooday, *The Morals of Measurement: Accuracy, Irony, and Trust in Late Victorian Electrical Practice* (Cambridge: Cambridge University Press, 2004), 173–218.

Maxwell's use of analogies and idealizations of real or imagined mechanisms in the construction of his electromagnetic theories.[6] Elements of Daniel Siegel's discussion of idealized capacitors in Maxwell's "On Physical Lines of Force" form a part of the forthcoming narrative.[7] However, historians have largely neglected to pursue any connections between Maxwell's models and analogies and the specific material technologies that may have inspired them.

Aside from these model histories, Maxwell's time as a member of the Committee on Electrical Standards (CES) has spawned the largest contingent of narratives seeking to trace the transfer of knowledge from technology to electromagnetic science. Hunt has argued that Maxwell's work with the CES to standardize electrical units shifted Maxwell's scientific methodology to an "engineering approach," avoiding hypothetical microphysical elements of the ether.[8] His CES work in aid of the telegraph industry is thus responsible for the methodological tone of his paper "A Dynamical Theory of the Electromagnetic Field." Looking at the same events, Daniel Jon Mitchell found Maxwell's motivation for a more concrete product, the invention of the dimensional formula, along with our concept of dimensions and its attendant misunderstandings.[9] Smith, Hunt, and Simon Schaffer have all examined the CES's attempt to set an absolute electrical standard value of resistance, the "ohm," in opposition to German industrial pressure to adopt a mercury unit, and in deference to British energy physics.[10] Maxwell's work with the CES

---

6. A sample of this literature: Joseph Turner "Maxwell on the Method of Physical Analogy," *The British Journal for the Philosophy of Science* 6, no. 23 (1955): 226–38; Norton Wise, "The Mutual Embrace of Electricity and Magnetism," *Science* 203, no. 4387 (1979): 1310–18; Peter Harman, *The Natural Philosophy of James Clerk Maxwell* (Cambridge: Cambridge University Press, 1998); Cameron Lazaroff-Puck, "Gearing Up for Lagrangian Dynamics: The Flywheel Analogy in Maxwell's 1865 Paper on Electrodynamics," *Archive for History of Exact Sciences* 69, no. 5 (2015): 455–90; Gooday, *The Morals of Measurement* (n.5), 180–86.

7. Daniel Siegel, *Innovation in Maxwell's Electromagnetic Theory: Molecular Vortices, Displacement Current, and Light* (Cambridge: Cambridge University Press, 1991).

8. Bruce Hunt, "Maxwell, Measurement, and the Modes of Electromagnetic Theory," *Historical Studies in the Natural Sciences* 45, no. 2 (2015): 181–271.

9. Daniel Jon Mitchell, "Making Sense of Absolute Measurement: James Clerk Maxwell, William Thomson, Fleeming Jenkin, and the Invention of the Dimensional Formula," *Studies in History and Philosophy of Science Part B* 58 (2017): 63–79.

10. Crosbie Smith, *The Science of Energy: A Cultural History of Energy Physics in Victorian Britain* (Chicago: University of Chicago Press, 1998); Bruce Hunt, "The Ohm Is Where the Art Is: British Telegraph Engineers and the Development of Electrical Standards," *Osiris* 9 (1994): 48–63; Simon Schaffer, "Late Victorian Metrology and Its Instrumentation: A Manufactory of Ohms," in *Invisible Connections: Instruments, Institutions, and Science*, ed. Robert Bud and Susan Cozzens (Bellingham: SPIE, 1992): 23–56.

straddles electrical engineering, experimental physics, and metrology, balancing competing needs from scientific and industrial communities.

The guiding influence of the submarine telegraph industry on the science of electromagnetism was not lost on those who participated in this collaboration, nor was it presumed to be limited to metrology or experimental physics. In his 1871 Presidential Address to the British Association, Thomson remarked that

> Those who perilled and lost their money in the original Atlantic Telegraph were impelled and supported by a sense of the grandeur of their enterprise, and of the worldwide benefits which must flow from its success; they were at the same time not unmoved by the beauty of the scientific problem directly presented to them; but they little thought that it was to be immediately, through their work, that the scientific world was to be instructed in a long-neglected and discredited fundamental electric discovery of Faraday's, or that, again, when the assistance of the British Association was invoked to supply their electricians with methods for absolute measurement (which they found necessary to secure the best economical return for their expenditure, and to obviate and detect those faults in their electric material which had led to disaster), they were laying the foundation for accurate electric measurement in every scientific laboratory in the world, and initiating a train of investigation which now sends up branches into the loftiest regions and subtlest ether of natural philosophy.[11]

This paper advances the historiography, moving beyond the limiting focus on the CES and metrology. It offers technological connections to more abstract corners of Maxwell's theories than the historiography has contained until now, further blurring disciplinary boundaries between even theoretical physics and technology. Delving inside Maxwellian theory, Pierre Duhem found it so haphazardly assembled and overburdened with mechanical models that instead of "entering the tranquil and neatly ordered abode of reason . . . we find ourselves in a factory."[12] While Duhem's comment was intended as an insult, he was only wrong in assuming that factories are disordered, illogical spaces. Following Maxwell, we *are* led into a factory, specifically, one of the

---

[11] William Thomson, "Presidential Address to the British Association, 1871" in *Report of the Forty-First Meeting of the British Association for the Advancement of Science Held at Edinburgh in August, 1871* (London: John Murray, 1872), xciii. Many thanks to Richard Staley for pointing me to this quote.

[12] Pierre Duhem, *The Aim and Structure of Physical Theory*, trans. Philip Wiener (Princeton, NJ: Princeton University Press, 1991), 71, 86. This is a translation of the 1914 second edition of Duhem's *Aim and Structure*.

great cable factories of the age viewing the aftermath of shoddily constructed submarine telegraph cables. Maxwell's theoretical achievements in electromagnetism were intimately shaped by the submarine telegraph industry, its materials, and its infamous early failures.

What follows charts a path from the failures of the initial Atlantic telegraph cable to Maxwell's mature electromagnetic theories. Frequently overlooked sections of Maxwell's "Dynamical Theory" as well as his *Treatise* that provide the first quantitative descriptions of electric absorption are built from Fleeming Jenkin's work on submarine telegraph cables. In concert with a more familiar tool of Maxwell's, the idealized capacitor, Jenkin's experimental work with cable insulation was incorporated into Maxwell's theory to make sense of electric absorption. A few years earlier, in "Physical Lines of Force," capacitors had helped Maxwell create the concept of the displacement current and begin a somewhat successful experimental program to verify his electromagnetic theory of light, which was complicated by electric absorption. The cable-inspired elements of Maxwell's "Dynamical Theory" deepen the explanatory power and reinforce the stability of his broader electromagnetic theory. Maxwell appreciated the importance of these additions, enough so that he flipped the sign in Ohm's law to salvage his treatment of electric absorption. Between Maxwell's "Dynamical Theory" and *Treatise*, his concept of electric displacement and understanding of electrical action within dielectrics shifted with his evolving treatment of electric absorption and capacitors. Capacitors and electric absorption then featured prominently in the work of Maxwell's successors under the guise of the "leaky condenser," motivating yet more reappraisals of electrical action in the dielectric. Ultimately, electric absorption remained a subject of study into the early twentieth century, but Maxwell's explanation has managed to survive.

Maxwell's incorporation of Jenkin's studies of submarine telegraph cables was contingent on the failure of specific undersea cables. Jenkin's work was commissioned by the private-public Joint Committee on the Construction of Submarine Telegraphs (JCCST) after the infamous failures of the first Atlantic cable. The Joint Committee was desperate to understand these costly failures and to repair the battered reputation of the submarine telegraph industry. Their report, which includes Jenkin's testimony, binds Maxwell and Maxwellians' theories to the political and economic forces behind the construction of these failed cables and the goal of improved future cables. The financial and imperial concerns of private industry and an expanding British Empire that came together to create the Joint Committee are stamped on the physics

Maxwell created out of the report the Committee produced. Similarly, the colonial and economic forces powering the trade in gutta-percha were incorporated into Maxwell's theory. Gutta-percha made up the majority of submarine cables' insulation, and it was this substance that occupied the majority of Jenkin's attention during his insulation experiments.

In addition to affecting theoretical physics, the JCCST report did reform the telegraph industry and insulate it from its own incompetence. Now a safe investment, British telegraphs snaked out in an effort to consolidate colonial gains and incorporate these new territories into a global British economy. Military, financial, and all other sorts of information could be managed from London. An immediate cost for this expanding network was paid in millions of trees felled across Southeast Asian colonies—harvested for their gutta-percha. Maxwell's electromagnetic theories are kin to the world made by the JCCST overhaul, one of imperialism, global markets, and ecological disaster.

SUBMARINE TELEGRAPHY AND FLEEMING JENKIN

The first trans-Atlantic telegraph cable, begun in August 1857 and laid by a steam-armada on loan from the American and British navies, was a total failure. The broken cable, slated to connect Ireland and Newfoundland, lay unrecoverable over two miles below the surface. Cyrus Field's Atlantic Telegraph Company was out approximately £100,000 and a comparable value in public good will.[13] Nevertheless, in 1858, the loaned flotilla returned with replacement cable in their holds. Despite a few hundred miles more of losses and some delay, this next attempt was successful. A working telegraph cable now spanned the Atlantic Ocean, binding a colony of the British old world to its colony in the new world with what seemed near instant communication.

Unfortunately, the cable's performance was quite poor. Queen Victoria and President Buchanan's short congratulatory exchange took hours to pass over the line and required an extended intermission for cable maintenance.[14] Still,

---

[13] Bern Dibner, *The Atlantic Cable* (New York: Blaisdell Publishing, 1964), 36–39; Charles Bright, *Submarine Telegraphs: Their History, Construction, and Working* (Cambridge: Cambridge University Press, 2014), 34–40.

[14] Bruce Hunt, *Imperial Science: Cable Telegraphy and Electrical Physics in the Victorian British Empire* (Cambridge: Cambridge University Press, 2021), 92; Vary Coates and Bernard Finn, *A Retrospective Technology Assessment: Submarine Telegraphy—The Transatlantic Cable of 1866* (San Francisco: San Francisco Press, 1979), 16.

celebrations rocked London and New York City in the days following their communications. But, while revelers were still nursing hangovers, the line went dead. The cable had failed after a mere four weeks in operation. It was unrecoverable, and the hefty public and private investment had returned nothing. Public enthusiasm for an Atlantic cable fell to an all-time low.

Neither the British nor American governments suffered much monetarily from the loss of the cable; ongoing payments were contingent on the cable continuing to work. International commerce's voracious appetite for timely information was expected to make up a bulk of the traffic across the line but was instead left unsated. Pricing between London and New York remained uneven and rife for exploitation. The acceleration and expansion of global futures markets would have to wait until undersea telegraphy had worked out its kinks. The Atlantic Telegraph Company was unsurprisingly on the verge of bankruptcy.

