What Theories Are Made Of:

How Industry and Culture Shaped Maxwell's Theories of Electromagnetism

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Abstract

James Clerk Maxwell's theories of electromagnetism are uniquely Victorian products. Maxwell and his physics have traditionally been viewed as aloof and disinterested, dating to the mid-to-late-19th century, but not party to the cultural, industrial, political, economic, and environmental turmoil of the era. This dissertation examines often ignored corners of Maxwell's electromagnetic theories and those of his successors to demonstrate that they were shaped by the technologies of their time. These technologies, steam engine governors, capacitors, and undersea telegraph cables are each, in their own way, responsible for the varying forms taken by Maxwellian electromagnetic theory. Each of these technologies also has its own history. These histories connect these technologies and thus Maxwellian theory to the newly emerging concept of efficiency, as well as the colonialism, economics, religion, and ecology of the British Empire. Governors, capacitors, and submarine telegraph cables serve as a historiographical bridge, allowing for the exploration of how empire-wide forces shaped the minutiae of Maxwellian electromagnetic theory.

To Katisha

Acknowledgements

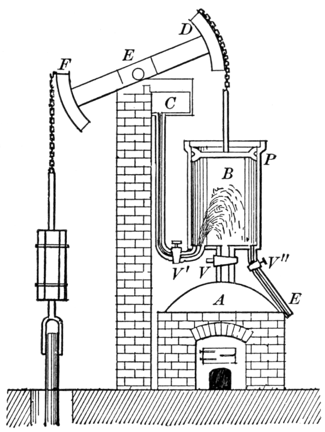
This dissertation would not have been possible without the help, guidance, and most importantly patience of Michel Janssen. Michel diligently read every draft, helped me through any mathematical issues, and encouraged me to reach beyond the history of physics. I would like to thank Jennifer Alexander without whom this dissertation would ultimately have taken a much different, and much impoverished form. Thanks as well to my committee members, Victor Boantza, Jos Uffink, and Alan Love, all of whom I have had the great pleasure of taking classes with and learning from over the course of graduate school. Thanks is also owed to all the friends I've made in graduate school whose conversations have helped make me a better thinker, writer, and historian and whose friendship kept me sane. This goes doubly for Cosima Herter and Charles Midwinter. I would of course like to thank my family for their support and encouragement. Without the mentorship of George Smith I would never have even known about the history of science, let alone gone to graduate school for it. Naturally, I must thank my dog Corey. Many of the ideas in this dissertation were first developed while walking him around Boston and I have no doubt that if he had never been adopted my thinking would have been worse for it. Finally, my most heartfelt thanks to my amazing wife Kate, who has been with me through the ups and downs of graduate school, reading drafts, making suggestions, encouraging me to think more clearly, and enriching every aspect of my life.

A note for any future reader: while I was initially lucky enough to visit incredible archives and libraries in the United States and Europe while researching this dissertation, it was partly written during the global pandemic that swallowed up the year 2020 and an as of yet unknown amount of 2021. Varying levels of lockdowns made additional research particularly difficult and without the digital library services provided by workers at or associated with the University of Minnesota, HathiTrust, Internet Archive, Google Books, and Sci-Hub, it would have been impossible to complete this project.

Contents

List of Figures

Chapter 1



Introduction: Machine-made Physics in the 19th Century

This dissertation aims to release classical electromagnetic theory from its historiographical isolation. James Clerk Maxwell, whose last name is synonymous with the equations of classical electrodynamics, has too often been cast in shoddy caricature as the aloof physicist, insulated from the vitality of his Victorian time and place. The presentism of modern physicists and indeed some historians of physics have colonized Maxwell's work in electromagnetism, claiming him and his work and recasting it in the image of a modern mathematical physics.[1] This is physics comfortable with abstraction and not beholden to any common sense understanding of our material world. Whether this image of theoretical physics accurately describes even 20th or 21st-century physics I will not consider here. It is, however, wholly inappropriate for describing how Maxwell went about developing his theories of electricity and magnetism. This historical imperialism does violence to Maxwell's connections

[1]Whittaker (1987); Darrigol (2000); Everitt (1975).

to the technologies of his time. Through their connections to these technologies, the historical context and contingencies of Maxwell and his electromagnetic theories are revealed: connections to particular concepts which developed alongside these technologies during the Industrial Revolution, to his own personal religious faith, to ecology and economics, and to politics and the non-metaphorical violent imperialism of the British Empire at the height of its powers.

By diving into the messy particulars of the development of Maxwell's electromagnetic theories, the messy historical context upon which his physical theories rest is revealed. Within the historiography, Heinrich Hertz's glib comment, "What is Maxwell's theory?... Maxwell's theory is Maxwell's system of equations"[2] has served as a useful opportunity to demonstrate just how different Maxwell's own understanding and concepts are from our own, despite our continued use of the same equations (in Heaviside's modified form).[3] But Maxwell's theories are much more than just his equations or even his equations and adjoining concepts. They are stained with all the features and facets of Victorian technology, culture, and politics, not just in England and Scotland where Maxwell resided, but out to the furthest reaches of an expanding British Empire.

Yet another snide remark comfortably wraps this all together. In his *Aim and Structure of Physical Theory*, the physicist and philosopher of science Pierre Duhem[4] takes a special pleasure in castigating the British tradition of physical reasoning for its logical discontinuity and its obsession with models. He famously complains that

> In it [English physical theories and Oliver Lodge's *Modern Views of Electricity* in particular] 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. We thought we were entering the tranquil and neatly ordered abode of reason, but we find ourselves in a factory.[5]

While Duhem obviously intended this as a witty insult, the entirety of this dissertation effectively argues in favor of the second half of this comment.[6] Factories, while infrequently tranquil, are of course hardly lacking in order or "reason." Whole disciplines are invested in tweaking their careful coordination and measuring the effects.

[2] Hertz and Thomson (1893, p. 21).

[3] Heaviside (1894).

[4] Duhem also became infamous for his shameful participation in the Dreyfus Affair

[5] While this comment is specifically directed at Oliver Lodge's *Modern Views of Electricity*, the rest of Duhem's commentary suggests he feels similarly about the entire British electromagnetic tradition, Maxwell included. Duhem (1991, pp. 70–71, 86).

[6] I am by no means the first to note that Duhem's criticism was fairly apt, if not as damning as he had intended it. See Hunt (2005, pp. 87–88).

Maxwell's theories of electromagnetism, much like a British factory during the Industrial Revolution, were messy, but also possessed by a certain productive logic and increasingly made use of novel industrial technologies. Far from Duhem's "gallery," full of paintings by an artist who "selected with complete freedom the objects he would represent and the order in which he would group them" (and thus "not a chain of syllogisms"), Maxwell's theories thoughtfully display their guiding methodologies and build on one another.[7] Not quite an assembly line leading to a final theory of electromagnetism, but hardly utter chaos. This methodological care and "reason" comfortably cohabitate with and indeed are shaped by both implicit and explicit references to industrial technology. As a consequence, the technical content and organization of these theories bear the marks of Victorian culture, imprinted on them by these technologies. Much of what made the British Empire of the late 19th century messy, steam engines and telegraphs, newly forming concepts of efficiency, the economics of an industrialized global empire, unique personal Christian faith, imperialist expansion and the maintenance of empire, and accompanying ecological devastation, all of these are reflected in the gory details of Maxwell's evolving theories of electromagnetism. It may not, as Duhem had intended, be an insult for this scientific "abode of reason" to be connected to industrial technologies, but these broader historical connections are often unflattering.

Ultimately, the central argument of this dissertation turns on a reversal of what has generally been the standard narrative of science shaping emerging technologies. Many of the details of Maxwell's electromagnetic theories are constructed through reference to industrial technologies which were themselves shaped by the broader historical context of late 19th-century Britain. A brief historiographical context for this reversal is warranted given the rarity with which the history of technology has been called upon in histories of scientific theory in contrast to the overwhelming number of accounts of technology having been formed out of clever applications of basic science. First, I must summarize how narratives have shifted to highlight the role of technologies in the formation of science, in particular scientific theories, and then even more particularly how the history of the development of classical electromagnetic theory has begun to acknowledge the role of technology. From there an accounting of the relative paucity of any such acknowledgements within the Maxwell historiography will help to situate this dissertation as a contribution not only to Maxwell scholarship, nor only to the history of 19th-century physics, but to the growing number of studies demonstrating the critical role of technology in shaping science, even in the most abstract sectors of theoretical physics.

[7] There is certainly room to argue that the methodology Maxwell promotes within each theory is more scientific propaganda than accurate history; however, Duhem seems content to criticize British theoreticians without assuming they misrepresent their process. Duhem (1991, p. 86); Lazaroff-Puck (2015): Olson (1975).

Treating technology as nothing more than applied science has thankfully been relegated to the status of historiographical relic. That said, the belief that engineering and technology were subordinate to science and thus the history of technology to the history of science, remained common amongst historians well into the second half of the 20th century.[8]

Edwin Layton heralded the beginning of the shift away from engineering as applied science. His analysis of the rise of academic engineering in the 19th century describes engineering not as a product of science, but instead its "mirror-image twin," equipped with its own theoretical and experimental branches (thanks in part to the emergence of engineering science).[9] Layton's work released the history of technology from assumed subservience and even suggested that histories of engineering science could reverse narratives of knowledge transmission between science and technology, reimagining the relationship as truly "symmetric."[10] Layton's usage of the word "symmetric" aside, his initially modest expectations for reclaiming historiographical territory in the name of the history of technology/engineering marked a beginning for a broader historiographical trend.[11] Science-technology narratives need not continue to be a one-way street.

This opposite approach, that technology and engineering might be similarly capable of shaping the content of even "pure" science is thus not new, but outside of the history of scientific instruments examples are still few and far between.[12] The history of theoretical physics, rife with stories of birthing new technologies, has largely avoided narratives that locate the origins of physical theories in technology or engineering. The classic 19th-century counter example is the intertwined history of water and steam engines and the science of thermodynamics presented in Donald Cardwell's *From Watt to Clausius*.[13] As regards the work of the father of thermodynamics, Cardwell notes Sadi Carnot's debt to the column-of-water engine as an analogy helpful in conceiving his maximally efficient heat cycle, i.e., literally lower levels for water to flow towards in an engine illuminate the role of a cold reservoir that will stimulate a "fall of caloric."[14] Similarly, Cardwell highlights the critical importance of Watt's separate condenser in inspiring Carnot's heat sink given that "[t]he need for and true function of the cold body in the operation of a heat-engine

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[8] Alexander (2012).

[9] Layton (1971).

[10] Layton's identification of certain fields as engineering science and outside of science is somewhat questionable. Layton (1971, p. 578).

[11] Layton's "Mirror-Image Twins" seems to have had an outsized influence in shaping the new "interactive" historiography of science and technology relations. Channell (1989, p. xxv, 47).

[12] More current examples are especially hard to come by as distinctions between science and technology break down around the mid-20th century, leaving what has come to be called "technoscience." Layton (1971); Gooday (2004, pp. 128–172); Latour (1987).

[13] Cardwell (1971).

[14] Cardwell (1971, pp. 193–196, 208).

could not be clearly inferred from the workings of the Newcomen engine or of the subsequent Trevithick high-pressure, non-condensing engine."[15] Cardwell highlights a litany of notable technology-led events in the history of thermodynamics: Watt's invention of the so-called expansive principle, emerging concepts of mechanical efficiency, and James Prescott Joule's work with dynamos and their role in his rejection of the conservation of heat and his expression of the mechanical value of heat in the more technologically oriented term "work."[16] *From Watt to Clausius* places the origins of the history of the science of thermodynamics in the work of engineers and in the water and heat engines employed in industries across Britain and continental Europe. Unconstrained by expectations of scientific primacy, Cardwell is free to carve out a richer "symmetric" history of thermodynamics. This narrative is one that acknowledges the role of technology not only as means to better instrumentation, but as one that bears immediately on the concerns of theoretical physicists. More recently, in *The Science of Energy*, Crosbie Smith has achieved a somewhat similar reversal of narrative charting the development of energy physics in the 19th century. Nevertheless, while Smith dutifully reconstructs how energy is "a construct rooted in industrial culture," technology is less present (especially in later chapters) and his work is naturally less focused on the construction of the physical theories that made their respective scientific disciplines and instead on the integration of the concept of energy.[17]

Beyond the unmistakable instances of steam technology shaping the content of thermodynamics presented by Cardwell, there exists a much less cohesive menagerie of examples from the history of that second pillar of 19th-century physics, classical electromagnetism. Here even Cardwell continued to assume a narrative proclaiming electrical technology simply a product of electrical science: "If we agree that thermodynamics was a gift from the power technologies to science and philosophy, the contemporaneous development of electromagnetic field theory was to prove no less important a gift, but in the opposite direction."[18]

Let the following accounting of this technology-to-electromagnetic theory historiography serve as an indication of just how sporadic and disconnected these histories of electromagnetism are, especially as compared to work in the history of thermodynamics. Ronald Kline has shown how engineers struggled to "apply" Maxwellian electromagnetic theory when designing induction motors in the late-19th century.[19] Scientific knowledge, specifically Maxwellian theory, had to be fundamentally trans-

[15] Cardwell (1971, p. 199).

[16] Cardwell (1971, pp. 232–238).

[17] Smith (1998, p. 3).

[18] He did, however, appreciate that this science-technology relationship was not *entirely* unidirectional, noting the role played by early radio technology in the discovery of the ionosphere. Cardwell (1972, pp. 174, 188).