With public perception at a new low and financial losses mounting, the British government's Board of Trade was inspired to create the JCCST in concert with the Atlantic Telegraph Company to investigate and improve the viability of undersea cables. The JCCST was packed full of cable engineering experts, industry figures, and scientists working on electricity. From December 1859 to September 1860, the JCCST listened to twenty-two sessions of expert testimony.[15] Once compiled, the report became a standard reference in the industry.[16]

The testimony included a thorough humiliation of the Atlantic Telegraph Company's chief electrician, Wildman Whitehouse, who, on top of the cable's slapdash construction, was blamed for the failure of the Atlantic cable.[17] Finding plausible scapegoats, be they human or object, helped heal the wounded reputation of the submarine telegraph industry, redirecting blame from the industry as a whole onto fixable (or firable) specifics. Nevertheless, if the JCCST's goal was to restore confidence in the industry, then equally as important was testimony that examined the most up-to-date cable research, as

---

[15] Bright, *Submarine Telegraphs* (n.13), 61; *Report of the Joint Committee Appointed by the Lords of the Committee of Privy Council for Trade and the Atlantic Telegraph Company to Inquire into the Construction of Submarine Telegraph Cables* (London: Her Majesty's Stationery Office, 1861).

[16] "Obituary of Douglas Galton," *The Electrician* 42, March (1899): 725; Bright, *Submarine Telegraphs* (n.13), 61.

[17] Bruce Hunt, "Scientists, Engineers and Wildman Whitehouse: Measurement and Credibility in Early Cable Telegraphy," *The British Journal for the History of Science* 29, no. 2 (1996): 155–169; *Joint Committee* (n.15), 69–82.

well as processes in manufacturing and installation, with the aim of establishing a more secure technical foundation for future cables.

Submarine cables were usually composed of essentially three separate layers: a core composed of copper wire, insulation mostly made up of the natural latex gutta-percha though frequently blended or layered with small amounts of other compounds, and a protective outer sheath of iron wire. The quality of the copper in the Atlantic cable had proved inadequate for long-distance telegraphy, as William Thomson himself complained.[18] Better copper sources and more rigorous quality control was needed. How to best insulate the copper core was less clear. As such, the Board of Trade tasked the JCCST to identify the "best form for the composition and outer covering of submarine telegraph cables."[19] The thrust of questions and the content of the JCCST reports reflect this insulation obsession. Ultimately, the JCCST's attention to insulation would prove influential beyond the limits of the telegraph industry.

At the time of his interview, December 22, 1859, Henry Charles Fleeming Jenkin had been employed at R. S. Newall and Co. for two years, arriving while the company was in the process of armoring their half of the first Atlantic cable.[20] As his friend and business partner William Thomson would later attest, Jenkin was a practically minded engineer, a gifted experimenter, and a keen electrical mind.[21] Jenkin was early in appreciating the assistance scientific theory could provide for the working engineer. Unsurprisingly, he became one of the first instructors in the nascent field of engineering science.[22]

The bulk of Jenkin's testimony and submitted paper (Appendix 14 of the report) concerned experiments he performed on the insulation of Gutta Percha Works cable sections at Newall's Birkenhead factory.[23] The most famous product of this work was Jenkin's measure of the specific resistivity of gutta-percha on the same scale as copper. Jenkin had placed non-conductors and conductors on the same scale, bridging a gap of some twenty orders of

---

[18] *Joint Committee* (n.15), xiii–xxv.

[19] Ibid., v.

[20] Gillian Cookson and Colin Hempstead, *A Victorian Scientist and Engineer: Fleeming Jenkin and the Birth of Electrical Engineering* (Brookfield: Ashgate, 2000), 32–36.

[21] Ibid., 37; Fleeming Jenkin, *Papers, Literary, Scientific, Etc. with a Memoir by Robert Louis Stevenson*, vol. 1, ed. Sidney Colvin and J.A. Ewing (London: Longmans, Green and Co., 1887), clv.

[22] Ben Marsden, "Engineering Science in Glasgow: Economy, Efficiency and Measurement as Prime Movers in the Differentiation of an Academic Discipline," *The British Journal for the History of Science* 51, no. 4 (1992): 319–46.

[23] *Joint Committee* (n.15), 135–48, 464–81.

magnitude, establishing the first "absolute measurement of the electric resistance of an insulating material," and breaking down the conceptual barrier between conductors and insulators.[24] Eventually, Jenkin's more routine testimony to the JCCST would have a similar effect on electrical theory.

This mundane work concerned the relation between the temperature of a submerged cable and its resistance (measured in current loss) and examined the change in this relation in two cables with different insulating materials. The cables were submerged in a bath of water with an insulated end (grounded through the water) and the other end connected to a Siemens and Halske sine galvanometer and then a battery (the other pole being grounded). Consequently, the current loss through the layer of gutta-percha insulation could be read on the galvanometer. By heating the bath, Jenkin was able to obtain a range of measurements of current leakage at various temperatures.

The first cable tested was insulated with pure gutta-percha, while Jenkin believed the second was made of alternating layers of gutta-percha and Chatterton's compound.[25] The mixed cable had less loss at high temperatures, while the pure gutta-percha cable was a better insulator at low temperatures.[26] Jenkin also provided charts illustrating the linear relationship between temperature and current loss and the superiority of gutta-percha over the mixed insulation at lower temperatures (more typical for a deep sea cable). Chatterton's compound is itself a mixture: one part Stockholm tar, one part resin, three parts gutta-percha. It seemed then that pure gutta-percha was a superior insulator to gutta-percha mixed with other substances. Jenkin was shocked that "so small a quantity of varnish as is employed, should so materially alter the insulating qualities of the coating."[27]

This was not all Jenkin uncovered. Another peculiar phenomenon he reported was a relationship between cable resistance and time spent electrified. As far as Jenkin was aware, this was a novel phenomenon afflicting cable insulation. The longer the cable was connected to the battery, the higher the apparent resistance of the gutta-percha insultation, particularly during the first

---

[24] Jenkin, *Papers* (n.21), clvi; Bruce Hunt, "Insulation for an Empire: Gutta-Percha and the Development of Electrical Measurement in Victorian Britain," in *Semaphores to Shortwaves*, ed. Frank James (London: Royal Society for the Encouragement of Arts, 1998), 96–97.

[25] Willoughby Smith of the Gutta Percha Company (which had manufactured the cables) claimed that Jenkin was misinformed and that the Chatterton's cable was actually insulated with their "special mixture." *Joint Committee* (n.15), 30–31, 137.

[26] Ibid., 136–37.

[27] Ibid., 467.

five minutes. Jenkin's cables seemed to get less leaky the longer they were charged. He also clarified that reversing the current completely destroyed this resistance-charging effect in the pure gutta-percha cable, but did not completely eliminate it in the layered cable. After a long charging time, rapidly reversing the current and reverting it back had only a minor effect on the built-up resistance—that is, it did not increase the current loss significantly.[28]

While impurities in gutta-percha insulation seemed to increase electrical loss, longer charging times had the opposite effect. The phenomena further intersected as impurities in the insulation made the charging effect more robust when currents were reversed. Jenkin believed he was the first to describe these phenomena. He was not, not even in cables; however, the connections he made between the phenomena and his experimental set up would prove to be the most significant, despite his lack of priority.

As for assigning a physical cause, Jenkin was more circumspect. Nevertheless, when pressed by the JCCST he did offer some vague ideas. Given that the phenomena varied according to the quantity of insulating material, he was certain that the phenomena came down to a physical change *within* the gutta-percha insulation and not just on its boundary surface between copper and gutta-percha. He identified polarization within the medium as the process that brought on these phenomena; however, he was still unsure of whether it was a polarization of the gutta-percha itself or of water absorbed by it.[29] Although gutta-percha was prized in part because it didn't take on much water compared to other common insulating materials like rubber, it was not impermeable. Despite the uncertainty regarding *what* exactly was being polarized, Jenkin had identified an underlying physical cause and explained how it might produce the observed extra resistance, namely a counter current: "It appears most probable to the author that the extra resistance is due to an effect of polarization taking place in the mass of the gutta-percha under the influence of the current, and causing a current in the opposite direction."[30]

Jenkin's next contribution to this saga came in 1862 in "Experimental Researches on the Transmission of Electric Signals through Submarine Cables. Part I. Laws of Transmission through various lengths of one Cables."[31] In spite

---

[28] Ibid., 136.

[29] Ibid.

[30] Ibid., 471.

[31] Fleeming Jenkin, "Experimental Researches on the Transmission of Electric Signals through Submarine Cables: Part I. Laws of Transmission through Various Lengths of One Cable," *PTRSL* 152 (1862): 987–1017.

of the paper's title, Jenkin claimed the phenomena he had reported to the JCCST had never made much of a difference to the day-to-day operations of telegraph lines as they were generally kept electrified, although when he said this Jenkin was thinking in terms of signaling procedures that were already out of date.[32] Unsurprisingly then, not all cable engineers were so nonchalant about its effects on signaling speed.[33] Across long-distance telegraph cables it could cause significant slowing, attenuation, and distortion of signals. Gutta-percha, however, exhibited relatively low levels of current loss, partially moderating the issue.[34] Although he didn't think it mattered much for telegraphy, Jenkin ultimately accounted for the phenomena of extra resistance and finally brought William Thomson's mathematical theory of submarine telegraph signaling into close agreement with observation. In the process of vindicating Thomson's theory, Jenkin was struck by the resemblance of plots of increasing resistance in a cable during charging and plots for the decrease of resistance when a reverse current was applied. It appeared to him that "the apparent increase of the resistance of the gutta percha is rather due to an absorption of electricity which is again given out, than to a real change in the conductivity of the material."[35]

This idea that cable insulation might "absorb" electricity was not new, nor, would it turn out, was its association with these phenomena. The cable engineer Cromwell Fleetwood Varley referred to a kind of slowing of signaling speed as "inductive absorption."[36] Thomson was the first to mathematically express this relation between the conductivity of a cable's copper core, the specific inductive capacity of its insulation, and the cable's total length to its potential signaling speed (this was the theory touched up by Jenkin in 1862), but Michael Faraday had already outlined the phenomena years earlier. Faraday understood that submarine cables act like giant capacitors, the cable and seawater acting as the conductive plates sandwiching the insulation serving as the dielectric.[37] Charging this giant capacitor caused signals to be slowed and elongated, muddling messages and confusing telegraph operators.

---

[32] Ibid., 1001, 997. The Siemens and Halske method (see starred footnote on 997) with which Jenkin was evidently unfamiliar became the standard across the telegraph industry.

[33] *Joint Committee* (n.15), 155.

[34] John Whitehead, *Lectures on Dielectric Theory and Insulation* (New York: McGraw-Hill, 1927), 19, 118.

[35] Jenkin, "Experimental Researches" (n.31), 1001.

[36] *Joint Committee* (n.15), 96, 152–53.

[37] Michael Faraday, "On Electric Induction—Associated Cases of Current and Static Effects," *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 7, no. 44 (1854): 200. While Faraday first learned of this phenomenon from Latimer Clark, Werner

Faraday had *also* noticed much of Jenkin's "new" phenomena over two decades earlier in 1837, although Faraday admits certain aspects of this phenomena were already "well-known."[38] In the eleventh installment of his "Experimental Researches in Electricity," Faraday noted the ability of certain solid dielectrics to recover same-signed charge after a seemingly complete discharge, across a variety of dielectric materials. This so-called "residual charge" was hardly news; it had an observational history dating back to Benjamin Franklin. Faraday tied these phenomena (and induction more generally) to a polarization of the particles that make up the dielectric, a general charging effect that over time could make the effect more pronounced, and more vaguely to some sense of "absorption."