[19] Kline (1987).

formed because in its original form engineers found it "inapplicable" to the process of technological design. Sungook Hong's account of the Ferranti Effect illustrates a similar inadequacy of Maxwellian theory to account for the realities of electrical engineering and the necessity of transforming and supplementing abstract theory to suit the engineer's purposes.[20] Beyond muddying narratives of engineers applying electrical science, Crosbie Smith and Norton Wise's biography of William Thomson (later Lord Kelvin), *Energy & Empire*, was an early and penetrating salvo illustrating how Thomson's scientific work on electromagnetism was deeply influenced by telegraphy.[21] Thomson's 1854 electrical theory grew out of his interest in submarine telegraph cables and remained a guiding force in his work even as his theories grew increasingly more complex.[22] Smith and Wise are also not blind to the economic and political context surrounding Thomson's electrical work, both scientific and engineering, as well as its connection to his own considerable gains in wealth and status.[23] Whereas Smith and Wise focus on Thomson as a unique exemplar of the collision between Victorian science and technology, Bruce Hunt has opened up this historiography, demonstrating that industry touched a much wider variety of electrical scientists.

Within his work on the Maxwellians, Hunt brought to light how George Francis FitzGerald's mechanical "wheel and band" model guided his conceptual understanding and how Oliver Heaviside's work as a telegraph engineer drew him to expand on Thomson's incomplete telegraph theory and to engage with Maxwell's electromagnetic theory.[24] Hunt connected the relatively warm reception of Michael Faraday's field theory in Britain to the attention paid to cable insulation because of the effects of signal retardation on the nation's expanding submarine cable network. Prussia's concurrent disinterest in field theory comes as no surprise, having already dug up its only underground line and lacking any submarine cables of its own.[25] This narrative accords well with the general preference of continental physicists for non-field theoretic approaches to electromagnetism, in particular action-at-a-distance formulations. The final sentence of Hunt's paper alludes generally to the argument I have assembled in Chapter 3: "I would suggest that it is to cable telegraphy, particularly the emphasis it placed on propagation phenomena, that we should look for clues to the direction British field theory took in the years after Faraday."[26] Most relevant for our purposes, Hunt traced the disappearance of hypothetical microphysical elements of the ether from Maxwell's electromagnetic theory between his second and third papers to his

[20] Hong (1995).

[21] On this same theme of knowledge transfer from technology to science, Smith and Wise also cover the influence of the steam engine on Thomson's work on thermodynamics. Smith and Wise (1989).

[22] Smith and Wise (1989, pp. 445–494, 667–683).

[23] Smith and Wise (1989, pp. 649–722); Wise (1988).

[24] Hunt (2005, pp. 65–72, 78–87).

[25] Hunt (1991).

[26] Hunt (1991, p. 15). Similar arguments are advanced in Smith (1998).

participation in the Committee on Electrical Standards' effort to standardize electrical units on behalf of the telegraph industry. The loosely operationalist mindset of the engineers that Maxwell worked alongside to develop the "ohm," the unit of electrical resistance, is supposed to have been carried over into his scientific methodology, refocusing his attention "not on devising hypothetical mechanisms but on formulating demonstrable relations between quantities he could measure and manipulate."[27] The theory described in his third electromagnetic paper, "A Dynamical Theory of the Electromagnetic Field," is the result of this methodological shift.[28] More recently Daniel Jon Mitchell has illustrated how this very same context, working with engineers on the Standards Committee, inspired Maxwell's invention of the dimensional formula. While Hunt traces a somewhat elusive but critical methodological shift back to an origin among engineering work, Mitchell describes a more concrete product of this work, namely our concept of dimensions and its attendant misunderstandings.[29]

Whatever their differences, Hunt and Mitchell's accounts are a lonely pair within a sprawling Maxwell historiography. The relationship between James Clerk Maxwell's science and technology has not been seen as a fertile area of study. There is of course an extensive literature covering Maxwell use of analogies to, or idealized forms of real or imagined mechanisms in the construction of his electromagnetic theories.[30] But as Otto Mayr notes, "[t]echnological utility simply was not a motive in his scientific work."[31] Maxwell's idealizations and analogies between contrived mechanisms and electromagnetic phenomena were rarely dependent on whether or not the analogous mechanism was in any way useful. A notable exception uncovered by Daniel Siegel is Maxwell's use of idealized capacitors in the scaffolding[32] of his second electromagnetic paper, "On Physical Lines of Force."[33] A modification of this technological idealization contributes significantly to arguments advanced in this dissertation. Historians, present company included,[34] have chosen not to pursue any connections between Maxwell's models and analogies and any material technologies that may have inspired them. As far as the historiography is concerned, Maxwell's models are purely scientific idealizations or thought experiments, not technologies with any material existence or history. Idealization aside, as Hunt and Mitchell have shown, Maxwell did perform eminently practical work to standardize electrical units for scientists and the telegraph industry alike and this technologically motivated work bled into his more

[27]Hunt (2014, p. 305).

[28]Hunt (2014); Hunt (2010, pp. 107–109).

[29]Mitchell (2017).

[30]A few examples include: Siegel (1991); Harman (2001); Wise (1979); Turner (1955); Morrison (1992); Chalmers (1973); Kargon (1969); Hon and Goldstein (2012); Lazaroff-Puck (2015).

[31]Mayr (1971b, p. 219).

[32]Janssen (2019).

[33]Siegel (1991, pp. 85–119).

[34]Lazaroff-Puck (2015).

abstract scientific theorizing. In the same year Mayr originally doubted Maxwell's interest in "technological utility," Edwin Layton commented how the physicist "consciously attempted to contribute to technology," even if engineers initially found his work difficult to understand.[35] Mayr's statement may be an exaggeration, but is this all? Is Maxwell's Standards Committee work the only point of knowledge transfer from the blossoming electrical technology industry into Maxwell's science? Given the attention it has attracted, we might be excused for thinking so.[36]

Unlike Thomson, Maxwell never worked in an engineering capacity for any firm, nor did he make a small fortune on his inventions. Unlike the Glasgow professor, Maxwell did not aim to raise generations of engineers. Maxwell's Cavendish Laboratory was a hot spot for metrology, but the goal of these measurements was still primarily scientific. Whenever he could, he retired to his inherited estate Glenlair to work and live the life of a country gentleman. He appeared every bit the aloof physicist, unperturbed by the Industrial Revolution that had upturned the nation since before his birth in 1831. If there were to be a 19th-century British physicist who stood a chance of being relatively unaffected by the technological upheaval of his time, whose science could be deemed well insulated from the material concerns of the factory, it would seem to be Maxwell.

Figure 1.1: Maxwell's Scottish Estate Glenlair[37]

And yet, some of the most novel elements of Maxwell's theoretical work are constructed out of the technologies of his time. Over the course of the two case studies presented in this dissertation, I demonstrate that mechanical and electrical technologies shaped the details of Maxwell's most famous contributions to electromagnetic

[35]Layton (1971, p. 577).
[36]Schaffer (1992); Schaffer (1995); Mitchell (2017); Hunt (2014); Hunt (1994).
[37]This photo was taken before the property was gutted by a fire in 1929. at Glenlair Trust (2012).

theory. I do not mean technology here in any vague sense, rather in both cases I examine specific machines and their particular historical contexts to appreciate the manner in which they affected the development of Maxwell's theories of electromagnetism.

In the first case study presented in Chapter 2, a peculiar speed governor designed by the Siemens brothers helped forge electromagnetic concepts in the mold of its mechanical components and relations and guided Maxwell's analysis by virtue of the governor's construction. The governor's unique motion meant it was well-suited to exemplify electromagnetic phenomena, while its extreme efficiency (as compared to competing governors) exemplified the nearly perfect efficiency of the electromagnetic ether. Maxwell's scientific commitments as well as his own personal religious faith demanded such a uniquely efficient machine to serve as the analogue of the electromagnetic ether. This particular choice of technological analogue, reconstituted in his work as his "flywheel," not only affects the understanding of concepts presented in the theories in which it appears, in at least one instance it also determines Maxwell's choice of mathematical analysis. Nevertheless, Maxwell's flywheel has largely been ignored in the historiography.[38] The flywheel (and thus the governor) endured as a piece of physics pedagogy, illustrating the same electromagnetic relations as in Maxwell's original analogy, long after his untimely death. This longevity was helped in part by Maxwell's decision to have a demonstration device built for the Cavendish, such that the very real physical machinery that had become idealized in Maxwell's work was again translated into a material object. The design of the governor, its focus on mechanical efficiency even at the cost of economic efficiency marks its connection to the evolution of the concept of efficiency.

The concept of efficiency itself is in turn born out of a wide-ranging revolution in thought occurring in the early 19th century across fields as varied as political economy and astronomy.[39] The physical theory Maxwell builds out of the governor is thus contingent not only on the design choices of the Siemens brothers and the commercial failure of a governor they created, but also upon the broad intellectual shift that gradually brought efficiency into relief and even Maxwell's own Christian faith. Two of Maxwell's most famous electromagnetic papers, "On Physical Lines of Force" and "A Dynamical Theory of the Electromagnetic Field," rely to varying extents upon the Siemens governor. Accordingly, the theories presented in each paper are products not only of their connection to this technology, but also products of the various cultural forces that shaped Maxwell's thinking and those that shaped the Siemens governor.

The second case study, presented in Chapter 3, links Maxwell's electromagnetic

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[38]See footnote 110 for a comprehensive account of the extent to which the flywheel has been ignored in the Maxwell historiography.

[39]Alexander (2008); Wise and Smith (1989a); Wise and Smith (1989b); Wise and Smith (1990).

theory to the failures of the initial Atlantic and Red Sea submarine telegraph cables as well as to idealized capacitors. Often ignored sections of Maxwell's "Dynamical Theory" as well as his *Treatise on Electricity and Magnetism* were inspired by the phenomena of "electric absorption," studied by Henry Charles Fleeming Jenkin in his work on submarine telegraph cables and incorporated into Maxwell's theory through the workings of idealized capacitors. These elements of Maxwell's theory deepen the explanatory power of and prove to be central to the stability of Maxwell's electromagnetic theories. The later point is one which Maxwell duly recognizes, going as far as sacrificing the conventional presentation of Ohm's law to preserve this stability. Maxwell's novel concepts of electric displacement and electric action within a dielectric shift with Maxwell's evolving treatment of electric absorption and capacitors. Capacitors have both an earlier connection to Maxwell's theoretical work, appearing in "On Physical Lines," where they help create the displacement current, and feature prominently in the work of Maxwell's successors. There under the guise of the "leaky condenser," electric action in the dielectric was once again examined to make sense of conduction, until Maxwellian theory collapsed in part due to this conduction confusion. In Maxwell's work, capacitors also inspired an (unsuccessful) experimental program intended to verify his electromagnetic theory of light.

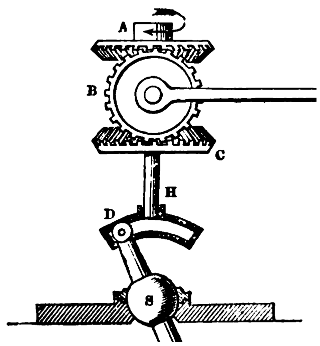
Maxwell's incorporation of studies of submarine telegraph cables, work that fundamentally shaped his electromagnetic theories, was itself contingent on the failure of specific cables, namely the first two Atlantic cables and the Red Sea cable. Jenkin's work was commissioned by the private-public Joint Committee on the Construction of Submarine Telegraphs, which was desperate to understand these costly failures and to save the submarine telegraph industry and those dependent on it from continuing along this same path. The Committee report including Jenkin's testimony and studies binds Maxwell and the Maxwellians' theories to the political and economic forces behind the construction of these failed cables and the hope for improved future cables. The financial and imperial concerns of private business and an expanding British Empire that drove the creation of the Joint Committee are thus stamped upon the physics Maxwell created out of the report that the Committee produced. In addition to novel physics, the Committee also did mostly achieve its goal of securing the submarine telegraph industry against 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 globalized British economy. Now troop movements, local bureaucracy, and commodity prices could all be managed from London. To supply this appetite for new cables, forests of Southeast Asian colonies were pillaged, millions of gutta percha trees felled, to supply the natural latex needed for thousands of miles of cable insulation. Maxwell's electromagnetic theories are kin[40] to the world made by this fix, one of violent British imperialism, global markets, and

[40] A close but explicitly non-causal relation.

ecological disaster.

These case studies aim to establish for Maxwellian electromagnetic theory what Cardwell's *From Watt to Clausius* did for the early history of thermodynamics. They might also be described as doing for Maxwell what Smith and Wise have done for Thomson: present a coherent narrative demonstrating how the guiding concepts and mathematical minutiae of theoretical development were contingent on material technology, engineering, and social forces, i.e., grounding the highly technical content of their physical theories in the technical and non-technical historical context of their lives. The Siemens governor, capacitors, and submarine telegraph cables were all conscripted by Maxwell to aid in his construction of his new theories of electromagnetism. I will use the technological context to bridge the gap between the broader history of late-19th-century Britain and the British Empire and emerging theories of electromagnetism. The historical contingencies of the technologies are shared with the theories they shape, allowing us to locate a shifting range of cultural and political forces within Maxwell's mathematical physics. Consequently, Maxwell is no longer the disinterested cartoon physicist that appears in the historical asides of so many physics textbooks, untouched by time and place. He and his electromagnetic theories are recast as products of British industry and commerce as well as British politics. A close look at Maxwell's physics reflects the broad historical context in which it was produced. Classical electrodynamics is inescapably Victorian.