Even in the JCCST report Jenkin was not the only expert to discuss these phenomena. In addition to his discussion of inductive absorption, C. F. Varley, both a member of the committee and on January 5, 1860, a witness before it, became the first to refer to (part of) the phenomena by the name that it carried for the rest of the nineteenth century. Varley introduced it as a modification to his "Law of Induction," happened upon in experiments dating back to 1854, relevant only for certain peculiar materials: "This difference from the law of induction (which holds good with such insulators as atmospheric air, and with some kinds of glass) is termed 'electric absorption.'"[39] Varley's mention of "electric absorption" appears to be the first use of that term to describe the phenomena.[40]

And yet, despite not being the first to notice the phenomena, nor the first to subject it to focused experiment, nor even the one to name it, it is Jenkin's experiments and subsequent presentation to the JCCST that proved most central to demystifying electric absorption.

The year before Jenkin published his "Experimental Researches," he had been named an inaugural member of the British Association's CES. Given his meticulous experimental work at Newall and Co. and his close ties to Thomson, Jenkin was a natural choice. The CES aimed to establish an absolute scale of electrical resistance with more utilitarian magnitudes, amenable to the needs

---

Siemens was the first to appreciate that insulated telegraph cables could be understood as large capacitors.

[38] Michael Faraday, "Experimental Researches in Electricity—Eleventh Series," *PTRSL* 128 (1838): 24.

[39] *Joint Committee* (n.15), 155.

[40] Varley uses "electric absorption" once in error when discussing inductive absorption. Ibid., 153.

of telegraph engineers. It finally achieved this goal with the release of an official unit resistance coil in 1865.[41]

As a member of the CES, Jenkin found himself working closely with James Clerk Maxwell, who had joined to work on the second report, issued in 1863. On the CES they were frequent coauthors and became close friends. As part of the second report, Jenkin and Maxwell coauthored Appendix C, "On the Elementary Relations between Electrical Measurements." Within part IV of this appendix, under the subsection "45. Practical Measurement of Electric Resistance," is found the following:

> Unfortunately, in those bodies, such as gutta percha and india rubber, the resistance of which is sufficiently great to make *t* a measurable time, the phenomena of absorption due to continued electrification so complicates the experiment as to render it practically unavailable for any exact determination. The apparent effect of absorption is to cause *r*, the resistance of the material, to be a quantity variable with the time *t*; and the laws of the variation are very imperfectly known.[42]

Although the measurement of the specific resistances of insulators was not critically important, electric absorption also complicated the measurement of specific inductive capacity, which not only factored into signal retardation but, as we will see, became increasingly important within electromagnetic field theory. As Jenkin reported to the JCCST, "this phenomenon has great influence on all tests of insulation."[43]

The CES reports contain no real advancement of the understanding of electric absorption. While the phenomena are more clearly described, there is no working theory or explanatory model. Jenkin and other members of the CES continued to discuss electric absorption occasionally, but only Maxwell advanced beyond Jenkin's initial work.[44] This second CES report embodies a baton passing from Jenkin to Maxwell, friends and colleagues on the CES but vastly different sorts of electrical professionals outside of it. With the

---

[41] Hunt, "Ohm Is Where the Art Is" (n.10); Simon Schaffer, "Accurate Measurement is an English Science," in *The Values of Precision*, ed. Norton Wise (Princeton, NJ: Princeton University Press, 1995), 135–72.

[42] Fleeming Jenkin, William Thomson, James Joule, and James Clerk Maxwell, *Reports of the Committee on Electrical Standards Appointed by the British Association for the Advancement of Science; with a Report to the Royal Society on Units of Electrical Resistance, and the Cantor Lectures Delivered by Prof. Jenkin before the Royal Society of Arts* (London: E. & F.N. Spon, 1873), 84.

[43] *Joint Committee* (n.15), 468.

[44] Jenkin et al., *Electrical Standards* (n.42), 138–39, 148, 232.

phenomena well described by Jenkin, but the laws still "very imperfectly known," an open challenge remained to create a theory of electric absorption.

The handoff of electric absorption from Jenkin to Maxwell was successful, but not clean. Inseparable from the phenomena is a sticky web of connections to the history of submarine telegraphy and consequently the British Empire. Foundational work on electric absorption is contained within Jenkin's JCCST report, a product of monumental failures of submarine telegraphy. The political and financial forces that inspired the Atlantic cable are stuck to Jenkin's work. This long-distance cable was meant to wire up the Empire and consolidate political and economic power in London. Electric absorption resurfaced as a more serious problem complicating Jenkin and Maxwell's study of insulation for the CES, another appearance arranged in the course of serving the interests of the telegraph industry.

Of course, another sticky connection to the phenomena is the viscous natural latex that Jenkin had been experimenting with and that insulated nearly every submarine telegraph cable, gutta-percha. The presence of the material itself is a manifestation of interconnected factors: British colonization of Malaya, the rise of Singapore as *the* regional trading hub, the power of British cable corporations, as well as the resourcefulness of intermediary Chinese traders and indigenous gutta-collectors. Historical regional trade networks in Southeast Asia cooperated with European agency houses to supply gutta-percha to cable companies for the Victorian equivalent of just-in-time manufacturing of cables. Gutta-percha became one of Singapore's primary export commodities during the late nineteenth century, albeit an exceptionally volatile one that could rapidly send economic shockwaves all the way down the trade network to the collectors in the jungles.[45] By the time Maxwell had encountered the phenomena, electric absorption had become deeply entangled with the uncertain fortunes of submarine telegraphy and gutta-percha itself and thus Britain's drive to fortify its overseas empire.

LINES OF FORCE

Before joining Jenkin as part of the CES, Maxwell had already completed what is likely his most significant contribution to the study of electricity and

---

[45] Helen Godfrey, *Submarine Telegraphy and the Hunt for Gutta Percha: Challenge and Opportunity in a Global Trade* (Leiden: Brill, 2018), 95–132.

magnetism. “On Physical Lines of Force,” published in *Philosophical Magazine* across four parts between 1861 and 1862, introduced Maxwell’s infamous honeycomb ether model, the displacement current, and his electromagnetic theory of light. The messy industrial appearance of the model is derived from a Siemens-designed governor that Maxwell had encountered in an introductory book of mechanisms and machinery.[46]

The one other technological influence of significance in “Physical Lines” is Maxwell’s treatment of capacitors. In concert with the mechanical model, capacitors assisted Maxwell in developing his displacement current and helped him chart a path toward a new empirical verification of his electromagnetic theory of light. All these appearances of capacitors, as reconstructed by Siegel, appear in the third part of the paper, published in early 1862, “The Theory of Molecular Vortices Applied to Statical Electricity.”[47]

As the title of part III suggests, Maxwell was working to extend his theory of electromagnetism, its mathematics and its mechanical model, to cover electrostatics. Siegel has illustrated that idealized capacitors are central to two of Maxwell’s approaches that each provide a share of physical reasoning for the displacement current. The first approach is a Faraday-inspired “field-first” conceptualization that implies a *reverse* polarization across a charging capacitor’s dielectric, that is, in the opposite direction as would result from a closed circuit’s electric field. This polarization, a displacement of electricity in some (reverse) direction, becomes Maxwell’s displacement current.[48]

The second approach makes use of Maxwell’s mechanical model, remaking his magnetic vortices as elastic to extend the model’s reach to electrostatics. Due to physical constraints imposed by the capacitor’s dielectric, the vortices there distort in the opposite direction of rotation. This distortion represents the displacement current and provides a physical distinction (distortion vs. rotation) between the two contributing current elements of Maxwell’s revised version of Ampère’s Law.[49] The charging capacitor treated within the context of the ether model and even within the field-first approach embodies the

---

[46] Cameron Lazaroff-Puck, “What Theories Are Made of: How Industry and Culture Shaped Maxwell’s Theories of Electromagnetism” (PhD Dissertation, University of Minnesota, 2021), 31–41.

[47] James Clerk Maxwell, “On Physical Lines of Force,” in *The Scientific Papers of James Clerk Maxwell*, vol. 1, ed. William Niven (Cambridge: Cambridge University Press, 2010), 489–502.

[48] Siegel, *Innovation in Maxwell* (n.7), 100–5.

[49] Ibid., 105–12.

displacement current and Maxwell's generalization of Ampère's Law from closed to both closed and open circuits.

Famously, Maxwell's newly minted elastic medium also allowed for the propagation of transverse waves. Part III of "Physical Lines" accordingly heralded the first incarnation of Maxwell's electromagnetic theory of light. The close agreement between the calculated ratio of electrostatic and electromagnetic forces (obtained from measurements of capacitors by Kohlrausch and Weber) and the measured velocity of light led Maxwell to conclude that "light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena."[50] Perched uneasily upon relatively close agreement of the two velocities was the weighty unification of electromagnetism and optics. Soon William Thomson was calling into question the agreement between these figures and thus Maxwell's electromagnetic theory of light.[51]

A third, more direct, invocation of capacitors, or more specifically a Leyden jar, immediately followed Maxwell's grand pronouncement about electromagnetic waves. Instead of providing physical reasoning for his theory, this technological interlude offered a new empirical prediction that, if confirmed, could offer further (and perhaps more direct) support for his electromagnetic theory of light. At first, Maxwell simply aimed to find the capacity of a Leyden jar, an expression that makes use of *E*, "a coefficient depending on the nature of the dielectric."[52] After constructing specific inductive capacity as a ratio of capacities, he broke *E* down further, arriving at an expression relating the specific inductive capacity of a dielectric to its index of refraction. Maxwell had derived an empirical prediction that could provide a second source of evidence for his unification of electromagnetism and optics.[53] At the time of publication there was no data against which to test his prediction. Nevertheless, it did suggest a research program that could validate Maxwell's electro-optical theory, long before anyone had produced or detected electromagnetic waves. He said as much to Faraday in an October 1861 letter, noting he hoped "soon to verify [the electro-optical relation] more completely" and inquiring if measurements

---

[50] Maxwell, "Physical Lines" (n.47), 500. Maxwell italicizes this dramatic conclusion in the original.

[51] Smith, *Science of Energy* (n.10), 235; Schaffer, "Accurate Measurement" (n.41), 148, 154.

[52] Maxwell, "Physical Lines" (n.47), 491.

[53] Siegel, *Innovation in Maxwell* (n.7), 141–42.

of specific inductive capacity had changed much since Series XI of Faraday's "Experimental Researches."[54]

In December 1861, Maxwell wrote to Thomson with a similar request, first summarizing the relation he had derived, and then inquiring:

> Do you know any good measures of dielectric capacity of transparent substances? I have read Faraday & Harris on the subject and I think they are likely to be generally too small. I think Fleeming Jenkin has found that of gutta percha caoutchouc &c. Where can one find his method, and what method do you recommend.[55]

These letters to Faraday and Thomson reveal Maxwell's belief in the power his nascent electro-optical experimental program held for validating his electromagnetic theory of light.[56] The capacitor had provided another empirical link between electromagnetism and optics, and Maxwell was eager to find the data to back it up. In "Physical Lines," the capacitor was not only a theoretical guide leading Maxwell toward novel electrical concepts but also an experimental inspiration to confirm those very same developments.

The letter to Thomson also marks Maxwell's first mention of Jenkin in any surviving letter or paper. Before their work together as members of the CES, Maxwell and Jenkin's scientific relationship commenced, fittingly, with concerns over dielectrics.