Chapter 2



Governing Physics: The Siemens Chronometric Governor, Efficiency, and Maxwell's Electromagnetic Theory

2.1 Introduction

> The governors constructed on this principle are remarkable for their instantaneous action upon the supply-valve of the engine. . . to the fullest extent. . . maintaining the regulated machine at the same speed, when the load reaches its maximum, as when it is at its minimum.[1]

The new engine governor designed by brothers William and Werner Siemens represented an extraordinary improvement over the devices which had preceded it, in particular the ubiquitous Watt governor. When complemented by a Siemens governor, engines, be they steam engines or water wheels or some other power source,

[1]Siemens (1866b, p. 659).

could be expected to run smoothly at a given speed without the kinds of fluctuations that plagued competing designs. Above all, the Siemens brothers' invention promised to remake its users into paragons of efficiency and precision. And yet, the governor sold poorly and was eventually abandoned. The governor's extreme mechanical efficiency was novel, but after considering the governor's high cost and questionable reliability, industry simply did not see it as a sound (economically efficient) investment. In the mid-19th century, the concept of efficiency was still being forged and despite the rejection of the Siemens governor, engineering remained at the forefront of this development.

While industry did not appreciate the mechanical efficiency and precision of the Siemens' governor, the scientific community did. First, Astronomer Royal George Biddell Airy, "whose tastes incline him to study the best constructions adopted by engineers, determined to adopt, for the regulation of the clock-work [in his transit instrument], the principle of the regulator known by engineers under the name of 'Sieman's [*sic*] Chronometric Governor'."[2] The governor was installed at the observatories of Liverpool, Cambridge, and Greenwich where its service life outlasted that of its inventor.[3]

The Siemens governor also attracted the attention of James Clerk Maxwell. This was due in part to the unique arrangement of the governor's mechanism as well as its prodigious mechanical efficiency. As a consequence, Maxwell's electromagnetic theories and the Siemens brothers' governor are connected by shared dynamical motions and by the concept of efficiency itself. Maxwell's theories are shaped by (an idealization of) the governor and thus understanding the governor and its connections to Maxwell's theories helps us to better understand the formation of electromagnetic theory. Insofar as the concept of efficiency makes up part of this connection, the development of the concept and the development of the theories are intertwined and they illustrate both the connection and divide between engineering and physics.

Efficiency is such a pervasive feature of modern life that it can be difficult to imagine a world without it, or at least one in which the concept is still developing.[4] Our own understandings of the world are so beholden to efficiency that what is "efficient" has often come to stand in for what is good or right. It has become so inextricable to modern life that it is difficult to imagine our economy, our technologies and sciences, or our politics as pursuing anything other than efficiency in some sense (or at very least giving lip service to the pursuit). Efficiency or attempts at it sit behind some of the more stunning achievements of the 20th and 21st centuries as well as some of the most profoundly destructive and evil manifestations of those same cen-

[2]Frederick and Herschel (1849, p. 76).

[3]Pole (1888, p. 111); Hartnup (1848, p. 35).

[4]This paper's investigation of the development of efficiency borrows heavily from Jennifer Alexander's *Mantra of Efficiency*. Alexander (2008).

turies. Efficiency finds itself just as applicable to an analysis of how to distribute social welfare or humanitarian aid as it does to planning an automobile production line or to masterminding the genocide of human beings according to race, religion, or ability. Conceptions of efficiency might help blunt a pandemic, but could just as easily make the same pandemic worse, letting vulnerable people die in an attempt to preserve profits. But this efficiency-obsessed world has not existed for very long, and in coming into being, the concept helped to shape the time in which it matured.

This chapter is concerned with a relatively benign instance of efficiency shaping 19th-century electromagnetic theory. There is no great moral conundrum behind *this* embrace of efficiency, instead it is an accounting of a small part of efficiency's eventual conquest of society. Here a novel technology, the Siemens' chronometric governor, the supposed utility of which relies on its remarkable mechanical efficiency, is imported into and ultimately shapes Maxwell's evolving electromagnetic theories. Maxwell famously made use of a mechanical model of the electromagnetic ether in his second major paper on electromagnetism, while in his third paper he demoted the status of his now pared-down mechanical model to a mere analogy. At the heart of the earlier model was the Siemens governor and after relegating the mechanical system to an analogy, the governor was all that was left. In both papers, although particularly in Maxwell's "Dynamical Theory of the Electromagnetic Field," intricate details of Maxwell's electromagnetic physics were shaped by the governor.

Why this device? What was it about the Siemens governor that attracted Maxwell to it initially and what about it encouraged him to keep it as part of his new electromagnetic theory after he exorcised the other mechanical elements of the earlier model? The answer is twofold. First, the unique mechanical action of the Siemens differential governor made it a very clear analogue and illustration of electromagnetic relations in the field that proved useful in grounding Maxwell's development of his theory. Second, the governor's purported advantage over competing designs was its supreme efficiency of operation, an advantage that Maxwell believed made it well suited to exemplify the naturally efficient electromagnetic ether itself. After this transfer of knowledge, Maxwell's electromagnetic theory eventually became the standard description of electromagnetic phenomena, while the governor faded into obscurity. It would seem then that the value of efficiency was not yet universally appreciated, or more accurately as efficiency evolved, different meanings were appreciated differently in different disciplines. Nevertheless, even as the governor receded into the background, its influence and consequently the legacy of efficiency were permanently stamped upon Maxwellian electrodynamics.[5]

[5]The central sections of this chapter pertaining to Maxwell's mathematical physics are for the most part borrowed from an earlier paper of mine, Lazaroff-Puck (2015). That paper was entirely concerned with tracking Maxwell's changing methodologies across his electromagnetic theories and correcting the Maxwell historiography that had ignored the physical analogy to a flywheel buried in

Section 2.2 briefly describes the evolution of the concept of efficiency and its outgrowth from the conceptual shift to temporal analyses. It culminates in a discussion of the arrival of a recognizably modern incarnation of efficiency in the late-19th century. Immediately following, in Section 2.3, I investigate the development of the Siemens brothers' chronometric governor, its supposed advantage over competitors as a preternaturally efficient apparatus, and its abject failure commercially. Section 2.4 first covers the intersection of Maxwell's Christian faith and its influence on his commitments regarding certain physical entities, in particular the electromagnetic ether. Then I examine the role of the Siemens governor as a critical part of Maxwell's ether model in his 1861–1862 paper "On Physical Lines of Force" and the scientific and non-scientific justifications for Maxwell's choice of mechanical model. In Section 2.5, I describe Maxwell's growing desire to create a new, more stable (less hypothesis-based) foundation for the novel electromagnetic results he achieved in "Physical Lines." In building this new theory, Maxwell relies heavily on an analogy to a flywheel, which is shown to be a simplified reimagining of the Siemens governor. Other than the final two sections, each section and subsection that follow expand on the role the flywheel/governor played in shaping Maxwell's "Dynamical Theory."

Section 2.6 covers the mechanical properties of Maxwell's flywheel, how it works and its specific components, both as an isolated mechanism and as an expanded flywheel system. The section highlights the concept of reduced momentum, which by analogy becomes a crucial feature of Maxwell's electromagnetic project. It concludes with a discussion of the example that Maxwell uses to clarify the flywheel's link to electromagnetic phenomena. The section also presents additional evidence for the link tying together the flywheel and the Siemens governor. Section 2.7 lays out the analogy between the mechanical flywheel and electromagnetism, drawing the necessary connections between components of the flywheel and concepts in electromagnetic theory. I then consider two specific cases where circuits act on one another through the field: Subsection 2.7.1 demonstrates the induction of a current in a passive circuit by changes in another circuit (first by alteration of its current and then by setting the circuit in motion). At the same time this section illustrates how the relevant concepts in electromagnetism are grounded in mechanical understanding by analogy to the flywheel. Subsection 2.7.2 looks at Maxwell's derivation of an equation of power and the implications his mechanical analogy has for his concept of the elec-

Maxwell's "Dynamical Theory." Little mind was paid to considering the flywheel as a technology, nor did I provide much history of the device itself. Not only does this chapter seek to uncover the history of the mechanical governor that (in the form of the flywheel) underpins Maxwell's theoretical work in "Dynamical Theory," it also seeks to understand the cultural forces that birthed this technology and Maxwell's attraction to the governor as a mechanical analogue for electromagnetic phenomena. While the analysis of the flywheel's role in "Dynamical Theory" is as important to this chapter as it is to my earlier paper, the narrative and arguments presented here are considerably different and less constrained by the history and philosophy of physics.

tromagnetic field by locating energy in the field itself. The conclusion of this section briefly parses Maxwell's justification for reversing the use of his mechanical illustration to now analyze how the field affects circuits. Section 2.8 investigates this shift to the field acting on circuits and the way in which Maxwell uses the flywheel to guide his piece-by-piece construction of a generalized equation for induced electromotive force. Subsection 2.8.1 serves as an introduction to electromagnetic momentum and electromotive force, considering these concepts localized at a point in the field.[6] Subsection 2.8.2 reconstructs Maxwell's derivation of the electromagnetic momentum of a circuit, illustrating the role of the flywheel in guiding Maxwell's mathematics. This section goes on to examine Maxwell's derivation of an expression for magnetic force in terms of electromagnetic momentum, which will prove useful in later sections. Subsection 2.8.3 illustrates how the flywheel aids the construction of the first piece of a generalized equation of induced electromotive force on a circuit. Subsection 2.8.4 reconstructs Maxwell's derivation of the final piece of this generalized equation for induced electromotive force, the induced electromotive force on a moving conductor. In the most dramatic example in this chapter, the mechanical flywheel is shown to direct Maxwell's analysis of this particular electromagnetic phenomenon, suggesting the inclusion of terms which are ultimately unnecessary for the purposes of this derivation.

The penultimate section, Section 2.9, describes the legacy of the flywheel/governor as an instrument of physics instruction for budding scientists and engineers. Finally, section 2.10 offers brief concluding remarks summarizing the findings of this chapter.

2.2 An Efficient Account of Efficiency

With Jennifer Alexander's *The Mantra of Efficiency* as a guide, we can begin to separate from our modern, efficiency-suffused context and begin to uncover the gradual evolution of the concept. The term's origins are Aristotelian. The efficient cause rounds out the four "causes of motion," describing what brings something into being or instigates that thing's changes. Early uses of efficiency reflect that origin. The term was used to describe the intrinsic power to produce change or shape something.[7] Our conception of efficiency, or at least qualitatively relating inputs to outputs, has its own origin in Archimedes and Pseudo-Aristotle's analyses of simple machines and later through lines in the work of Galileo, among others.[8] However, before attempting

[6]What Maxwell calls electromagnetic momentum is what is now called the vector potential **A**. It should not be confused with the modern definition of electromagnetic momentum, $\varepsilon_0(\mathbf{E} \times \mathbf{B})$, where ε_0 is the dielectric constant *in vacuo* and **E** and **B** are the electric and the magnetic field, respectively.

[7]OED (2020).

[8]Alexander (2008, pp. 1–14); Mitcham (1994, pp. 225–228).

to retrace the development of efficiency, I must also clarify a seismic intellectual shift early in the 19th century, one which shaped not only the concept of efficiency but reoriented a wide array of human knowledge-making.

The gradual maturation of efficiency is in part a natural outgrowth of a broader shift across nearly the entire spectrum of 19th-century thought. This shift has been described as a change from static to dynamical thinking, an injection of temporality, or "a move from balancing models of natural systems to engine models."[9] But what is most critical for the purposes of this chapter is the way in which this conceptual shift was digested, what Norton Wise and Crosbie Smith have called the "discourse of work and waste."[10] It is in the process of this discourse that the concept efficiency begins to take shape.