After the publication of the fourth and final installment of "Physical Lines" in February 1862, Maxwell joined the CES. In the laboratory at King's College, London, where Maxwell still held a professorship, he and Jenkin made precision measurements alongside the physicist Balfour Stewart. In 1863, Stewart was replaced by a new Cambridge graduate and future cable engineer, Charles Hockin. The work of these four was compiled into the report discussed above, a report plagued at nearly every mention of insulation by electric absorption. Maxwell's own electromagnetic theory of light was similarly besieged by electric absorption. The phenomena complicated measurements of the ratio of electrostatic and electromagnetic units. Discharging capacitors with solid dielectrics could "continue for hours, if not days," skewing values for the ratio

---

[54] James Clerk Maxwell, *SLP1*, ed. Peter Harman (Cambridge: Cambridge University Press, 1990), 683.

[55] Ibid., 696.

[56] Maxwell also wrote to Cecil James Monro in February, 1862, detailing his own plans to take similar measurements. Ibid., 710.

of units.[57] And yet, these were hardly Maxwell's most pressing electromagnetic issues. The conceptual novelties introduced in "Physical Lines" remained precariously balanced atop his speculative ether model. A new electromagnetic theory was needed, and so much the better if it could deal with electric absorption.

A DYNAMICAL THEORY

Maxwell's next electromagnetic theory appeared in 1864 as "A Dynamical Theory of the Electromagnetic Field." There are unfortunately few surviving early drafts or relevant letters that clarify Maxwell's process. What fragments do exist suggest that Maxwell devised the bulk of the paper during the summer of 1864, ultimately completing it by late October.[58]

Maxwell's "Dynamical Theory" did relieve his dependance on a mechanical model. Maxwell's general field equations, electric displacement and the displacement current, and his electromagnetic theory of light were all reconceived "without any hypothesis about the structure of the medium."[59]

Hunt has insisted that Maxwell's "close collaboration in this period with Fleeming Jenkin and other telegraph engineers led him to adopt, at least for a time and for the purposes at hand, an 'engineering approach' to electrical questions."[60] Given Maxwell's approach in "Dynamical Theory" and its timing, this all tracks. While still making theory-relevant measurements with Jenkin, Maxwell strips his electromagnetic theory of its most fanciful mechanical speculations, leaving it less concerned with ethereal microstructures than relations between measurable quantities. It does appear that conducting precision measurement work surrounded by cable engineers wore off on Maxwell.

There was of course still plenty of methodological continuity on display. Both "Physical Lines" and "Dynamical Theory" are guided by machinery, although to differing degrees.[61] The ethereal medium remained elastic, and

---

[57] James Clerk Maxwell, "On a Method of Making a Direct Comparison of Electrostatic with Electromagnetic Force; With a Note on the Electromagnetic Theory of Light," *The Scientific Papers of James Clerk Maxwell*, vol. 2, ed. William Niven (Cambridge: Cambridge University Press, 2010), 136.

[58] The paper was submitted on October 27, 1864. James Clerk Maxwell, *SLP2*, ed. Peter Harman (Cambridge: Cambridge University Press, 1995), 189.

[59] Ibid., 187–88.

[60] Hunt, "Maxwell, Measurement" (n.8), 305.

[61] Lazaroff-Puck, "Gearing up" (n.6).

the association of elasticity with electric displacement remained, without any vortices.[62]

Nevertheless, operationalist philosophy was not all that Maxwell picked up during his collaboration with Jenkin. Jenkin shared a particular conceptualization of electric absorption with Maxwell that found its way into his "Dynamical Theory," and it is through this lineage that technology made an undeniable impact on his electromagnetic theory. With this in mind, their finely polished reports for the CES are less instructive than Jenkin's earlier work for the JCCST.

Capacitors were allotted prime real estate in "Dynamical Theory." They were no longer just implied theoretical guides or buried in the wake of his electromagnetic theory of light. Instead, part V of Maxwell's "Dynamical Theory" was reserved for his "Theory of the Condenser."[63] This now consistently ignored section, preceding his reformulated electromagnetic theory of light (part VI), begins mostly as a retread of what he had published in 1862. What follows, however, is an account of charge dissipation, residual charge, and secondary discharge—that is, electric absorption, built from Maxwell's concept of displacement. And Maxwell is not stingy crediting the empirical work that made his account possible:

> These phenomena have been described by Professor Faraday (Experimental Researches, Series XI) and by Mr F. Jenkin (Report of Committee of Board of Trade on Submarine Cables), and may be classed under the name of "Electric Absorption."[64]

In part I, Maxwell also found cause to cite Jenkin, "[a]lmost all solid dielectrics exhibit this phenomenon [electric absorption], which gives rise to the residual charge in the Leyden jar, and to several phenomena of electric cables described by Mr F. Jenkin."[65] The footnote accompanying this sentence marks out the pages that begin Jenkin's testimony in the Joint Committee report as well as the appendix containing Jenkin's submitted paper. Series XI of Faraday's Experimental Research is similarly narrowed down to sections 1233–1250 where Faraday identified residual charge and secondary discharge in various solid dielectrics.

---

[62] James Clerk Maxwell, "A Dynamical Theory of the Electromagnetic Field," in *The Scientific Papers of James Clerk Maxwell*, vol. 1, ed. William Niven (Cambridge: Cambridge University Press, 2010), 531.

[63] Ibid., 572–76.

[64] Ibid., 573.

[65] Ibid., 532.

Maxwell's "Theory of the Condenser" is not just his reflections on an idealized capacitor but also involves a deep consideration of Jenkin's JCCST cable experiments. That this is in a sense both a theory of the capacitor and of submarine cables should come as no surprise. As Faraday preached, a submerged telegraph cable and a capacitor are essentially one and the same, albeit on *slightly* different scales. Economic and political pressures, the concerns of private industry, and those of the British Empire that drove early submarine telegraphy are taken into Maxwell's theory along with Jenkin's testimony. Although this intrusion may appear contained within a more marginal, practically oriented cul-de-sac of Maxwell's theory, it actually seeped into the very heart of Maxwell's "Dynamical Theory."

Part V begins with Maxwell constructing an expression for the capacity of a simple parallel plate capacitor, replacing the Leyden jar referenced for the same purpose in "Physical Lines." While Maxwell again derives the specific inductive capacity, he does not follow it up by connecting it to the index of refraction.

This relation between optical and electromagnetic properties does appear halfway through part VI, "Electromagnetic Theory of Light," in a much reduced form.[66] As outlined in Maxwell's CES report and the introduction to "Dynamical Theory," electric absorption still complicated accurate measurements of specific inductive capacity and thus his experimental program. But now, in a new paper containing a new theory of electric absorption, there was reason for optimism even if he lacked sufficient measurements at the time of submission.

Having tabled the electro-optical discussion for part VI, Maxwell begins a qualitative discussion of the phenomena that occupy the rest of his "Theory of the Condenser," namely electric absorption. Maxwell quickly summarizes the action of electric absorption in a capacitor, remarking that "when left charged, [it] gradually loses its charge, and in some cases, after being discharged completely, it gradually acquires a new charge of the same sign as the original charge, and this finally disappears."[67] The mathematical analysis of electric absorption that follows is an account of an idealized technology, made from a combination of Faraday and Jenkin's experimental contributions. This technology is a parallel plate capacitor containing a dielectric made up of a number of different layers of different materials that will be charged and discharged,

---

[66] Ibid., 582–83.

[67] Ibid., 573.

exhibiting electric absorption under particular conditions. The physical structure of the device *is* the explanation for electric absorption. While the phenomena of electric absorption were already adequately presented by Faraday, it is Jenkin's investigation of electric absorption in submarine cables and his appreciation for how its effects varied with the purity of cable insulation that most shapes Maxwell's approach. The very real alternating layers of gutta-percha and Chatterton's compound that insulated the copper core of Jenkin's cable from surrounding water became the idealized flat dielectric layers sandwiched between a capacitor's conductive plates in Maxwell's explanation of electric absorption.

Making good use of his general equations of the electromagnetic field from part III of "Dynamical Theory," Maxwell obtains expressions for the charge on each surface (the surfaces between each layer of dielectric and finally the between dielectric and plates) and how they change over time. He then creates a critical two-part expression relating the potential difference across each layer to his Equation of Electric Elasticity (E) (multiplied by layer thickness) and his Equation of Electric Resistance (F), better known as Ohm's law. From this relation, Maxwell is eventually able to derive an expression for the instantaneous discharge of the capacitor after it had been charged. The battery remains disconnected after this discharge, and thus the only current in each layer is apparently the displacement current. Here the two-part relation made from equations (E) and (F) is again used to obtain a differential equation, which when solved, gives the displacement in any layer at time t. This solution for displacement is made complete by using the instantaneous discharge (the solution at $t = 0$) to solve for the unknown coefficient. Finally, Maxwell constructs an equation for the difference in potential at time t following instantaneous discharge.[68]

$$\psi' = \psi\left\{\left(\frac{r_1}{r} - \frac{a_1 k_1}{ak}\right)e^{\frac{-a_1 k_1}{r_1} t} + \left(\frac{r_2}{r} - \frac{a_2 k_2}{ak}\right)e^{\frac{-a_2 k_2}{r_2} t} + \ldots\right\}$$

This equation in combination with the idealized stratified capacitor is the first quantitative explanation of the suite of phenomena known as electric absorption. The equation shows that the now isolated capacitor will recover charge after the initial discharge, giving an adequate accounting of residual charge. Over time, this charge will dissipate in accordance with the insulating properties of the dielectric layers. Maxwell's equation further emphasizes the

---

[68] Ibid., 574–75.

importance of the stratified capacitor idealization; electric absorption is a product of the inhomogeneous structure of the dielectric. A homogeneous dielectric becomes completely discharged and never recovers any charge. To cap off part V, Maxwell investigates a secondary discharge of the capacitor, but this time looks for the quantity of electricity passing through a more practically relevant wire, that is, one that actually possesses resistance.[69]

Having reassembled his equation describing electric absorption, the centerpiece of part V, we can now sift through it to isolate the specific impact of the two sources of inspiration that Maxwell cites, Faraday and Jenkin. Despite preceding Jenkin's work by nearly two decades, Faraday more clearly lays out the suite of phenomena that make up electric absorption, neatly linking residual charge to conductivity in the dielectric. Jenkin also notes a residual charge and connects it to current leakage through the insulation. Regarding Maxwell's displacement-focused approach, both Faraday and Jenkin argued that polarization *within* the dielectric (although not necessarily *of* the dielectric) was responsible for the phenomena. While Jenkin and Faraday both suggest that electricity in some sense penetrates the dielectric, Maxwell credits Faraday for experimentally demonstrating that an absorption process analogous to that of heat was *not* what was happening.[70]

Nevertheless, despite its vagaries it is Jenkin's JCCST report that is most pertinent to Maxwell's explanation for electric absorption. Faraday (and later Varley) associated electric absorption with particular dielectric materials. Jenkin's report is the only source that hints the phenomena is a consequence of the combination of *multiple* different materials. If we visualize Jenkin's second cable, insulated in alternating layers of Chatterton's compound and pure gutta-percha, and take a cross section, we are left with nearly the same picture as the parallel layers of Maxwell's capacitor, just with the sea as the second plate. In Jenkin's JCCST report, electric absorption was contextualized in a manner that led neatly not only to Maxwell's general explanation of the phenomena, an inhomogeneous dielectric, but also to the idealized model of a layered dielectric that suggests how electric absorption functions and from which is derived his quantitative theory.

---

[69] For a more complete mathematical account: Lazaroff-Puck, "What Theories Are Made of" (n.46), 117–29.