The 19th century saw political economy move from familiar concerns of reaching ever more optimized states of economic balance to an economy where growth could be expected to continue without end. Following Maxine Berg, Smith and Wise find an inflection point in the work of David Ricardo. While Ricardo ultimately remained firm in his belief that economies would eventually trend towards some equilibrium state, he also admitted the destabilizing and progressive effects of mechanization. Ricardo retained his pessimistic view that inevitably some economic equilibrium would be reached that would keep the working poor forever in misery, but in the short term machinery could generate new wealth; "he [Ricardo] contributed to a growing perception that machinery did not act merely as an instrument of the division of labour—thus of balancing—but also as a force in its own right, albeit an accidental force which disturbed the natural equilibrium."[11] In the mid-19th century, the assumption of natural equilibrium behind balance models of political economy collapsed and they were replaced by progressive growth models. More politically radical than most of his peers, the famed mathematician and inventor of the analytical engine, Charles Babbage's obsession with engines led him to a vision of an ever expanding economy driven by mechanization and the economies of scale it would make possible. The working poor would not be relegated to the miserable existence Ricardo considered inevitable, rather they would find better occupations on "higher levels [of] the hierarchy of labour."[12]

Similar changes occured within physical astronomy as Laplace's nebular hypothesis gained popularity. The solar system was supposed to have come into being through a gradual process of cooling, and according to new observations planets would eventually end up being consumed by the sun as orbits degraded. Observations of Encke's Comet suggested it was being slowed by some resisting medium. If the comet's mo-

[9] Wise and Smith (1990, p. 221); Alexander (2008).
[10] Wise and Smith (1989a); Wise and Smith (1989b); Wise and Smith (1990).
[11] Wise and Smith (1989b, p. 394).
[12] Wise and Smith (1989b, p. 414).

tion was retarded by the medium so too must the motions of the planets; their orbits would, in time, decay. The stability of the heavens was not permanent. This accorded well with views already held by geologists, that the Earth's own history was one of gradual cooling. Astronomy and geology were linked through heat flow and adjoining causal explanations of phenomena.[13]

Natural history in the hands of Charles Darwin also managed to escape balance. Natural selection did not balance those species that were selected for with those selected against. Branches of Darwin's tree of life extended in only one direction, it "had no roots."[14] The end of a particular path, i.e., an extinction event, was not an adequate balance for continued descent with modification and adaption.[15]

The science of heat itself needed to evolve to match this intellectual shift. Even though thermodynamics was built up (much more directly) from the same guiding model, the steam engine, it did not initially derive the same lessons, or at least took longer to process them. Sadi Carnot's analysis of the work of contemporary engineers, combined with his own father's earlier work describing the maximum efficiency of (non-heat driven) machines birthed a general theory of heat engines. What Sadi Carnot produced was a theory of heat engines dependent on temperature difference. Engines performed work when a quantity of heat passed from hot to cold and power was derived from this flow of heat. In the case of a steam engine, this meant heat (for Carnot, caloric) passing from the fire stoked beneath the boiler into the expanding steam and finally being reabsorbed in the engine's condenser. The same amount of heat was involved in each step, i.e., no heat was consumed to produce work, heat was conserved. Carnot's conception of heat engines and the attendant conservation of heat began to gain in popularity during the 1830s and 1840s (in a more mathematically rigorous form presented by Emile Clapeyron). It was James Prescott Joule's theory of the equivalence of heat and work and reevaluation of Carnot's theory by Rudolf Clausius that finally set thermodynamics on par with the other intellectual revolutions brought about by the steam engine.[16]

Joule's experimental work during the 1840s, inspired by his interest in electrochemistry, led to his construction of a device in which mechanical work produced an electric current which could then generate heat. Joule quickly superseded this initial illustration of the mechanical equivalent of heat with a more direct demonstration wherein a paddle-wheel device was used to generate heat through mechanical work via friction. Consequently, he developed a physical theory emphasizing the mutual convertibility of heat and work, his own thinking laden with ideas of the balance and order implied by forces' inter-convertibility and thus indestructibility.[17]

[13]Wise and Smith (1989b, pp. 398–400, 424–434).
[14]Alexander (2008, p. 63).
[15]Alexander (2008, pp. 60–64).
[16]Harman (1982, pp. 45–71).
[17]Harman (1982, pp. 35–41); Sibum (1995).

Clausius recognized the apparent contradiction between Joule's results and Carnot's insistence on the conservation of heat. Simply put, if Joule's results regarding the equivalence of heat and work were to be believed, then some heat must be lost in the operation of a heat engine. Heat was expended to produce work. Nevertheless, despite highlighting the conflict between Joule and Carnot, Clausius did not feel any pressure to choose between them. Rather, by recentering the importance of Carnot's contributions on the directionality of heat flow and scrapping ideas regarding the conservation of heat, Clausius found a fruitful compromise between Joule and Carnot. Some quantity of heat moved from hot to cold, but some portion of heat was also expended to produce work. Restated by Clausius, this compromise theory became the first and second law of thermodynamics, fundamentally reshaping the core of thermodynamics. Thus remade, thermodynamics was (finally) free to fully embrace the example of the technology that had birthed it.

Heat conservation had burdened thermodynamics with vestiges of universal balance despite the theories' origins in heat engines. Only after shedding this connection could thermodynamics evolve fundamentally temporal, irreversible relations like the second law. In the hands of William Thomson, Clausius' compromise was further reinterpreted, the portion of heat not converted into work was now supposed to be irreversibly dissipated. For Thomson this reconceptualization figured into his larger interest in energy physics, but here it highlights his full digestion of the shift from balance to engine models. Heat and energy were not destroyed but were dissipated, i.e., they could be wasted. Practical examples of waste in for example, steam engines, had become deep lessons about the true nature of the physical world; "Heat, and heat engines, were supplying a new epitome for scientific explanation in natural philosophy as in political economy."[18]

Ideas embracing decay of the material realm found partners among radical Christians and conservatives who begrudged the apparently diminished (or nonexistent) role of God in a world subject to equilibrium assumptions. The decay of the universe mirrored the material decay on Earth and even the moral decay of those in states of sin. William Whewell was early to the new view of the universe and natural laws as temporary and wasteful. Laplace's nebular hypothesis combined with the end suggested by Encke's comet implied a moment of creation. Laplace's ideas which had once been the height of atheistic heresy had been absorbed into a new Christian piety. Whewell's conservatism gave him some reason for hope, but even more cause for concern, pernicious waste was everywhere and had to be avoided. Avoiding waste was a moral imperative as mankind's time in a deteriorating universe was necessarily finite.[19] Meanwhile, Babbage's politics led him to celebrate the potential for growth and improvement ahead. While Whewell pressed for moral action by appropriate

[18] Wise and Smith (1989b, p. 429); Harman (1982, pp. 45–71).
[19] Wise and Smith (1989b, pp. 398–400).

authorities to stave off societal degradation and make the most of nature's inevitable decay, Babbage extolled the virtues of scientific/engineering knowledge that would make for a better world for all. Babbage was still cognizant of waste and interested in improving efficiency, as evidenced by his proposed improvements for iron furnaces that aimed to reduce power wasted on compressing gases that did not contribute to coal combustion.[20]

And yet, as Smith and Wise note, for all his obsession with machines, Babbage never got around to adding more exacting machine-like units to his discussions of human labor. This was in part because the quantity of "work" was not yet standardized. There were numerous options for work-like concepts to choose from, and a variety of names for each, some more popular in Britain, others finding a home on the continent. "Work" did not triumph in Britain until the mid-century. Just as important, however, was the relative scarcity of industrial machines during the early-19th century. The dominance of human labor in Britain at the time meant that rather than measuring the productive capacity of human beings in mechanical terms, machines were measured against their human competitors. Machines were effectively measured in terms of their comparative efficiency versus some number of men working for some period of time. Insofar as the men's wages were known, such measures of comparative efficiency were not only crude measures of relative working power, but also of economic efficiency, measuring the value of machines against the labor value of human workers.[21]

And so, at the dawn of the 19th century, efficiency was far from having conquered the world. Alexander highlights the emergence of quantitative conceptions that resemble prototypes of efficiency's current meaning in the course of famed civil engineer John Smeaton's experiments on waterwheels in the mid-18th century and in the Franklin Institute's similar investigations nearly a century later. While neither Smeaton nor the Franklin Institute used the term efficiency, both produced ratios of the waterwheels' effects to the power consumed. Smeaton determined the velocity of the waterwheel via a counterweight system meant to match its speed to that caused by the force of water and eventually calculated virtual head, "a dynamic measure" which "led him into more fundamental discussions of how to characterize and measure motion."[22] By contrast, the Franklin Institute experiments not only lacked Smeaton's philosophical motives, they were largely disinterested in generalization at all. Instead, voluminous tables were produced so that any interested engineer could find figures for any number of specific waterwheel configurations. Most critically the data that made up these tables were obtained by comparing static before and after states, setting up a clear distinction of statics versus dynamics embedded in each

[20] Wise and Smith (1989b, pp. 410–421).
[21] Wise and Smith (1989b, pp. 416–417).
[22] Alexander (2008, pp. 21–23).

quantitative prototype of efficiency.[23] These differing approaches of Smeaton and the Franklin Institute reflect the two sides of the static/dynamic shift in 19th-century thought discussed above, albeit in a reversed chronology.

Statics, dynamics, and waterwheels aside, Smeaton and the Franklin Institute did not quite reach our modern concept of efficiency, nor did either make use of the term itself. Both created a ratio of inputs to outputs, but neither could settle the issue of what sorts of units should enter into this ratio, nor was there a clear understanding of bounds on the ratio.[24] Contemporary to Smeaton, the "efficiency" of water engines was commonly represented as a fraction describing to what extent it could recover the driving force (water) to its original position.[25] More modern units would have to wait until the second half of the 19th century, for the synthesis of Sadi Carnot's idealized heat engine and Joule's insights into the mechanical equivalent of heat, as discussed above.

For steam engines operating at the valuable mines in Cornwall, the lack of nearby sources of coal led to ludicrously high prices and thus a strong pressure to construct the most efficient engines possible. The extreme conditions imposed by having to import coal by sea led to a fanatical attention to each and every detail of Cornish steam engines in an attempt to improve overall efficiency. Reducing coal consumption and thus maximizing mechanical efficiency was the central concern of Cornish engineers.[26] A common representation of the proto-efficiency of steam engines in the early-19th century and one standardized by Cornish engineers was "duty." This was a measure of the weight of water raised per weight of coal consumed (both in lbs).[27] While ostensibly a measure of mechanical efficiency, "duty" was, like Babbage's measure in terms of man hours, also an expression of economic efficiency given that coal was by far the largest cost incurred in operating an engine.[28]

Eventually, in the hands of the consummate practitioner of engineering science, William Rankine, efficiency came into common use with a meaning mostly alike our modern understanding. Rankine's conception of efficiency was not only couched in recognizably modern units of work and energy, it also included quantified economic concerns.

Bridging the gap between science and engineering, Rankine found himself struggling to establish his reputation in either, working hard not to alienate powerful university interests or industrialists and practicing engineers.[29] In an early contribu-

[23] Alexander (2008, pp. 15–32).
[24] Alexander (2008, pp. 15–32).
[25] Cardwell (1971, pp. 198–199).
[26] Cardwell (1971, pp. 154–157); Nuvolari (2004).
[27] Cornish steam engines were primarily occupied by pumping water out of ever deeper metal mines.
[28] Nuvolari (2004, p. 352); Cardwell (1993).
[29] Marsden (2013).

tion to the Mechanical Science section of the British Association for the Advancement of Science (BAAS), Rankine constructed an equation containing both purely technological or scientific quantities as well as purely economic ones, fusing them together such that the resulting equation yielded optimal dimensions for Cornish steam engines, "which. . . shall perform a given amount of work at the least possible pecuniary cost."[30] Here Rankine had established a fully quantized efficiency-maximizing equation, incorporating the dual concerns of engineering into a single mathematical expression. For Rankine himself, this development endeared him and his burgeoning field of engineering science to Glasgow industrialists: "Using quantified economy to promise optimal numerical 'solutions' to engineering 'problems' was powerful propaganda for academic engineering."[31] University forces initially reluctant to accept engineering within their walls were similarly swayed by the "scientific" varnish of precision that Rankine's quantified economic efficiency had brought to engineering.

Initially, an understandable confusion had surrounded Rankine's founding of engineering science: why exactly should budding engineers learn mechanics from William Rankine, Professor of Engineering Science, instead of from a seemingly similarly qualified professor of pure science? Rankine's quantitative melding of mechanics and economy into a unified analysis differentiated Rankine's new field from the pure sciences, it was instead "pure science *regulated by economy*, particularly economy in its financial sense."[32]

Rankine's conception of efficiency was key to this distinction he drew between engineering science and pure sciences. Efficiency, while still conveying a sense of accurate measure, was *not* precision. Holding engineering to similar demands of "precision" as expected in the sciences (even if not to the same extent) naturally conflicted with the economic interests an engineer was required to respect. Efficiency could be defined so that it included the financial side of a project. Precision could not, instead it might have to be sacrificed to save costs. For all the skills of scientific calculation that Rankine would pass on to his students, of equal importance was their ability to know when "to deviate from the exactness required by pure science."[33] It was critical that engineers' knowledge not be limited to "the mechanical principles of his art" as they "might lead him into needless expense in the production of a degree of mechanical efficiency not required by the circumstances of particular cases; he ought also to have a sound judgment regarding the commercial result of the adaptation of engines of a given kind to a given vessel, intended for a given trade."[34] By focusing his engineering science on efficiency, Rankine could sidestep the adversarial relationship between

[30]Rankine (1881, p. 288); discussed in Marsden (1992, p. 341).
[31]Marsden (1992, p. 341).
[32]Marsden (1992, p. 342).
[33]Rankine (1972, p. 270); discussed in Marsden (1992, p. 330).
[34]Rankine (1883, p. 11); discussed in Marsden (1992, p. 344).

practical engineering and academic science that he was attempting to bridge.[35]

In the second half of the 19th century, the concept of efficiency within engineering came not only to describe the mechanical efficiency of engines but also the economic efficiency of their creation or use. For his part, William Rankine formalized this evolution such that economic efficiency was an equally quantitative element of the concept. Lacking the same constant economic pressures, efficiency in the sciences, to the extent it was used, did not absorb financial connotations and thus the meanings within engineering and the sciences diverged. The pursuit of ever greater precision and efficiency remained a frequent target within science, without any sense that something would have to be sacrificed in its pursuit. Within the sciences only a lack of precision or mechanical efficiency could be wasteful, there was no additional variable (like cost in engineering) that might constrain attempts for greater and greater precision or increasingly more perfect efficiency. This distinction between understandings of efficiency in engineering and the sciences in the second half of the 19th century is illustrated by the reception of a peculiar device, the Siemens brothers' chronometric governor.