[70] James Clerk Maxwell, *A Treatise on Electricity and Magnetism*, 1st ed., vol. 1 (Cambridge: Cambridge University Press, 2010), 51–52; Maxwell, *SLP2* (n.58), 958–59; James Clerk Maxwell, *SLP3*, ed. Peter Harman (Cambridge: Cambridge University Press, 2002), 325; Faraday, "Experimental Researches—Eleventh Series," (n.38): 23–24.

The above equation and nearly every step in reaching it is made possible by the Equation of Electric Resistance (F), what we would now call Ohm's law. However, the equation Maxwell uses is *not* Ohm's law but rather a sign-flipped version of it. This added negative sign might initially appear to be a simple mistake—Maxwell is notorious for having "sign dyslexia"—but the nature of the sign-swapped equations in his "Dynamical Theory" suggests intentionality. Sign errors in "Physical Lines" were mostly limited to intermediate stages in Maxwell's derivations, while in "Dynamical Theory" these sign "errors" appear in final, lettered equations, the apogee of his electromagnetic theory. The final equations in "Physical Lines" are consistent among themselves, if different from modern equations, while certain final equations in "Dynamical Theory" are internally inconsistent.[71] An early draft of "Dynamical Theory" shows Maxwell laboring over the addition of negative signs in Equation (E) that ultimately did not make the final paper.[72] Given this level of care, it seems unlikely Maxwell would flippantly add a negative sign to Ohm's law, Equation (F), the very next equation. The negative sign seems very contrived in Ohm's law, reimagining the relation between the electromotive force and the resulting current.

Indeed, the earliest surviving draft fragment of Maxwell's "Dynamical Theory," dated approximately to the summer of 1864, shows that Maxwell initially wrote Equation (F) *without* a negative sign.[73] Shortly after, in a letter dated September 7, 1864, Maxwell wrote to his CES colleague Charles Hockin:

> I have been doing several electrical problems. I have got a theory of "electric absorption," i.e., residual charge, etc. and I very much want determinations of the specific induction, electric resistance, and absorption of good dielectrics, such as glass, [bug] shell-lac, gutta-percha, ebonite, sulfur, etc.[74]

It appears then that before Maxwell had developed his theory of electric absorption, he had assumed the entirely familiar, positively-signed version of Ohm's law. Why then would Maxwell change the sign of one of his eight general equations of the field?[75]

Equation (F), Ohm's law, played a critical role in Maxwell's derivation of his equation of potential difference after instantaneous discharge, the equation

[71] Siegel, *Innovation in Maxwell* (n.7), 214–15n10.

[72] Ibid., 180–81.

[73] Maxwell, *SLP2* (n.58), 160.

[74] Ibid., 164.

[75] Counting every component equation, as Maxwell did, gives twenty equations.

that essentially embodies electric absorption. After the capacitor is discharged and the battery disconnected, the equation linking potential difference in the capacitor to equations (E) and (F) is modified, replacing the current in a given layer in Equation (F) with the displacement current in that layer. Solving the resulting differential equation gives the exponent in the equation modeling electric absorption.[76] The added negative sign in Equation (F) finds its way into that exponent and ensures that the difference of potential does not explode exponentially thanks to some seemingly infinite wellspring of electricity within the dielectric and instead decreases, reflecting the dissipation of charge in an imperfect dielectric. Why then did Maxwell modify one of his fundamental equations of electromagnetism? The answer is that it was necessary to reasonably model electric absorption. Maxwell changed Ohm's law to satisfy the needs of an investigation of electrical technology. The abstract theoretical physics of his "Dynamical Theory" was subordinated to modeling an idealized capacitor and an explanation borne from failed submarine telegraphy. That the theory of the capacitor receives its own section, in the same sense that the general equations or the electromagnetic theory of light do, is not a meaningless quirk of the paper's organization. While obviously not equal in significance, his treatment of the capacitor is not just supplementary. Maxwell reaches back into the general equations and rewrites fundamental theoretical physics to accommodate electrical technologies. In doing so, he grounds his electromagnetic theory in the explanatory power of his account of electric absorption.

The concept of electric displacement, itself born from idealized capacitors, is buoyed by Maxwell's ability to model electric absorption. This is most true in the sense that displacement was central to his construction of what he believed at the time of writing was a novel account of a previously confounding set of empirical phenomena, that is, the first successful *quantitative* account of electric absorption.[77] Few other concepts or relations can even approach the

---

[76] Only Olivier Darrigol has previously noted this reasoning behind Maxwell's sign swapped Ohm's law. Olivier Darrigol, *Electrodynamics from Ampère to Einstein* (New York: Oxford University Press. 2000), 162n60.

[77] By the time he had sent the paper to the Royal Society, Maxwell had "seen a paper by M. Gaugain . . . in which he has deduced the phenomena of electric absorption and secondary discharge from the theory of compound condensers." Maxwell, "Dynamical Theory" (n.62), 576. Gaugain, a French engineer, reported experiments describing similar *qualitative* features as Maxwell's then unpublished theory. Jean-Mothee Gaugain, Mémoire Sur la conductibilité électrique et la capacité inductive des corps isolants," *Annales de Chimie et Physique* 4, no. 2 (1864): 311–16.

importance of displacement in his account of electric absorption, streamlining the contingencies of his "Theory of the Condenser." The efficacy of his theory of electric absorption is almost exclusively tied to the efficacy of his concept of displacement. His electromagnetic theory of light is similarly dependent on the concept of displacement, although not quite as singularly as in electric absorption. Maxwell's theory of electric absorption does not confer the same explanatory power as his electromagnetic theory of light; however, with Hertz's observation of electromagnetic waves still years away and inadequate data for his relation between specific inductive capacity and index of refraction, his unification of electromagnetism and optics stood on shaky empirical grounds. Successfully modeling a well-observed set of complex phenomena like electric absorption illustrated the explanatory power of Maxwell's "Dynamical Theory" in general, the concept of displacement in particular, and helped bolster other elements of his theory, such as the electromagnetic theory of light, that were uniquely dependent on displacement.

Not only is displacement buoyed by electric absorption, so too are the core analogical relations underpinning his electromagnetic theory. Maxwell's conception of an elastic ether provided the impetus for electric displacement and the displacement current in "Physical Lines." Beyond the mathematics associated with it, electric displacement maintained links to its conceptual lineage. It was not a fluke that Equation (E) was named the "equation of electric elasticity." In "Dynamical Theory," Maxwell analogizes electric absorption to a sort of imperfect elastic yielding:

> The yielding due to electric absorption may be compared to that of a cellular elastic body containing a thick fluid in its cavities. Such a body, when subjected to pressure, is compressed by degrees on account of the gradual yielding of the thick fluid; and when the pressure is removed it does not at once recover its figure, because the elasticity of the substance of the body has gradually to overcome the tenacity of the fluid before it can regain complete equilibrium.
>
> Several bodies in which no such structure as we have supposed can be found, seem to possess a mechanical property of this kind[1]; and it seems probable that the same substances, if dielectrics, may possess the analogous electrical property . . .[78]

---

[78] The footnote in the quote above lists substances like "glue, treacle, &c., of which small plastic figures are made, which after being distorted gradually recover their shape." Maxwell, "Dynamical Theory" (n.62), 532.

His successful treatment of electric absorption simultaneously vindicates the original elastic character of electric displacement and his analogy between electric absorption and elasticity. These analogies become mutually reinforcing as a consequence of the critical role displacement plays in accounting for electric absorption. Maxwell's reasoning closes the loop; the success of his electromagnetic theory, built from elastic concepts, authorizes further elastic-led reasoning, that is, his "Theory of the Condenser," and the success of both justifies the dynamical approach underpinning the construction of the whole theory.[79]

There remains of course the matter of the empirical issues a theory of electric absorption might help alleviate. Electric absorption was still a serious impediment to accurately measuring specific inductive capacity, and thus to confirming the relation between it and the index of refraction and then ultimately his electromagnetic theory of light. Part V, in combination with part VII, "Calculation of the Coefficients of Electromagnetic Induction," were intended to assist Maxwell's own planned experimental determination of the ratio of units—that is, the wave velocity. In 1868, Maxwell clarified that correcting for electric absorption could also help affirm his electromagnetic theory of light by explaining away some of the disagreement between his calculated wave velocity and other contemporary measurements of the speed of light. Kohlrausch and Weber's experiments with capacitors from which Maxwell had sourced the values that made up the wave velocity in "Physical Lines" and "Dynamical Theory" were flawed. Maxwell insisted that since their experiments used solid dielectrics that would suffer from electric absorption, residual charge recovered by the capacitor after each discharge would result in too large a value for capacity. Too large a value for capacity and "the number of electrostatic units in the discharge would be overestimated, and the value of *v* would be too great . . . I am obliged to attribute the difference of their result from mine to a phenomenon [electric absorption] the nature of which is now much better understood than when their experiments were made.[80] Maxwell's claim was correct, although his own determination of *v*, presented just before this quotation, was very nearly as inaccurate, just now too low.[81]

---

[79] George Smith, "Closing the Loop: Testing Newtonian Gravity, Then and Now," in *Newton and Empiricism*, ed. Zvi Biener and Eric Schliesser (New York: Oxford University Press, 2014), 262–352.

[80] Maxwell, "Electrostatic with Electromagnetic Force" (n.57), 136.

[81] This inaccuracy was largely a consequence of the inaccurate value of the ohm previously obtained by Maxwell and Jenkin as a part of the CES.

Submarine cables and capacitors, real and idealized, came together in Maxwell's "Dynamical Theory" and led the way toward explanations for electrical action in dielectrics, bolstered abstract analogies between mechanical and electromagnetic realms, and offered hope for troubled empirical programs. The tradeoff was some abuse of a certain fundamental equation of electricity. Nevertheless, eight years later in Maxwell's *Treatise*, these technological co-conspirators would leave their most lasting impact on Maxwellian electromagnetic theory.

A TREATISE ON ELECTRICITY AND MAGNETISM

In volume 1 of Maxwell's 1873 *Treatise on Electricity and Magnetism*, chapter X, "Conduction in Dielectrics," expands slightly on his "Theory of the Condenser," charting a totally new course over now familiar terrain.[82] This difference in approach would prove instrumental in shaping the work of physicists who learned electricity and magnetism from the *Treatise* and worked as "Maxwellians" at least until the advent of Larmor's electron theory.

The section that mirrors his prior work on electric absorption is aptly titled "Theory of a Composite Dielectric."[83] While it derives *nearly* identical versions of equations he had arrived at in "Dynamical Theory," this time Ohm's law was freed of its contrived negative sign. Laying out the relevant equations and variables at the beginning of the section, this positively signed version of Ohm's law signals a new approach. As it would turn out, this change in approach also heralded a notable reconceptualization of dielectrics.

The guiding idealization remains the same as in "Dynamical Theory," a capacitor with a layered, inhomogeneous dielectric. After some small tweaks to variables and coefficients, once again Maxwell considers the state of this isolated capacitor immediately after an instantaneous discharge. In the *Treatise*, he finds a new starting point, his equation of total current, u, the sum of the conduction and displacement currents. This same equation was present in "Dynamical Theory;" there is nothing in the *Treatise*'s version of the derivation that was unavailable to Maxwell in 1864. His new derivation is made possible by the assumption that after the connection between the plates is broken the total current is zero. It is by integrating this equation with respect to the

---

[82] Maxwell, *Treatise*, 1st ed., vol. 1 (n.70), 374–87.

[83] Ibid., 376–81.

electric force in a layer (substituted in for the conduction current and displacement) that Maxwell achieves his negative exponent. The rest of the derivation proceeds similarly to "Dynamical Theory," using the instantaneous discharge to solve for the unknown coefficient of integration, and then finally combining terms.[84] The primary difference between his new equation and the equation derived in "Dynamical Theory" is the migration of the term for layer thickness, a_i, from the exponent to the first coefficient.

Ultimately, this shift in approach highlights an accompanying conceptual shift obscured by Maxwell's vague discussion of electrical action in the dielectric. In "Dynamical Theory" there was only a displacement current in the layered dielectric of the post-discharge capacitor. Maxwell's assertion that the total current is zero communicates his belief that the dielectric contains two opposing currents, a displacement current *and* a conduction current, which ultimately balance one another out and yield no total current. Brief statements at the opening of each section illustrate this change in thought. In 1864, Maxwell insists that "[w]hen the dielectric of which the condenser is formed is not a perfect insulator, the phenomena of conduction are combined with those of electric displacement."[85]

The idea of "combination" is reflected in his derivation; he inserts the displacement current into Ohm's law, replacing the standard conduction current. Maxwell's brief discussion of dielectrics in 1868 suggests a similar conception. The dielectric supports *only* the increase or decrease of electric displacement, which is equivalent in effect to an electric current.[86] In 1873, when faced with the same situation, Maxwell notes the simultaneous nature of the phenomena: "dielectric media, with very few, if any, exceptions, are also more or less imperfect conductors . . . Hence we are led to study the state of a medium in which *induction and conduction are going on at the same time*."[87]

This reformed explanation of electric absorption in a stratified capacitor also provided a physical and mathematical justification for the asymmetry of magnetic field effects and capacitors. Why do capacitors not produce a magnetic field as their charge dissipates? Because there is no net current to produce it. The yielding of displacement within the dielectric is accompanied by an equal and opposite conduction current. Once again, it is technology, the capacitor,

---

[84] Ibid., 379.

[85] Maxwell, "Dynamical Theory" (n.62), 573.

[86] Maxwell, "Electrostatic with Electromagnetic Force," (n.57), 139.

[87] Maxwell, *Treatise*, 1st ed., vol. 1 (n.70), 374 (emphasis added).

and thanks to Jenkin, the submarine cable, etching new understanding into electromagnetic theory and placing a physical asymmetry at its heart.

Just as the fundamental equation of electric absorption from "Dynamical Theory" is remade in the *Treatise*, so too are the accoutrements that originally filled out part V. In the *Treatise*, there is a touch more humility about the complications of accounting for electric absorption in non-idealized "cases in which the materials are arranged otherwise [i.e., not in parallel layers]."[88] While this chapter does not include a citation of Jenkin's JCCST report or Faraday, tucked into a subsection on dielectrics in the "Description of Phenomena" that opens chapter I is a description of electric absorption citing Faraday and containing a clear, albeit uncited, reference to Jenkin's experiments: "Thus, when the insulation of a submarine cable is tested, the insulation appears to improve as the electrification continues."[89]

Picking up that promising idea first floated in connection with Leyden jars in "Physical Lines," Maxwell finally delivers empirical data regarding the relation between a material's specific inductive capacity and its index of refraction. In chapter XX, "Electromagnetic Theory of Light," he reports what might be generously described as a tentative confirmation of his prediction. Maxwell's data for paraffin was fairly close, but as he readily admitted, the error was "greater than can be accounted for by errors of observation."[90] Maxwell still held out hope that if similar agreement could be found across a wider range of materials, the relation could be proven *mostly* true.[91] Unfortunately, by 1891, when J. J. Thomson was editing the third edition of the *Treatise*, multiple experiments on glass had done nothing but further confuse the situation.[92]

In 1872, before the publication of the *Treatise's* first edition, Ludwig Boltzmann had conducted his own experiments, eventually publishing his account in 1874. The agreement between values in Boltzmann's account is worse than Maxwell's for paraffin, although they do cover a wider range of materials.[93] Although Boltzmann's experiments did not make it into any of the *Treatise*'s

---

[88] Ibid., 381.

[89] Ibid., 51.

[90] James Clerk Maxwell, *A Treatise on Electricity and Magnetism*, 1st ed., vol. 2 (Cambridge: Cambridge University Press, 2010), 388–89.

[91] Ibid., 389.

[92] James Clerk Maxwell, *A Treatise on Electricity and Magnetism*, 3 rd ed., vol. 2 (Mineola, NY: Dover, 1954), 438.

[93] Ludwig Boltzmann, "Über die Verschiedenheit der Dielektricitätsconstante des krystallisierten Schwefels nach verschiedenen Richtungen," *Sitzungsberichte der Kaiserlichen Akademie der Wissenschaften* 70, no. 2 (1874): 342—366.

three editions, he was still personally confident he had experimentally validated Maxwell's theory: "By verifying this conclusion on sulfur crystals . . . the correctness of Maxwell's theory was already made probable long before Hertz's classical experiments."[94] His overconfidence aside, Boltzmann's comments illustrate the seriousness of this experimental program, another long-running precision enterprise with the goal of empirically verifying Maxwell's electromagnetic theory, with practitioners both in Britain and on the continent. Before Hertz's experiments, the empirical credibility of the electromagnetic theory of light did not rest exclusively on precision measures of the ratio of units and their agreement with the speed of light. Even so, both methods were indebted to capacitors.

MAXWELLIANS, THE "LEAKY CONDENSER," AND NEW THEORIES OF ELECTRIC ABSORPTION

Following Maxwell's untimely death in 1879, his electromagnetic theory was clarified and extended by a loose cohort of mostly British physicists, the so-called "Maxwellians." Among these Maxwellians, charge dissipation, a constituent phenomenon of electric absorption illustrated by the stratified capacitor, profoundly colored their physical theories. Charge dissipation became commonly referred to by the device it was most commonly associated with, the "leaky condenser." In particular, it was the equal but opposing currents as defined in Maxwell's *Treatise* that occupied the Maxwellians. As Jed Buchwald argued, "most of the major conceptual changes in Maxwellian theory that took place between 1885 and 1895 were in some way connected with this type of situation [the leaky condenser]."[95]

Building on his famous 1884 theory of energy flow in the electromagnetic field, John Henry Poynting published a theory the following year describing the lateral motion of tubes of displacement/induction. These tubes moved sideways along the path of energy flow, the end points eventually coming together, marking the total decay of the displacement tube. Energy flow now described a "real" motion of an element of the field. Decay became what separated conduction and displacement currents. Both described a motion

---

[94] James Clerk Maxwell, *Ueber physikalische kraftlinien*, trans. Ludwig Boltzmann (Leipzig: Wilhelm Engelmann, 1898), 140; Maxwell, *SLP1* (n.54), 687n17.

[95] Jed Buchwald, *From Maxwell to Microphysics: Aspects of Electromagnetic Theory in the Last Quarter of the Nineteenth Century* (Chicago: University of Chicago Press, 1985), 32.

of the tubes, but only conduction currents also involved their decay.[96] By 1886, Poynting had arrived at a view faintly reminiscent of Maxwell's "Dynamical Theory," which he clarified in a letter to Oliver Lodge:

> I think Hopkinson goes in for the yielding of displacement towards the + plate accompanied by an equal conduction current in the opp dir like Maxwell where as I only think of the yielding of displacement and omit the conduction current as unnecessary and doing nothing.[97]

Poynting's next contribution was to reconceive the stratified capacitor problem in Maxwell's *Treatise* to incorporate his new beliefs on currents and displacement in the dielectric. The math is essentially identical except the variable marking the "current due to conduction through each stratum" now represented "the amount of decay of induction per second in each stratum."[98] Poynting began the paper with the fair complaint that Maxwell's dueling current theory "gives no help in forming a mental picture of the process actually going on in the dielectric."[99] Instead of equal and opposite currents yielding zero net current, Poynting simply found that "no fresh tubes enter any layer, so . . . $u = 0$."[100]

Even by 1895, as the electron was emerging and traditional Maxwellian theory was breathing its last gasps, Poynting was still writing to Joseph Larmor to explain why charge decay in a capacitor did not produce a magnetic effect (at least at larger than molecular levels). Once again, Poynting was content to "take shelter behind Maxwell," citing $u = 0$ from Maxwell's *Treatise*, although not content enough to stick with the "mere mathematical fiction" of Maxwell's dual-current explanation.[101]

---

96. John Henry Poynting, "On the Connection between Electric Current and the Electric and Magnetic Inductions in the Surrounding Field," in *Collected Scientific Papers*, ed. Guy Barlow and Gilbet Shakespear (Cambridge: Cambridge University Press, 1920), 194–223.

97. John Henry Poynting, "Letter from John Henry Poynting to Oliver Lodge," 24 June 1886, University College London Special Collections, MS ADD 89/85, 2.

98. Maxwell, *Treatise*, 1st ed., vol. 1 (n.71), 376; John Henry Poynting, "Discharge of Electricity in an Imperfect Insulator," in *Collected Scientific Papers*, ed. Guy Barlow and Gilbet Shakespear (Cambridge: Cambridge University Press, 1920), 232.

99. Poynting, "Discharge of Electricity" (n.98), 224.

100. Ibid., 234.

101. John Henry Poynting, "Letter from John Henry Poynting to Joseph Larmor," 20 Sep 1895, Library of the Royal Society of London, MS 603/A/167 (1599), 4; Buchwald, *Maxwell to Microphysics* (n.95), 32.

Poynting dropped some of the conceptual baggage Maxwell had saddled the dielectric with, simplifying the electrical action to a single element that could move and decay and was generally more physically comprehensible. J. J. Thomson expanded on Poynting, examining how displacement tubes would break down to molecular dimensions within a conductor.[102] The extensive theoretical work by Thomson and Poynting served to entrench this explanation amongst British physicists even if other Maxwellians derided excessive literalism regarding displacement.[103] Larmor's electron and the Hall effect sounded the death knell for the displacement tube cottage industry, and by 1895 Larmor could confidently assert that "the conduction current does not involve elastic displacement."[104]

Until Larmor ended its reign, the leaky condenser had become so imbedded in Maxwellian thinking that in a moment of historical reflection, Oliver Heaviside wrote "it was probably by consideration of conduction in a leaky condenser that Maxwell was led to his inimitable theory of the dielectric, by which he boldly cut the Gordian knot of electromagnetic theory."[105] Setting aside the historical accuracy of his statement, Heaviside's reverence for the leaky condenser demonstrates its lasting influence among the Maxwellians, and thus the lasting influence of Maxwell's theory of electric absorption and Jenkin's submarine cable experiments.

Up through the 1920s, a small community was still working on new theories of what had come to be called dielectric absorption. By 1927, there were enough competing theories to encourage the American professor of electrical engineering J. B. Whitehead to lay out a taxonomy of approaches. The first notable attempt to replace Maxwell's theory was the 1876 elastic theory of his contemporary and countryman John Hopkinson, which Maxwell reviewed

---

[102] J. J. Thomson, *Notes on Recent Researches in Electricity and Magnetism: Intended as a Sequel to Professor Clerk-Maxwell's Treatise on Electricity and Magnetism* (Cambridge: Cambridge University Press, 2010), 1–52; Jaume Navarro, *A History of the Electron: JJ and GP Thomson* (Cambridge: Cambridge University Press, 2012), 60–70. See also John Henry Poynting, "Molecular Electricity," in *Collected Scientific Papers*, ed. Guy Barlow and Gilbet Shakespear (Cambridge: Cambridge University Press, 1920), 224–43.