2.3 Differential Welcome

In 1843, desperate for money to continue his younger siblings' educations, William Siemens[36] arrived in England aiming to find a buyer for his brother Werner's electroplating process. William quickly sold the patent for a healthy sum and returned to his work at the Stollberg factory in Germany. This quick money inspired the two Siemens brothers to tinker with some of their other inventions with the aim of capitalizing on the apparent English appetite for their work. And so, with the help of the watchmaker Ferdinand Leonhard, William and Werner set to work on improving a design Werner had outlined in 1842 for a new kind of steam engine governor. William had been enthusiastic about Werner's design for what they initially called "The Pendulum" in letters they exchanged in mid-1842. Werner's original idea had blossomed from a problem William had been set, to merge a steam engine and water wheel such that the water wheel always operated at full capacity and the steam engine only functioned to make up whatever power was still needed.[37] When, in the closing months of 1843, they returned to the device that William would come to call their "Chronometric Governor," this enthusiasm resurfaced and after successful trials and a German patent, William left for England in early 1844 to sell their new governor.[38]

[35]Marsden (1992, pp. 340–344).

[36]William Siemens was born Carl Wilhelm Siemens, but given his early move to England, I will refer to him by his chosen anglicized name Charles William Siemens.

[37]Siemens (1966, p. 86).

[38]Werner referred to it as the differential regulator. Siemens (1966, p. 87).

Thereafter, William Siemens made England his home and built a successful British branch of the Siemens company. This success, however, was not a consequence of wild sales of the chronometric governor. As a commercial product, the governor was a complete flop. And yet, while the governor was bad for business, it was great for physics.

The Siemens brothers' chronometric governor was, like all engine governors, designed to account for fluctuations in engine speed. It was to correct for irregular motions resulting from changes in power supplied by the engine or work being done by it. The Siemens governor contains a central differential made up of three bevel gears. Bevel gears allow the communication of motions between the gears arranged on nonparallel axes. In this case the gears are arranged such that they mesh at right angles, two gears rotating around the same vertical axis and both connected perpendicularly to the third gear. The two parallel wheels rotate in opposite directions, one following the engine, the other following a heavy conical pendulum acting as a speed reference. The intermediate gear is free to track around the perimeter of the other two as the speeds of the engine and pendulum fall out of sync, "the rate of its angular displacement is the required measure of speed-error."[39] The central gear will remain stationary if the other two gears rotate with the same speed (in opposite directions). This intermediate gear is connected such that while free (within limits) to roam around the other two gears it is also connected to a series of levers and a weight which will move and operate a valve according to the gear's displacement. Thus the displacement of the central gear regulates the engine's speed.

While the design is certainly novel, why adopt it? In what way was it an improvement over the venerable Watt centrifugal governor? First, a quick description of a Watt centrifugal governor: two weighted arms are attached to the top of an axle geared into the engine. These arms are free to pivot up and away from the central axle, gradually rising as the engine speed is increased. At a given point the rising arms, through some linkage, effect the closing of a valve thereby regulating the engine's speed. The Watt governor was simple and rugged and was widely adopted by the time the Siemens governor was introduced. Nevertheless, the Siemens brothers claimed their governor was designed to surpass Watt's governor in two key respects. The first relates to a natural feature of the Watt governor, namely that the angular position of the weighted arms (tucked in, or "balls out") reflects their speed of rotation and consequently that of the engine. The rise (or fall) of the arms is what ultimately acts to open or close the engine valve regulating speed. As such, only *after* a "permanent" change in engine speed (which in turn raises or lowers the arms) will the valve be affected. As William Siemens derisively put it, the Watt governor "can-

[39]Fuller (1996, p. 388).

[40]Siemens (1853, Plate 17 Fig. 7).

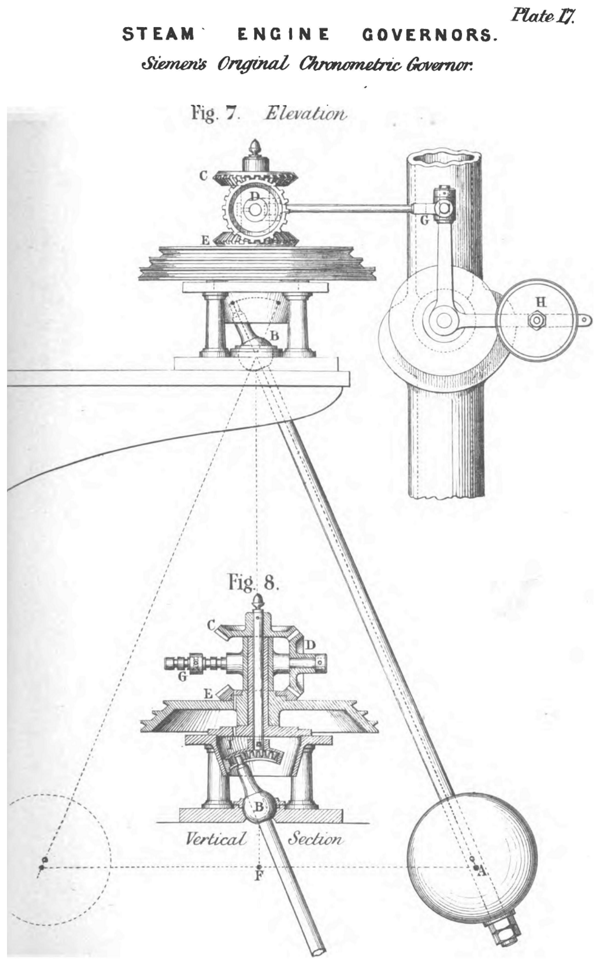


Figure 2.1: Siemens Governor as Presented to the Institution of Mechanical Engineers (1853)[40]

not *regulate*, but only *moderates* the velocity of the engine."[41] Nevertheless, Siemens admits that newer governors had overcome this issue, giving special attention to a winged design by John Hick.[42] The Siemens governor does not contain parts that need to spin up to reflect the engine speed, to a high degree of approximation it maintains a constant speed set by the pendulum, unlike the Watt governor which necessarily spins at different speeds given the valve position.

Siemens suggests that the second deficiency of Watt's governor, however, is a

[41]Siemens (1853, p. 76).

[42]Siemens and Joseph Wood would later partner with John Hick to sell steam engines already equipped with their chronometric governor. König (2020, p. 26).

[43]Siemens (1853, Plate 15 Fig. 1).

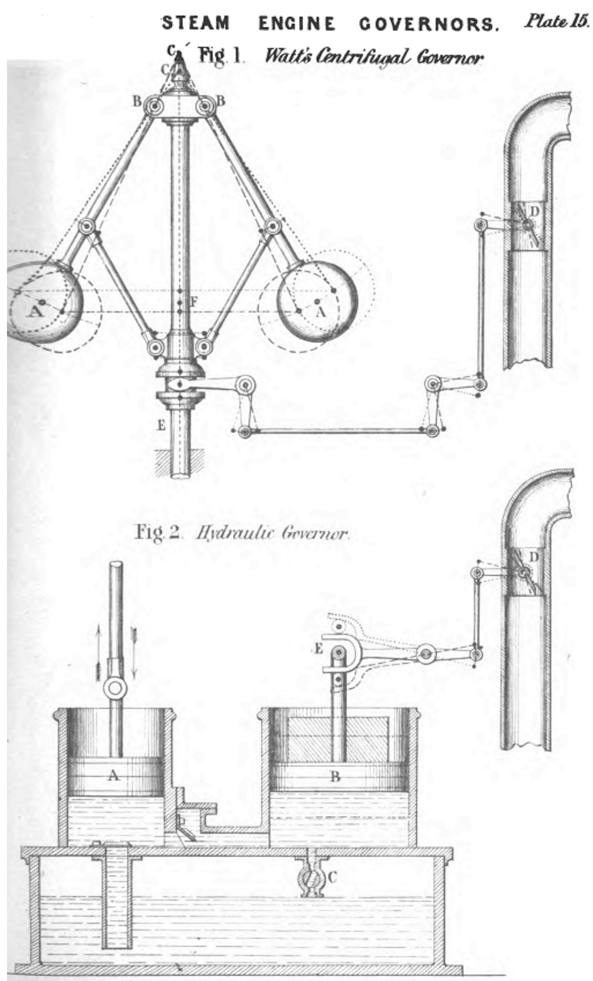


Figure 2.2: Diagram of a Watt Governor Included in Siemens' Presentation to the Institution of Mechanical Engineers (1853)[43]

universal defect plaguing all governors (including Hick's) save his and his brother's contribution. This second shortcoming is much like the first, although it is derived from a much less unique element of Watt's design. Again the issue surrounds the inability of the governor to react quickly to correct unwanted changes in engine speed. In this case, the issue surrounds the stable state of equilibrium the Watt governor (and most other governors) finds itself in at the moment engine speed notably changes. The speed change is not acted on until it builds up to such an extent that the governor system overcomes the friction of the valve. Dutifully, if not punctually, roused out of its equilibrium state, the governor overcorrects the valve due to this lost time, and continues to overcorrect leading to a series of fluctuations until the engine reaches the desired speed. William Siemens provides a helpful thought experiment to illustrate this problem:

> Let it be imagined that the engine is working at its medium speed, and that the Governor balls are revolving in equilibrium. Suppose a string to be tied between the two balls A A, of tensile strength equal to the resistance to the motion of the throttle valve. Let a portion of the load be thrown off the engine, and the velocity of its fly-wheel and of the Governor balls will gradually increase; but no alteration in the angular position of the balls can take place until their increase of centrifugal force suffices to break the string. The velocity will at this moment be proportionate to a much higher position of the levers than the adjustment of the valve D requires; they will, however, ascend into that position, and remain until the velocity of the engine has dropped sufficiently below its proper speed to accumulate acting power in the Governor in the opposite direction.[44]

By contrast, the Siemens governor acts on changes in engine speed extremely quickly, William claims that "only about 1-50th of a revolution in advance of the uniform motion would suffice to shut the valve entirely, the adjustment of the same [the valve] is effected before a sensible fault can occur."[45] There is no need to built up energy to overcome the resistance of the valve, the momentum of the heavy conical pendulum is more than enough to open or close the valve as required to equalize the speed difference. Further he insists that this has been backed up by trials wherein "the entire load of engines having frequently been thrown off without being perceived in the enginehouse."[46] How then might we describe these supposed advantages of the Siemens governor? Let us look to how the Siemens brothers characterized them.

The first public promotion of the Siemens governor in early 1846 was to the Institution of Civil Engineers, presented by an associate of William Siemens, an engineer named Joseph Woods. Up to this point, William had been unable to find a buyer for the governor's patent, in part because he expected an unreasonable amount of £36,000. Even granting licenses failed to entice business, so Siemens and Woods were forced to manufacture the devices themselves and supposedly were even inclined to bribe operators to keep the governors working their best.[47] In his presentation to members of the Institute, Woods suggested that mills in particular have been left wanting equipment capable of regulating of power and achieving "uniform velocity."[48] Here the Siemens' design for their chronometric governor lacks the later

[44]Siemens (1853, pp. 76–77).
[45]Siemens (1853, p. 81).
[46]Siemens (1853, p. 81).
[47]Pole (1888, p. 53, 59).
[48]Woods (1846, p. 225).

three-wheel differential, instead utilizing a similar screw and pinion system. Without being prompted by Woods, respondents appreciated the improvements over the Watt governor in essentially the same way as outlined by William Siemens in his later description. It's immediacy in adjusting engine speed made it "a very valuable instrument, where regularity of speed was important, as in grinding grain, spinning, &c., and as an ingenious contrivance, he [railway engineer Robert Stephenson] thought it well worthy of the attention of the mechanical world."[49] The governor made automatic the careful hand adjustments to the engine valve necessary to maintain regular motion when large variations could be expected, in essence deskilling the engine operator.[50] Henry Carpenter, who operated corn-mills at Shad-Thames in South East London, had apparently used the chronometric governor in his mill for the past nine months and found it exceptionally helpful, expounding upon the many problems irregular motion can heap onto a corn mill, from smaller yields and lower quality flour to the need for greater maintenance. Others claimed to be similarly satisfied with the Siemens governor in their saw mills and paper mills, working with both steam engines and water wheels.[51]

In a paper read before the Institute of Mechanical Engineers in mid-1853, William Siemens described the three gear differential governor outlined above as well as another version which did away with the conical pendulum, replacing it with a segmented flywheel. Here William Siemens opens with his sales pitch for his governor and thus for the importance of accurately controlling engine speed:

> If it is the duty of the engine to impart motion to manufacturing machinery, the greatest possible regularity of motion is a desideratum of first importance, for it enables the manufacturer to work his machines at the highest speed consistent with safety, and produce the largest quantity and a uniform quality of goods; it saves in personal attendance upon the machines; and, lastly, it increases the durability of the entire mechanism employed by preventing back-lashes and jerks.[52]

Siemens' argument largely reflects the compliments of the men who praised his device at the Institution of Civil Engineers in 1846. His governor would help you produce more and better goods with less manpower and less risk to the engine driving the operation. William claimed that some examples of his chronometric governor had

[49] Woods (1846, p. 261).

[50] Woods (1846, p. 262). The labor savings are made clearer in Siemens' next presentation: "In practice, the defects of the [Watt] Governor are ameliorated by personal attendance to the engine at such times when considerable changes in load are expected to take place. In cotton and flour mills, for instance, the attendant on the engine is always forewarned of such changes by a bell, and effects the adjustment of the valve by hand." Siemens (1853, p. 77).