[103] George Francis FitzGerald, "Sir W. Thomson and Maxwell's Electromagnetic Theory of Light," in *The Scientific Writings of the Late George Francis FitzGerald*, ed. Joseph Larmor (London: Longmans, Green, and Co., 1902), 173.

[104] Joseph Larmor, "A Dynamical Theory of the Electric and Luminiferous Medium," *PTRSL (A)* 186 (1895): 723; Buchwald, *Maxwell to Microphysics* (n.95), 127.

[105] Oliver Heaviside, *Electromagnetic Theory*, vol. 1 (London: The Electrician Printing and Publishing, 1894), 29.

and recommended for publication in *Philosophical Transactions*.[106] Despite recommending it, Maxwell's review involved substantial criticism and an unsurprising preference for his own theory.[107] After Hopkinson, the enterprise soon moved to continental Europe where names like Houllevigue, Pellat, Décombe, von Schweidler, and Wagner labored over new methods.[108]

The half century between Maxwell's work and Whitehead's lectures had not unearthed any material pure enough to be entirely absent of electric absorption. Supporters of Maxwell's stratified dielectric theory could only insist these substances were slightly adulterated; after all, the theory suggested that even trace impurities could lead to substantial absorption. While Maxwell's theory continued to prove difficult to verify experimentally, subsequent theories of absorption only marginally improved on the empirical fit, while requiring ontologically greedy additions like a viscous ether, electron deformation, or an absurd range of molecule types. And so, despite a mostly qualitative empirical backing (and even some notable experimental contradictions), Maxwell's stratified dielectric has survived to the present day as the preferred explanation for (di)electric absorption thanks to its economy and simplicity, the same characteristics that helped it bolster his electromagnetic theory.[109]

SUBMARINE CABLE SUCCESSES, EXCESSES, AND TREES

A new Atlantic cable was in the works almost immediately after the JCCST delivered their report. By 1864, the largest cable manufacturer, Glass, Elliot and Company, absorbed the largest manufacturer of cable cores, the Gutta Percha Company, forming the Telegraph Construction and Maintenance Company (Telcon), took on a majority of shares in the Atlantic Telegraph Company, and set to work on a new cable. Following the recommendations of the JCCST, the

---

[106] Before Hopkinson, Herbert Spencer solicited comments from Maxwell on Spencer's own hypotheses about the nature of electricity, including residual discharge. Maxwell, *SLP2* (n.58), 956–61.

[107] Maxwell, *SLP3* (n.70), 324–29.

[108] Whitehead, *Dielectric Theory* (n.34), 1–78.

[109] In the mid–twentieth century, the hyphenate "Maxwell-Wagner" was used, indicating some appreciation of Wagner's explanation, a *homogeneous* dielectric with embedded conductors. Wagner also extended Maxwell's theory to cover alternating potentials. Ibid., 92–102; J. B. Birks and J. Hart, eds., *Progress in Dielectrics*, vol. 3 (London: Heywood, 1961), 89, 137–44, 153–63; Alan Owen, "Electric Conduction and Dielectric Relaxation in Glass," in *Progress in Ceramic Science*, vol. 3, ed. J. E. Burke (New York: Pergamon Press, 1963), 159, 179.

new cable was covered in thicker (although less pure) insulation, had a larger-diameter copper core, a more robust steel and hemp sheath, and was subjected to much more rigorous testing. The 2,700 miles (~4,350 km) of cable were produced in a single piece, necessitating a truly enormous cable laying vessel. Luckily, the behemoth steamship *Great Eastern*, another catastrophic failure left over from the 1850s, was waiting for just such an opportunity.[110]

After a retrofit, the ship was loaded, and after landing the cable on July 23, 1865, proceeded from Foilhummerum Bay, Ireland, across the Atlantic. Two-thirds of the way into its journey, the cable broke and sunk in over two and half miles of water. The *Great Eastern* returned to port "shattered in hopes as well as in ropes."[111]

The next year, the *Great Eastern* set out again with new recovery equipment, what was left of the old cable, and an entirely new full length of cable with the intent of not only laying a trans-Atlantic submarine cable but of raising the failed 1865 cable and completing it as well. By July 28, 1866, the new cable was successfully landed in Trinity Bay Newfoundland, and by September 7, the 1865 cable had been located, raised, spliced, and landed as well.[112]

In the aftermath of the double success of the Atlantic cable enterprise, a new era of submarine telegraphy dawned. Before 1870, Telcon laid the Malta-Alexandria cable, another Atlantic cable between France and Canada, a new Red Sea cable connecting Egypt and India, and even more across the Mediterranean.[113] During the 1870s, British telegraph companies laid cables to Singapore, Hong Kong, mainland China, and New Zealand. By the close of the century, there were twelve working Atlantic cables and a truly global undersea network.[114] Some of these undersea cables were commercially viable; others were simply projections of imperial power.

With few exceptions, this new connected world was shaped by British interests. Only Britain possessed the economic might and taste for risk to fully exploit this high-technology industry. Technical knowledge of how to build and lay submarine telegraphs remained greedily guarded.

---

[110] Dibner, *Atlantic Cable* (n.13), 87–94; Coates and Finn, *Retrospective Technology Assessment* (n.14), 23.

[111] Bright, *Submarine Telegraphs* (n.13), 90.

[112] Ibid., 78–105; Dibner, *Atlantic Cable* (n.13), 84–149.

[113] Bright, *Submarine Telegraphs* (n.13), 108–109; Bill Glover, "Submarine Telegraphy - Cable Timeline 1845–1900," History of the Atlantic Cable & Submarine Telegraphy. https://atlantic-cable.com/Cables/CableTimeLine/index1850.htm

[114] Daniel Headrick, *The Invisible Weapon: Telecommunications and International Politics, 1851–1945* (New York: Oxford University Press, 1991), 35.

Together with steamships, submarine telegraphy remade global shipping and commodities markets. Telegraphy greatly accelerated the speed of transactions on futures markets, spread their reach globally while simultaneously centering markets on exchanges, converged price differences between these exchanges, and subordinated present pricing of goods to pricing on corresponding futures markets. Although submarine telegraphy quickly smoothed over price differences between far-away markets, it also transmitted economic instability. This helped spread the economic crisis of 1873 globally, a crisis ironically exacerbated by overcapitalization of telegraph companies.[115]

British wire services dominated the mostly British lines, delivering a British perspective to colonies and competitors. Public hopes for peace through constant telegraphic communication, much like hopes for a tranquil market, were never realized. In actuality, diplomatic cables were rare, and quick communication appeared just as likely to inflame international incidents as to quell them.[116] Even these unrealistic expectations of peace were never meant to be universal, as the *London Daily News* made clear upon the initial success of the 1858 Atlantic cable. While extending warm feelings westward, the *News* warned:

> If it be our mission to civilize the dark abodes of cruelty and anarchy in the East; if the empire of the East, as well as the Western Indies, is to be preserved for our rulers; if justice and peace are to succeed lawless rapine and demoniac strife, the electric cord which shall unite England with her Indian Empire cannot be longer neglected.[117]

The British Empire swelled as near instant telegraphic communication optimized the business of subjugation and economic exploitation. During this period of explosive growth of British telegraphy following the JCCST, the wave of British colonial expansion in Africa and attendant colonial wars inspired a number of new connections, assisted by the revival of government subsidies for submarine lines. By the late 1880s, Africa had become a continent of submarine cables, lacking a substantial overland network. The telegraph companies saw no profit in Africa's interior due to the difficulty of constructing lines through such harsh terrain, but also due to the poverty of the peoples in those colonies. Africa's submarine cable network was a uniquely

---

[115] Alexander Engel, "Buying Time: Futures Trading and Telegraphy in Nineteenth-century Global Commodity Markets," *Journal of Global History* 10 (2015): 284–306.

[116] Coates and Finn, *Retrospective Technology Assessment* (n.14), 20, 83, 90.

[117] "The Daily News," *London Daily News*, 18 August 1858, 4.

imperialistic tool. The "nerves of the British Empire" carried troop orders and communicated the political and economic wants of colonists while shutting out indigenous participation.[118]

The telegraph was a premier imperial technology. In the words of Karl Marx: "That unity [of India], imposed by the British sword, will now be strengthened and perpetuated by the electric telegraph."[119] The submarine cable network transformed the oceans into agents of the empire, furnishing Britain with the means to centralize control over its sprawling empire, as long as it secured a steady supply of gutta-percha.

This natural latex, whose name originates from the Malay word *getah* for "gum," comes from the sap of a number of rainforest trees indigenous to Southeast Asia belonging to the genus *Palaquium*. Malayans had traditionally made handles, figures, and waterproof containers from gutta-percha, but by 1846 economic botany brought the material to the attention of William and Werner Siemens and later Michael Faraday, both of whom independently realized its potential as an electrical insulator. While mature trees reached heights of sixty to eighty feet (∼18–24 meters), they also required twenty to thirty years to reach a harvestable size. And even mature trees yielded a pitiful amount of high grade—that is, suitable for electrical work—gutta-percha, just about one pound (∼0.5 kg)[120] This valuable latex ran in unconnected veins through the trunks. To collect it, trees were felled and inefficiently drained through multiple incisions.[121]

Indigenous peoples planned large, months-long expeditions, steeped in custom and ritual, into island interiors in search of gutta trees. Their knowledge was indispensable, not only for finding the trees but also for negotiating with hostile groups living nearby and surviving the dangers of the forest for months at a time. The decentralized nature of collection (as opposed to plantation work) meant that savvy collectors were able to maintain traditional lifestyles and venture out into the forests only when they had an economic

---

118. Iwan Rhys Morus, "'The Nervous System of Britain': Space, Time and the Electric Telegraph in the Victorian Age," *The British Journal for the History of Science* 33, no. 4 (2000): 455–75.

119. Karl Marx, "The Future Results of British Rule in India," in *Marx & Engels Collected Works: Marx and Engels: 1853–1854*, vol. 12 (London: Lawrence & Wishart, 1979), 218.

120. Godfrey, *Hunt for Gutta* (n.45), 279–80. Around one pound is a reasonable estimate of average yield, following Godfrey. However, as she documents, the literature is a confused mess of lower and higher estimates further confused by shifts in techniques, unclear specification of the gutta-percha-bearing species being discussed, and the loss of mature trees.

121. Ibid., 3.

need or high prices made it worthwhile. Eventually, however, as they ventured farther in the hunt for gutta-percha, indigenous groups were dragged into spirals of violent conflict with one another, punctuated by colonial reprisal.[122] After harvesting, the raw gutta-percha made its way through a network of Chinese merchants who brought it to Singapore where European agency houses arranged for it to be sold to a cable manufacturer like Telcon who would further purify it.[123] The heavily mechanized global telegraph industry was completely dependent on the unique skills of indigenous laborers to supply its insulation.