[51] Woods (1846, pp. 262–265).

[52] Siemens (1853, pp. 75–76).

been in operation "night and day for upwards of seven years."[53] This boast, however, was intended to offset the criticism that he had already encountered regardings the governor's "delicacy, and more particularly the expense... [which] have been serious impediments to its more general introduction."[54] The new flywheel chronometer and the addition of a second differential gear were intended as the solutions for these problems. A second differential wheel meant less oiling and cleaning. Again respondents were met with assurances that their machines would work faster and produce more with less "constant attendance."[55] Indeed, discussion of Siemens' governor ended as

> The Chairman expressed his opinion of the great practical utility of the new governor and thought its application might be advantageously extended to the engines of iron works and steam boats.[56]

The Siemens brothers remained similarly confident, besides England they also took out patents on their governor in France, Belgium, Austria, and the majority of the German states, at great personal expense.[57]

Siemens was selling efficiency and precision. As he proudly declared, his governor was so precise that it was employed by the Astronomer Royal for timing purposes. Astronomer Royal George Biddell Airy had been desperate for any equipment that might smooth out the rotation of his equatorial telescopes as they tracked stars across the night sky. Uneven and irregular motion, even only slight deviations, made observations incredibly difficult through high magnification telescopes. The chronometric governor proved to be the right device for the job:

> I introduced the use of Siemens's Chronometric Governor for giving horary motion to an Equatoreal there. I have since introduced the same principle in the Chronograph Barrel and the Great Equatoreal at Greenwich: I consider it important.[58]

Given William Siemens' more notable machine association, the regenerative furnace, which consumed so much of his attention, it should come as no surprise to find him so persistent in marketing the ultra efficient governor. William was deeply concerned with waste and thus with efficiency.[59] And yet this efficiency and precision could not make the device an economic success for Siemens. In his memoir, Werner von Siemens reflects that the chronometric governor "is neither as simple nor as cheap

[53] Siemens (1853, p. 81).
[54] Siemens (1853, p. 81).
[55] Siemens (1853, pp. 83–84).
[56] Siemens (1853, p. 87).
[57] Pole (1888, p. 59).
[58] Airy (1896, pp. 179–180); discussed in Mayr (1971b, pp. 206–212).
[59] Hessenbruch (1993, p. 55).

as the Watt-regulator, which in later years has been considerably improved, but the differential movement... has proven an exceedingly fertile element of construction."[60] Despite reassuring anecdotes to the contrary, the governor's spotty reliability was another cause for concern.[61] Simply put, the unique mechanical efficiency of the Siemens governor was not valuable enough to overcome its cost and complexity; "it was of greater sensitiveness than was required in ordinary steam machinery."[62] Most factory owners saw the Siemens governor as solving a problem that did not really exist. Outside of Cornwall, the British mostly saw coal as a nearly infinite resource so cheap that it was not worth conserving. The majority of the costs associated with employing an engine in a commercial setting were associated with the initial cost of the machine, maintenance, and wages for operators, not fuel.[63] The level of efficiency made possible by the governor was simply not in demand.

Their governor may have been mechanically efficient, but it was not economically efficient, a lesson illustrated by the father of quantitative efficiency, William Rankine:

> The object of improvements in the economy of the marine steam-engine is to increase as far as practicable, consistently with due regard to economy in first cost, each of the four factors of the efficiency [the efficiency of the furnace, boiler, engine, and propeller]. Judgement, as well as skill, is specially required in applying to practice in marine steam-engineering improvements whose objects are to increase the mechanical efficiency of the furnace and boiler, of the steam in the cylinder, and of the mechanism; for those improvements for the most part tend more or less to increase the cost of construction; and thus there arises in each case the commercial question, Whether the economy in working to be attained by means of a given increase of efficiency is sufficient to warrant the additional expenditure?[64]

In an ironic turn of events, a still further improved version of the governor was put to work in prisons across England, as an energy sink for the endless toil of prisoners that would amount to nothing. The governor that had been designed to minimize waste now maximized it, perpetually dissipating prison labor in the name of punishment and rehabilitation.[65]

[60] Siemens (1966, p. 87).

[61] Pole (1888, p. 54).

[62] Pole (1888, p. 111).

[63] Cardwell (1993, p. 122).

[64] Rankine (1883, p. 10); discussed in Marsden (1992, p. 344). Marsden's quotation of Rankine contains a typographical error. Rankine's original reads, as given above, "... a given increase in *efficiency* is sufficient" not "... a given increase in *expenditure* is sufficient."

[65] Pole (1888, p. 157).

The Siemens governor was never an exemplar of Rankine's all-encompassing engineer's efficiency. The brothers' obsession with mechanical efficiency was never moderated by any similar concern for the economics of their device. Theirs was an outdated or at least misplaced conception of efficiency (perhaps more accurately referred to as precision), one better suited for the sciences where issues of economics were less central than in industry.[66]

William continued to sporadically promote the governor, although he had mostly turned over its commercialization to competing firms.[67] In 1866, he delivered a second paper to the Institution for Mechanical Engineers containing the aforementioned improved governor, with yet another timing system (a rotating fluid this time).[68] The same year he presented "On Uniform Rotation" to the Royal Society for publication in Philosophical Transactions. Unsurprisingly, he took the opportunity to boast about the chronometric governor, although he was noticeably more open about its shortcomings.[69] Ignored by industry, the governor nevertheless found its way into the sciences, into astronomy as a valued instrument and eventually into electromagnetism through a much less direct path. The governor's circuitous route from industrial object to physicist's idealization begins with a textbook.

2.4 Maxwell, Faith, and "Physical Lines of Force"

The Clerk Maxwell family were students of British industry and technology. James Clerk Maxwell and his father frequently visited "manufactures" and "great buildings."[70] In preparation for an Easter vacation in Birmingham while studying for the Cambridge University Tripos exam, Maxwell's father wrote encouraging his son to

> View if you can, armourers, gunmaking and gunproving—swordmaking and proving—*Papier-maché* and japanning—silver-plating by cementation and rolling—ditto, electrotype—Elkington's Works—Brazier's works, by founding and by striking up in dies—turning—spinning teapot bodies in white metal, etc.—making buttons of sorts, steel pens, needles, pins, and any sorts of small articles which are curiously done by subdivision of labour and by ingenious tools—glass of sorts is among the works of the

[66]The governor might have come just slightly *before* its time. The rise of the electrical power industry in the last twenty years of the 19th century required high speed steam engines running at a constant speed to drive dynamos/alternators and produce electricity. Particularly in the early years of the power industry, the Siemens governor would seem to have been an excellent match, if and only if the problem of its questionable reliability had been solved. Cardwell (1993, p. 122).

[67]Pole (1888, p. 111).

[68]Siemens (1866a).

[69]Siemens (1866b, pp. 658–660).

[70]Campbell and Garnett (1882, p. 7).

> place, and all kinds of foundry work—engine-making—tools and instruments (optical in philosophical) both coarse and fine.[71]

Apparently, Maxwell dutifully started his tour with the glassworks.[72]

When a 25-year-old Maxwell left Cambridge for Aberdeen in 1856 it was to take up his first professorship at Marischal College. Having spent three years at the University of Edinburgh, Maxwell was well acquainted with Marischal's Scottish-informed emphasis not only on teaching but also on providing instruction to an economically diverse student body. Unlike Cambridge, Aberdeen was a commercial, industrial, and agricultural hub. Paper mills powered by nearby rivers, textile production, shipbuilding, a granite finishing industry, and a new rail link to London all contributed to the vitality of the city.[73] Accordingly, Maxwell's students were mostly the sons of tradesmen. And after he began teaching an evening class at the Aberdeen School of Science and Art in 1857, Maxwell's students included the tradesmen and mechanics themselves.[74] In 1858, the British Association for the Advancement of Science held their annual meeting in Aberdeen and Marischal college was the central venue. Attendees were witness to numerous talks and demonstrations, including a mechanical model exemplifying Maxwell's findings on the problem of Saturn's rings, and even visited local factories.[75]

Maxwell's time in Aberdeen, although thoroughly steeped in its industrial context, was brief. Marischal College was merged with King's College to create the University of Aberdeen. The new university, with room for only one professor in each subject, saw fit to release Maxwell so as to avoid duplication. Maxwell quickly landed on his feet and took over for the outgoing T.M. (Thomas Minchin) Goodeve at King's College, London. Although their time at King's did not overlap, Maxwell did join a number of his King's College colleagues in publishing a textbook (*Theory of Heat*) as part of the Longmans' series "Text-books of Science" under the editorship of Goodeve.[76] Maxwell's relationship with Goodeve is a part of the core connective tissue that binds this narrative of efficiency, governors, and electromagnetism together, but it is one of Goodeve's rather anodyne books that serves as the point contact. I will return to Goodeve shortly.

Maxwell's time at King's was perhaps the most creative and productive of his scientific career. During his tenure at King's College he published some of his most famous papers in both the kinetic theory of gases and electromagnetism, while still

[71] Campbell and Garnett (1882, p. 185); discussed in Smith (1998, p. 215).

[72] Campbell and Garnett (1882, p. 7).

[73] Flood et al. (2014, p. 18).

[74] The Aberdeen School of Science and Art operated as something like a partner institution of the Aberdeen Mechanics Institute. Flood et al. (2014, pp. 22–28).

[75] Flood et al. (2014, pp. 38–41); Maxwell (1990, p. 618).

[76] Flood et al. (2014, p. 49); Maxwell (1891).

reserving time to make contributions to color theory. The relatively new King's College, London aimed to provide a practical technical education for those who wished to join the growing class of professional engineers, inventors, and mechanics. Indeed Maxwell was teaching students within the Department of *Applied* Sciences. Maxwell helped raise this new crop of professionals and as in Aberdeen, taught evening classes for those who had to work during the day.[77] The material reality of Britain's rapid industrialization and the influx of professional students in Maxwell's courses left him ripe for thoughts of machines and mechanism. Throughout his scientific career, when in need of a clarifying comparison or analogy Maxwell's mind invariably manifested something suitably industrial. Meanwhile, Maxwell's Christian faith pointed him towards a complementary concept, efficiency.

In spring 1862, while still at King's, Maxwell wrote to his lifelong friend Lewis Campbell that:

> We can also form a rough estimate of the efficiency of a man as a mere machine, and find that neither a perfect heat engine nor an electric engine could produce so much work and waste so little in heat. We therefore save our pains in investigating any theories of animal power based on heat and electricity. We see also that the soul is not the direct moving force of the body. If it were, it would only last till it had done a certain amount of work, like the spring of a watch, which works till it is run down.[78]

Maxwell illustrates his familiarity with efficiency as a useful quantitative concept applicable to a broad range of disciplines from physiology to issues of steam and electrical technology. But more specifically, here Maxwell uses the concept of efficiency much like Smeaton, to investigate deep philosophical issues, i.e., the soul and "theories of animal power," instead of merely as a practical tool to develop "better" machines. Efficiency is crucial, enough so that it can rule out entire paths of theoretical and theological pursuit.

This tangle involving Maxwell's religious conviction and efficiency was not limited to casual banter between close friends. In the late-1860s Maxwell made reference to the idea of a beginning and end to the universe. The same issues of temporality and energy dissipation that had moved William Whewell, at one time Maxwell's Trinity College master, reappeared again and again in Maxwell's letters and papers, although more explicitly focused on the implications of the second law of thermodynamics than, as in Whewell's case, some ethereal retarding force.[79] Maxwell's physics and religion were entwined in the same dialogue of work and waste. That said, Maxwell did note a singular exception to the ubiquitous decay of all nature, most directly stated in his *Theory of Heat*:

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[77] Flood et al. (2014, pp. 44–49).
[78] Campbell and Garnett (1882, pp. 335–336).
[79] Flood et al. (2014, pp. 270–271).

> In the case of the molecules, however, each individual is permanent; there is no generation or destruction, and no variation, or rather no difference, between individuals of each species. . .
>
> But if we suppose the molecules to be made at all, or if we suppose them to consist of something previously made, why should we expect any irregularity to exist among them? If they are, as we believe, the only material things which still remain in the precise condition in which they first began to exist, why should we not rather look for some indication of that spirit of order, our scientific confidence in which is never shaken by the difficulty which we experience in tracing it in the complex arrangements of visible things, and of which our moral estimation is shown in all our attempts to think and speak the truth, and to ascertain the exact principles of distributive justice?[80]

Eschewing his usual caution, Maxwell had found a clear role for God in his science, as maker and guaranteer of the unnatural timelessness of molecules.

Maxwell's religiously infused molecular hypothesizing became even more direct and controversial in the wake of his remarks at the 1873 British Association meeting in Bradford.[81] Much like his *Theory of Heat*, his BAAS lecture titled "Molecules" closed with Maxwell's comments on faith and molecules in a universe undergoing inescapable decay:

> Natural causes, as we know, are at work, which tend to modify, if they do not at length destroy, all the arrangements and dimensions of the earth and the whole solar system. But though in the course of ages catastrophes have occurred and may yet occur in the heavens, though ancient systems may be dissolved and new systems evolved out of their ruins, the molecules out of which these systems are built—the foundation stones of the material universe—remain unbroken and unworn.
>
> They continue this day as they were created—perfect in number and measure and weight, and from the ineffaceable characters impressed on them we may learn that those aspirations after accuracy in measurement, truth in statement, and justice in action, which we reckon among our noblest attributes as men, are ours because they are essential constituents of the image of Him Who in the beginning created, not only the heaven and the earth, but the materials of which heaven and earth consist.[82]

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[80]Maxwell (1891, pp. 330–332).