In just a few short decades, what had been a sustainable local practice was transformed into an ecological catastrophe by Western demand. The small yield per tree and the appetite of the submarine telegraph industry proved disastrous for some of the more coveted species of gutta-percha trees; *Palaquium gutta*, also called *Isonandra gutta*, went extinct in Singapore by 1857, and by the mid-1870s in Malacca and Selangor as well.[124] Between 1849 and 1896, gutta-percha imports to the United Kingdom averaged over three million pounds per year.[125] Felling millions of slow-growing trees every year would never be sustainable. The heavily insulated 1865 Atlantic cable consumed around 500 tons of gutta-percha, or one million trees. While insulation thickness would drop from the highs of the 1865 cable, thicker insulation was still common on longer cables. By the turn of the century, a reasonable estimate suggests around fifty million gutta trees had been cut down to supply the submarine cable industry.[126] Colonial extraction of gutta-percha from Southeast Asia only reinforced Western imperialism in the region. Gutta-percha came home in the form of submarine cables, consolidating British control over Malaya (and for their part, Dutch control over the Dutch East Indies) and the gutta-percha trade. Western concerns over the sustainability of the

---

[122] Ibid., 149–50, 246–66.

[123] Ibid., 113.

[124] John Tully, "A Victorian Ecological Disaster: Imperialism, the Telegraph, and Gutta-Percha," *Journal of World History* 20, no. 4 (2009): 572–74.

[125] Eugene Obach, *Cantor Lectures on Gutta Percha* (London: Society for the Encouragement of Arts, Manufactures, & Commerce, 1898), 97.

[126] Obach's estimate of 16,000 tons of gutta-percha used by the submarine telegraph industry grows to over 18,000 tons if we extend his analysis to the cables laid through 1900. While his estimated 100,000 additional miles of government cable is plausible, that it contains 24,000 tons of gutta-percha is not. Following his analysis again, 8,700 tons is a more reasonable estimate, giving a total tonnage just under 27,000. Ibid., 72–73; Glover, "Cable Timeline 1845–1900" (n. 113).

gutta-percha trade never manifested any serious conservation attempts; instead, Europeans were happy to condemn the environmental "vandalism" of their colonial subjects while incentivizing and profiting from it.[127]

Eventually, felling gutta trees was half-heartedly outlawed in British Malaya, but the practice continued unabated.[128] Tapping trees was tried but never caught on due to poor yields. Mechanical and finally chemical leaf extraction made nondestructive gutta plantations viable only in the last years of gutta-percha insulation.[129] And yet despite decades of destructive extraction, gutta trees remained reasonably plentiful deeper in the jungles of Malaya. Supply issues did not doom the gutta-percha market. Ultimately, demand for new cables dropped considerably in the early twentieth century after most long-distance lines had already been completed and practical wireless telegraphy became available. New materials and compounds further dampened demand for gutta-percha. The 1920s brought paper insulation, and then by the 1940s polythene became the standard choice for submarine cable insulation. Gutta-percha lines were rare even by the 1930s, although the Japanese military laid a handful during World War II. In 1950, at the outset of the Korean War, United Nations Forces appear to have laid the last pure gutta-percha cable connecting Tsushima Island and the South Korean mainland.[130]

In an ironic twist, the collapse in demand for gutta-percha has put *Palaquium gutta* under threat once again. Gutta trees and the surrounding forest are now felled because of the land's potential value, primarily as palm oil plantations.[131]

The explosion of cable laying following the publication of the JCCST's report reinforced the Empire, remaking markets, pacifying colonies, and reshaping the global flow of information to fit a British mold. In turn, millions of gutta trees were cut down to coat the nervous system of the British Empire so that the wishes of London might be made real on the other side of the globe.

---

127. Daniel Headrick, "Gutta-percha: A Case of Resource Depletion and International Rivalry," *IEEE Technology and Society Magazine* 6, no. 4 (1987): 13.

128. Tully, "Ecological Disaster" (n.124), 574.

129. Godfrey, *Hunt for Gutta* (n.45), 81–94.

130. Bill Glover, "Cable Timeline 1901–1950," History of the Atlantic Cable & Submarine Telegraphy; https://atlantic-cable.com/Cables/CableTimeLine/index1901.htm; NTT World Engineering Marine Corporation, "Chronology of Submarine Communication Cables in Japan," NTT World Engineering Marine Corporation; www.nttwem.co.jp/english/special/cable_history/chronological_table/

131. S. B. Olander and P. Wilkie, "Palaquium gutta," The IUCN Red List of Threatened Species 2018. https://dx.doi.org/10.2305/IUCN.UK.2018-2.RLTS.T61965223A61965225.en

CONCLUSION

This paper examined a lineage of knowledge transfer from Victorian electrical technology to electromagnetic theory. Knowledge gleaned from particular technologies, submarine telegraph cables and capacitors, were combined by Maxwell to form an idealized stratified capacitor used in both his "Dynamical Theory" and his *Treatise*. Idealized capacitors were significant contributors to the theory presented in "Physical Lines" and when combined with Jenkin's experiments on varying purities of gutta-percha insulation they produced Maxwell's stratified capacitor. The stratified capacitor served as a physical explanation for the phenomena of electric absorption and the basis of a quantitative theory of electric absorption based on inhomogeneous dielectrics. This theory of electric absorption in turn bolstered Maxwell's broader electromagnetic theory, especially his concept of electric displacement, shaping Maxwell's understanding of electrical action in the dielectric. In "Dynamical Theory," constructing the theory required him to distort a foundational component of his electromagnetic theory, Ohm's law. That Maxwell was willing to privilege this theory born from capacitors and cables over Ohm's law demonstrates the importance he ascribed to it. In his *Treatise*, he substantially reworked his approach to preserve his theory of electric absorption without changing Ohm's law, thus reimagining electrical action in the dielectric in a way that would prove central to the Maxwellians.

In addition to theoretical contributions, idealized capacitors had, since "Physical Lines," established a new empirical program with the potential to validate Maxwell's electromagnetic theory of light. In conjunction with new measurements, Maxwell's theory of electric absorption was supposed to shore up this program.

With all the machines in and around these theories, Duhem's insult comparing Maxwellian theory to a factory seems rather perceptive. The remark was actually directed specifically at Oliver Lodge's *Modern Views of Electricity*. Immediately before the factory quip, Duhem writes, "In it [*Modern Views*] there are nothing but strings which move around pulleys, which roll around drums, which go through pearl beads, which carry weights; and tubes which pump water while others swell and contract; toothed wheels which are geared to one another and engage hooks."[132] The mechanics Duhem lists are specific,

---

[132] Duhem, *Aim and Structure* (n.12), 70–71.

referencing a model first developed by Lodge in his 1876 paper "On a Model illustrating Mechanically the Passage of Electricity through Metals, Electrolytes, and Dielectrics, according to Maxwell's Theory." There Lodge makes clear that he has designed the model with the expressed purpose of demonstrating Maxwell's theory of electric absorption: "This is Professor Clerk Maxwell's theory of a composite dielectric."[133] Evidently, electric absorption was central not only to Maxwellian theory but also to the infamous continental derision that it inspired. And as Lodge himself acknowledged, undersea telegraphy was always an inseparable part of the story of electric absorption:

> This is actually observed in the dielectric of submarine cables (cf. Maxwell, art. 366). The insulating material of a cable, in fact, consists of layers of different materials (gutta percha, Chatterton's compound, &c.) laid in strata over the conductor, as if these residual-charge effects were exactly what was wanted to make a good cable.[134]

---

[133] Oliver Lodge, "On a Model illustrating Mechanically the Passage of Electricity through Metals, Electrolytes, and Dielectrics, according to Maxwell's Theory," *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 2, no. 12 (1876): 357. While Lodge admits to some practical difficulties that complicate perfectly fitting the model to Maxwell's theory of electric absorption (the version presented in Maxwell's *Treatise*), those seeking to more clearly picture Maxwell's theory will benefit from consulting Lodge's model. Current is represented by a cord pulled across a series of pullies and through a number of beads/buttons, which are held in place by elastic strings. These buttons represent layers of a dielectric. The extent to which the cord is able to slip, or "leak," through the buttons when pulled reflects the conductivity of a layer. If the cord does not slip at all, then the layer is a perfect insulator. An inhomogeneous collection of buttons, each one stretching its elastic strings in different amounts, illustrates the phenomena of residual charge in an inhomogeneous dielectric. After an initial movement of the cord and a relief of the tension in the elastic strings (after the cord is clamped), they will seemingly regain force after it was apparently exhausted, thereby powering a second motion of the cord (once the cord is unclamped). Ibid., 353–63.

Maxwell apparently appreciated Lodge's model enough that after the paper was published, he wrote to him to suggest improvements. "I received an interesting and humorous and quite long letter from Clerk Maxwell himself! A letter which, I regret to say, through 'moving accidents by flood and field,' has vanished into oblivion. I know that in it he suggested 'lubricating' the beads with Canada balsam, of all strange substances." Oliver Lodge, *Advancing Science: being personal reminiscences of the British Association in the nineteenth century* (London: Ernest Benn, 1931), 43.

[134] Lodge, "Model illustrating Mechanically the Passage of Electricity" (n.133), 358. Many thanks to Bruce Hunt for leading me to the connection between Lodge's model and Maxwell's theory of electric absorption.

Duhem *had* found himself in a factory, but given the origins of Maxwell's theory of electric absorption, in failed Atlantic cables, the JCCST, and Jenkin's experiments at Newall's Birkenhead factory, it should never have come as a surprise. The actual barb behind Duhem's insult—that being associated with industry necessarily suggests unreasonableness—is defanged by the logical path this submarine industry history traced from failure to the JCCST and eventually into Maxwell's theory. Ultimately, the sharp disciplinary boundary between technology and theoretical physics that Duhem takes for granted is actually much more fluid. Even abstract corners of electromagnetic theory were shaped by the practical concerns of submarine telegraphy. Jenkin's experiments at Newall, Maxwell and Jenkin's work for the CES, and even Maxwell's theory of electric absorption, that is, the theory of the compound condenser, cannot be easily labeled as either science or engineering (nor pigeonholed as engineering science). The cables served as experimental laboratories and lessons while Maxwell's theory was itself full of (idealized) technology and intended for practical utility, covering an obscure topic of interest primarily among cable engineers. The supposed boundary between these disciplines is illusory.

Critical breakthroughs in Maxwell's electromagnetic theories are evidently bound up with Victorian technology and thus the broader Victorian context. While the capacitor was undoubtedly a constitutive part of his theory of electric absorption, it was the knowledge bestowed by gutta-percha cable insulation that allowed Maxwell to do what earlier electrical theorists had not. The manual labor of indigenous peoples in the forests of Southeast Asia provided the literal raw materials that inspired Maxwell's theorizing. The economic and imperial concerns that surrounded the first Atlantic cable, left unmet upon the cable's failures, birthed the JCCST and are thus mixed into the genesis of Maxwell's theory of electric absorption. Maxwell's electromagnetic theory is a product of the economy, politics, and technology of the Victorian British Empire. The success of the JCCST in curing the incompetency of the submarine telegraph industry attaches an addendum to this recontextualization of Maxwell's electromagnetic work. The tentacles of the British overseas telegraph network share a bond of kinship with Maxwell's theories. Both are born from the JCCST and concerned with gutta-percha, and consequently the market-shaping, military-moving, forest-razing colonial legacy of Britain's submarine cable network is woven into the fabric of Maxwell's electromagnetic theories.

Acknowledgments

Research and writing of this paper were supported by a postdoctoral fellowship from Department I of the Max Planck Institute for the History of Science. I would like to thank Michel Janssen and my wife Kate for their help over the course of this project, as well as Bill Burns and the *HSNS* editors and referees for their generous contributions.