[81]John Tyndall used his position as BAAS president to deliver the (in)famous *Belfast Address* to criticize Maxwell's molecule to God inference. A series of criticisms of both Maxwell and Tyndall followed. Flood et al. (2014, pp. 275–276); Marston (2007).

[82]Maxwell (1890c, p. 377).

These unchanging perfect molecules are windows into the characteristics of the creator. Borrowing language from John Herschel and William Whewell, Maxwell noted that exactness by which species of molecules were alike one another suggested that they had "the essential character of a manufactured article" thereby suggesting a manufacturer. Maxwell found in molecular physics an argument for God as creator and designer and an argument for God's perfection.

Of course, Maxwell was also intimately acquainted with the other hypothetical entity that stalked 19th-century physics, the electromagnetic ether. While he was generally less willing to court controversy when it came to the ether, buried underneath his caution was a familiar religious sentiment. In response to an 1876 letter from an Anglican Bishop who had taken note of Maxwell's comments on molecules and was curious to hear his take on the creation of light in the book of Genesis, Maxwell included a warning:

> I should be very sorry if an interpretation founded on a most conjectural scientific hypothesis were to get fastened to the text in Genesis, even if by so doing it got rid of the old statement of the commentators which has long ceased to be intelligible. The rate of change of scientific hypothesis is naturally much more rapid than that of Biblical interpretations, so that if an interpretation is founded on such an hypothesis, it may help to keep the hypothesis above ground long after it ought to be buried and forgotten.
>
> At the same time I think that each individual man should do all he can to impress his own mind with the extent, the order, and the unity of the universe, and should carry these ideas with him as he reads such passages as the 1st Chap. of the Ep. to Colossians (see Lightfoot on Colossians, p. 182), just as enlarged conceptions of the extent and unity of the world of life may be of service to us in reading Psalm viii; Heb. ii. 6, etc[83]

This is hardly a condemnation of reasoning from science to faith. The only risk he sees is adding undue weight to soon to be outmoded scientific ideas through biblical connection. Maxwell is clearly comfortable finding support for his own religious convictions in his scientific work and is comfortable recommending that others find support for their personal faiths in their own understandings of the universe.

As regards the Bishop's specific question regarding Genesis and light:

> If it were necessary to provide an interpretation of the text in accordance with the science of 1876 (which may not agree with that of 1896), it would

[83] Campbell and Garnett (1882, pp. 394–395); discussed in Flood et al. (2014, pp. 278–279). The section of Colossians pertains to the "active role of Christ in Creation." Maxwell's reference to the work of his friend J.B. Lightfoot only further underscores the emphasis Maxwell places on Christ's activity in the process of creation.

> be very tempting to say that the light of the first day means the all-embracing aether; the vehicle of radiation, and not actual light, whether from the sun or from any other source.[84]

Evidently, Maxwell also felt some pull towards aligning his understanding of the ether and his own understanding of the bible. He would further clarify his feelings on this connection in comments made before the Royal Institution in the same year as his communication with the Bishop. In his wide ranging discussion of action-at-a-distance, he arrives finally at electromagnetic phenomena and the electromagnetic ether.

> The vast interplanetary and interstellar regions will no longer be regarded as waste places in the universe, which the Creator has not seen fit to fill with the symbols of the manifold order of His kingdom. We shall find them to be already full of this wonderful medium; so full, that no human power can remove it from the smallest portion of space, or produce the slightest flaw in its infinite continuity. It extends unbroken from star to star; and when a molecule of hydrogen vibrates in the dog-star, the medium receives the impulses of these vibrations; and after carrying them in its immense bosom for three years, delivers them in due course, regular order, and full tale into the spectroscope of Mr Huggins, at Tulse Hill.[85]

The ever present ether seems to save much of God's creation from the moral judgement that would by this point in the 19th century accompany "waste." With the ether present everywhere and between everything, there is no wasted, flawed space. Much like his assessment of molecules as "manufactured articles," Maxwell viewed the ether as embodying the order, continuity, and perfection of God.[86] Maxwell impressed these ideas of the ether on his own mind and they evidently stuck with him and were reinforced as he studied his bible. It seems reasonable then to expect that Maxwell's conceptualizations of the ether reflect exactly this sort of holy perfection and order.

Between 1861 and early 1862 and spread across four parts, Maxwell's "On Physical Lines of Force" revealed the most novel features of his electromagnetic theory, the displacement current and electromagnetic waves, in conjunction with an intricate mechanical model of the electromagnetic ether. It is in the paper's second installment, "The Theory of Molecular Vortices Applied to Electric Currents," that the connection between Maxwell, Goodeve, the Siemens brothers, and efficiency is neatly encapsulated in a single footnote. The passage in "Physical Lines" that demanded this citation comes as the solution to an engineering problem in the development of Maxwell's ether model.

[84] Campbell and Garnett (1882, pp. 393–394); discussed in Flood et al. (2014, pp. 278–279).
[85] Maxwell (1890e, p. 322).
[86] Flood et al. (2014, pp. 270–278).

> I have found great difficulty in conceiving of the existence of vortices in a medium, side by side, revolving in the same direction about parallel axes. The contiguous portions of consecutive vortices must be moving in opposite directions; and it is difficult to understand how the motion of one part of the medium can coexist with, and even produce, an opposite motion of a part in contact with it.[87]

To represent a magnetic field, the rotating molecular vortices of Maxwell's model should all be turning in the same direction as far as the field extends, otherwise the fields exemplified by their rotations would cancel one another out. However, the electromagnetic illustration and the mechanical reality of the model are at odds. Gears in contact with one another rotate in opposite directions. Nevertheless, Maxwell had a mechanical solution that contributed valuable electromagnetic insights:

> The only conception which has at all aided me in conceiving of this kind of motion is that of the vortices being separated by a layer of particles, revolving each on its own axis in the opposite direction to that of the vortices, so that the contiguous surfaces of the particles and of the vortices have the same motion.
>
> In mechanism, when two wheels are intended to revolve in the same direction, a wheel is placed between them so as to be in gear with both, and this wheel is called an "idle wheel." The hypothesis about the vortices which I have to suggest is that a layer of particles, acting as idle wheels, is interposed between each vortex and the next, so that each vortex has a tendency to make the neighboring vortices revolve in the same direction with itself.[88]

In the "idle wheel," Maxwell had found a mechanical solution for his problem. Given that Thomson had made no mention of anything resembling these idle wheels in his initial discussion of molecular vortices, nor did Maxwell bring them up in any correspondence in the waning years of the 1850s, it is safe to assume the idle wheels were added later, in keeping with the way Maxwell represents the chronology in "Physical Lines."[89]

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[87] Maxwell (1890h, p. 468).

[88] Maxwell (1890h, p. 468). It is worthwhile to keep in mind that Maxwell and his contemporaries usage of "gear" and "gearing" does not perfectly reflect our present day conception, i.e., enmeshed toothed wheels. The 19th-century usage is significantly more general. As Goodeve defines it: "*Gearing* and *Gear* are the words used to indicate the combination of any number of parts in a machine which are employed for a common object." Immediately after this remarkably broad definition Goodeve discusses toothed wheels being "in" or "out of gear," so it may still be fair to expect that toothed wheels were the objects most commonly associated with "gearing" even then. Goodeve (1860, p. 7); Siegel (1991, p. 202 n19).

[89] Siegel (1991, p. 65).

If it were just that, placing another fixed set of wheels between the vortices so that each vortex could rotate in the same direction, then there would be no expectation of any sort of explanation regarding the source of the idea. However, Maxwell chose a more complicated solution which ultimately greatly extended the explanatory power of his mechanical model and guided him towards the novel electromagnetic phenomena he would pioneer in "Physical Lines."

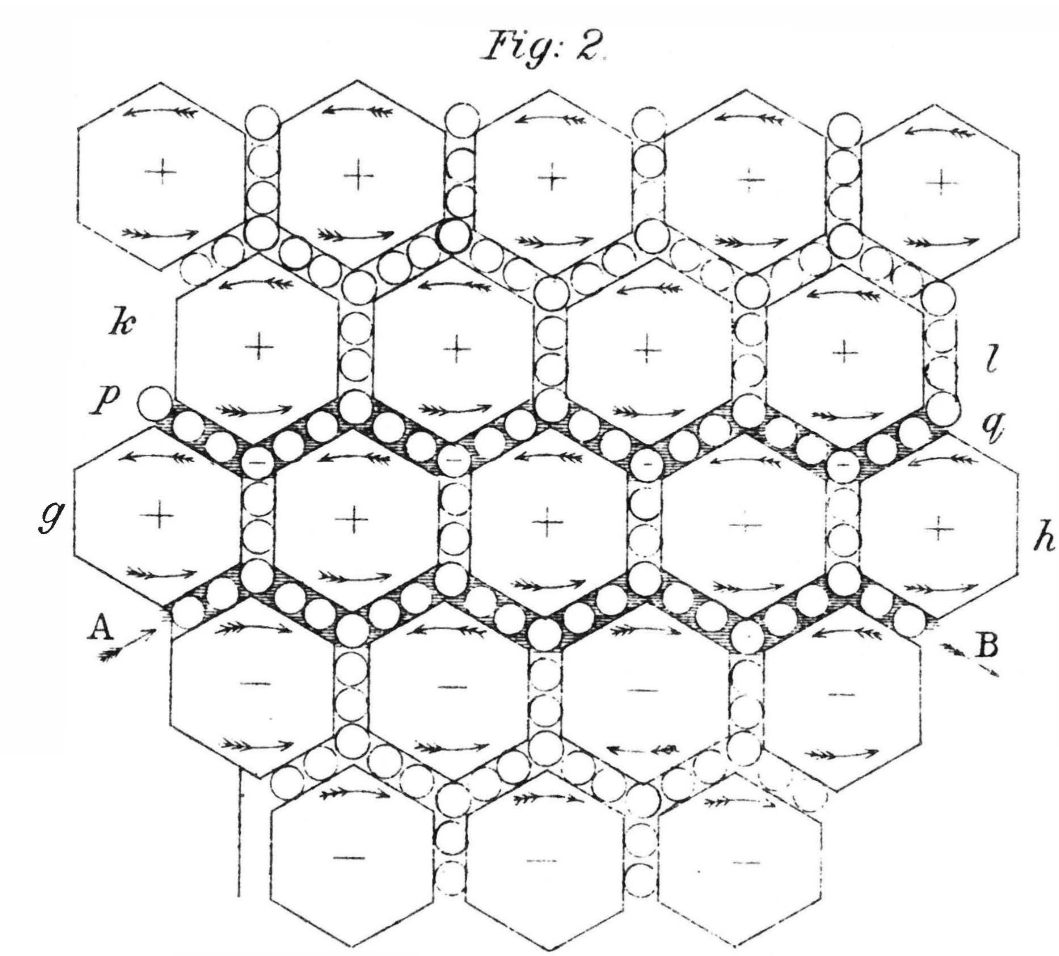

Figure 2.3: Mechanical Model of the Electromagnetic Ether[90]

[90]In this two dimensional image from "Physical Lines," Maxwell's vortices are imagined to be hexagonal. Meanwhile, in his analysis in Part III, he imagines the vortices as spherical. There is no compelling evidence that can decide the matter: whether Maxwell was merely approximating a more complicated multifaceted three dimensional figure with a sphere or if the hexagons were simply a stylistic choice, perhaps intended to better differentiate them from the circular idle wheels. Maxwell (1890h, p. 492, 488); Siegel (1991, p. 70).

> In mechanism, the idle wheel is generally made to rotate about a *fixed* axle; but in epicyclic trains and other contrivances, as, for instance, in Siemens's governor for steam-engines*, we find idle wheels whose centres are capable of motion. In all these cases the motion of the centre is the half sum of the motions of the circumferences of the wheels between which it is placed.[91]

Maxwell made his idle wheels mobile, able to roll between the vortices, and so "according to our hypothesis, an electric current is represented by the transference of the moveable particles [idle wheels] interposed between the neighboring vortices."[92] Effectively, Maxwell realized that when representing an inhomogeneous magnetic field, the vortices in his model would rotate at different velocities, in turn causing the idle wheels to move within the channels between these vortices. In calculating the net amount of idle wheels moving through a given volume (one suffuse with vortices), Maxwell derives an equation eerily reminiscent of Ampère's circuital law. Thus, Maxwell had afforded himself some justification for his association of idle wheel translation and electric currents.

To summarize Maxwell's version of events: further investigation of the mechanical issue solved by static idle wheels showed that they could potentially move as well as rotate and that this translation would serve as an appropriate analogue for electric current. Whether Maxwell's account is wholly accurate is both unknowable and mostly beside the point. The mobility of the idle wheels and their further interpretation as particles of electricity set the stage for the expansion of Maxwell's model. That this one change to the model extended its explanatory range to include electric currents (and eventually electromagnetic induction) *and* solved the mechanical problem at the heart of the model mutually bolstered the choice in each realm of physics.[93] Nevertheless, given the arguments concerning science-technology relations that run through this chapter and the next, I take solace in Maxwell's chosen rhetoric, in which, as Siegel puts it: "Maxwell presented himself as mechanical engineer of the magnetoelectric medium."[94]

The growing complications of his mechanical model, of which the mobile idle wheels were the first significant addition and the elastifying of the vortices in Part III the next, would build to Maxwell's invention of the displacement current, prediction of electromagnetic waves, and his electromagnetic theory of light.

As suggested by his reference to "Siemens's governor for steam-engines," the citation accompanying the * mark, is to an illustration and discussion of the Siemens'

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[91] Maxwell (1890h, pp. 468–469).
[92] Maxwell (1890h, p. 471).
[93] Siegel (1991, pp. 65–73).
[94] Siegel (1991, p. 67).

chronometric governor on page 118 of T.M. Goodeve's *Elements of Mechanism*.[95] Goodeve's book of mechanics and mechanisms is part of a long tradition of machine books stretching back to the Renaissance. Written as an introductory text for applied science students at King's, the book certainly did not herald the arrival of any hitherto unknown mechanical knowledge, but did nevertheless present a number of little used mechanical contrivances, including of course the Siemens' governor. Not full of entirely novel nor exclusively well established mechanical knowledge, *Elements of Mechanism* seems to be somewhat between the two machine book traditions outlined by Ferguson. Given its purpose and audience, however, it seems more appropriate to slot it within the less technologically innovative branch, alongside Agricola's *De Re Metallica*, Leupold's *Theatrum Machinarum*, and eventually Diderot's *Encyclopédie*.[96] And yet these continental examples of machines books were largely unavailable to British mechanics, lacking as they were any English translations. Watt was forced to learn German so that he might glean knowledge of steam engines from Leupold. When Britain began to produce its own machine books, they were less ornate and much shorter than their continental kin. The pictorial innovations of the continental machine books, however, carried over.[97] Goodeve's *Elements* is no exception, incorporating various isometric and perspective views with the precise detail afforded by copperplate engravings. The change effected by Goodeve was much the same as the earlier machine books: "The circle of technologists whose minds could be engaged by a particular problem or stimulated by a particular idea was thus indefinitely enlarged."[98] In this case, the minds "stimulated" were not limited to technologists.

Inheriting Goodeve's position at King's evidently led Maxwell to look into Goodeve's work, within which Maxwell found the answer to his mechanical problem. Goodeve's section on the Siemens governor immediately follows a similar explanation of the Watt governor. Not only does Goodeve provide an extensive analysis of the workings of the Siemens governor as well as a helpful diagram, he is also more than happy to speak to its advantages:

> In some cases, as where the engine drives machinery for very fine spinning, it may be desirable to obtain an almost absolute uniformity of motion; or, again, it may be an object to avoid the fluctuations in speed to which the common governor is liable when any sudden change occurs in the load upon the engine.
>
> In order to control the engine with almost theoretical exactness, and to provide against the objections to which Watt's governor is exposed in cer-

[95] Goodeve (1860).
[96] Ferguson (1977).
[97] Hindle (1981, pp. 5–6).
[98] Ferguson (1977, p. 828).

> tain extreme cases, Mr. Siemens has put forward a remarkable adaptation of epicyclic trains to the conical pendulum...[99]

Incorporating the Siemens' mechanism into his ether model allowed for the kinds of motions that Maxwell needed to expand the model's explanatory power. That said, it would also imbue his ether model with the Siemens governor's prodigious efficiency and precision, as was established in Section 2.3 and which Maxwell was unquestionably aware of having read Goodeve's account of the governor's orderly, smooth operation due to the nearly limitless precision that the machine made possible. Goodeve also mentions the governor's adoption by the Greenwich Observatory to aid in timing star transits.[100] When returning to the Siemens governor in 1868, Maxwell wrote to the Astronomer Royal, George Airy, to request additional details on the particulars of the Greenwich model.[101]

Maxwell's limited discussion of the general nature of the ether in "Physical Lines" is in line with what was inferred above from his comments on religion and science. The model was imagined to be capable of "perfect rolling contact... without slipping" between vortices and idle wheels so as to better illustrate the efficiency of the ethereal medium it was imitating. He recognized that the model he had invented was probably not an accurate representation of the reality of the microscopic structure of the ether, however, it was

> a mode of connexion which is mechanically conceivable, and easily investigated, and it serves to bring out the actual mechanical connexions between the known electro-magnetic phenomena; so that I venture to say that any one who understands the provisional and temporary character of this hypothesis, will find himself rather helped than hindered by it in his search after the true interpretation of the phenomena.[102]

The specifics of the wheels and vortices, the honeycomb construction Maxwell had fit them into, all of this was artificial. Nevertheless, the differential relations between these structures and the general efficiency of motion transfer through the mechanical ether structure, both embodied by the Siemens governor, were lessons illustrated by Maxwell's ether model but which could also survive apart from the model itself.

2.5 Building "A Dynamical Theory"

By late 1865 Maxwell was clearly familiar with treating efficiency quantitatively. In notes describing the engineer James Thomson's (brother of William Thomson) vortex

[99] Goodeve (1860, pp. 117–118).
[100] Goodeve (1860, p. 120).
[101] Maxwell (1995, p. 351).
[102] Maxwell (1890h, p. 486).

turbine that appear to date from this time period, Maxwell derives an equation for what he explicitly refers to as the device's "efficiency." Maxwell's modernized efficiency is measured by useful work per second divided by applied work per second.[103]

A couple of years before this Maxwell had begun work on what would become his 1868 paper "On Governors."[104] In a September 1863 letter to William Thomson, Maxwell wrote that he had "been working at the conditions of steady motion for your governor (T) for Jenkins (J) for yours & J^s in series TJ, for T & J independent on the same axle T + J and for Siemens S."[105] Although it was not expanded upon in this letter, the final device referenced is undoubtedly the Siemens chronometric governor. Now, instead of settling for vaguely comprehending the general operation of the machine, Maxwell was concerned with understanding its intricacies quantitatively. As 1864 dawned, the Siemens governor had once again found purchase in Maxwell's mind.

At the same time Maxwell began to feel uneasy about the stability of the theoretical innovations he had pioneered in "Physical Lines." He had come to appreciate how precarious of a situation he had left the displacement current and his electromagnetic theory of light in, perched as they were atop his hypothetical model of the microstructure of the electromagnetic ether. Maxwell wanted to build a new theory that would maintain the novel elements of "Physical Lines," but "without any hypothesis about the structure of the medium or any mechanical explanation of electricity of magnetism."[106] During the summer of 1864 Maxwell constructed a new theory designed to reground his conception of electromagnetic relations without recourse to any specific hypothetical ether model.

There are limited surviving records that would allow for any detailed accounting of Maxwell's path towards this new electromagnetic theory.[107] What is left is the final result of this process, Maxwell's "Dynamical Theory of the Electromagnetic Field," received by the Royal Society's Philosophical Transactions in late October 1864, read in December, and published early the next year.[108] In "Dynamical Theory," Maxwell's honeycomb ether has disappeared. The historiography has typically insisted that in building this new "dynamical" theory, Maxwell made a conscious choice to do away with mechanical models in favor of Lagrangian dynamics.[109] This

[103]Maxwell (1995, pp. 237–238). As is typical for Maxwell's notes and even his published works, the derivation contains numerous careless sign errors.

[104]Maxwell (1890g).

[105]Maxwell (1995, pp. 113–114). Fleeming Jenkin is a central character in the next chapter and is discussed extensively in Section 3.2.

[106]Maxwell (1995, pp. 187–188).

[107]Some of what is left in this mostly barren historical record will be discussed in the next chapter where the piecemeal development of the theory that *can* be retraced is more relevant.

[108]Maxwell (1995, p. 189).

[109]Harman (2001, pp. 113–124); Everitt (1975, pp. 93–105).

interpretation of "Dynamical Theory" slots cleanly into what has become a popular narrative of Maxwell's transition away from mechanical models towards increasingly abstract mathematics, from "Physical Lines" to "Dynamical Theory" and culminating in his *Treatise on Electricity and Magnetism.*

This is not to downplay the importance of abstract mathematical analysis to "Dynamical Theory." Maxwell did remake his general equations of the electromagnetic field and reinterpret certain associated concepts with the help of his more "sophisticated" mathematical approach. However, there is another methodological tool that was similarly critical in helping Maxwell construct his new electromagnetic theory. In addition to Lagrangian dynamics, Maxwell's "Dynamical Theory" is guided by a mechanical analogy linking the electromagnetic field to a differentially geared flywheel system. Mentioned only very briefly at the beginning of the paper, this often ignored "fly-wheel" is merely a simplified version of the Siemens governor.[110]

But how can we be sure this "fly-wheel" system that Maxwell devotes only a single paragraph to refers to the Siemens governor? Unlike "Physical Lines," there is no obvious footnote connecting this device to the Siemens governor, nor is there any image included in "Dynamical Theory" that would allow us to easily examine mechanical similarities.

First, let us peruse Maxwell's 1873 list of wanted instruments for the new Cavendish Laboratory, which he was to direct. Listed under the heading "Lecture Room" is a "Fly wheel driven by a winch with pulley and band."[111] Picking up this line of inquiry in an 1876 letter to Maxwell's friend Lewis Campbell, Maxwell reveals that

> I have been making a mechanical model of an induction coil, in which the primary and secondary currents are represented by the motion of wheels,

[110]Maxwell (1890a, p. 536). The governor is largely absent from the historiography concerned with "Dynamical Theory." Olivier Darrigol is aware of the presence of the flywheel in the 1864 paper, although he does not seem to believe it is of much significance. Darrigol (2000, p. 156). Francis Everitt explains how the analogy between this flywheel and electromagnetism works, but stops short of suggesting any serious role for it. Everitt (1975, pp. 103–105). Citing Everitt, Daniel Siegel similarly describes the general outline of the analogical connection, but doesn't have much room for concerns outside of "Physical Lines." Siegel (1991, p. 199). In his excellent accounting of Maxwell's scientific letters, Harman does occasionally reference the flywheel analogy although largely separate from any discussion of "Dynamical Theory." Graeme Gooday describes Maxwell's flywheel as his "most widely known representation of self-induction," detailing the electromagnetic analogy and the device's mechanical limitations. Gooday reminds readers that beyond appearing in the third edition of Maxwell's *Treatise*, it was actually built for the Cavendish Laboratory. Gooday (2004, pp. 185–187). Goldman ignores its existence entirely. Goldman (1983). In his guided study of Maxwell's work in electromagnetism, Thomas K. Simpson hints that the flywheel might be somewhat underappreciated: it need "not necessarily be an inferior but quite possibly a more insightful way of grasping the principles of a connected mechanical system" Simpson (1997, p. 367). My own view is that all of these historians have drastically understated the importance of the flywheel/governor. Lazaroff-Puck (2015).

[111]Maxwell (1995, p. 871).

> and in which I can symbolise all the effects of putting in more or less of the iron core, or more or less resistance and Leyden jars in either circuit.[112]

A short time after this letter, the Elliott Brothers instrument makers delivered a working model to the Cavendish. This model now resides at Cambridge University's Whipple Museum of the History of Science (see Fig. 2.4).

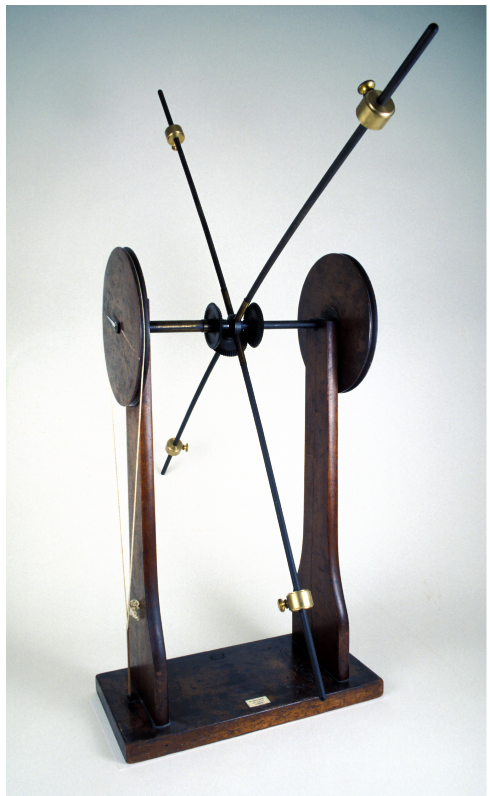


Figure 2.4: Maxwell's Flywheel Model Built for the Cavendish Laboratory[113]

A sketch and extended description of this device initially appeared in the first, unabridged edition of *The Life of James Clerk Maxwell*. There William Garnett, demonstrator in experimental physics at the Cavendish under Maxwell and responsible for the scientific half of the biography, notes that the device pictured and described is the same one that Maxwell had constructed for the Cavendish for "illustrat[ing] in a very beautiful manner the principal phenomena of induced currents."[114] Echoing Maxwell's comments in "Physical Lines," Garnett also points out that the flywheel

[112]Maxwell (2002, p. 421).
[113]In the Collection of the Whipple Museum of the History of Science, University of Cambridge (Wh.2455)
[114]Campbell and Garnett (1882, p. 551).

essentially amounts to a "differential train." Just like the governor, two bevel gears are linked perpendicularly to a central bevel gear that is free to rotate, or if the speeds of the outer wheels are unequal, translate along the circumference of the other wheels, causing the flywheel to flip end over end. At its heart the mechanism functions identically to the Siemens governor (sans conical pendulum of course).[115] A more in-depth discussion of Maxwell's device will follow in Section 2.6.

A practically identical sketch can be found in the third edition of Maxwell's *Treatise*.[116] This later drawing from Maxwell's *Treatise* is shown in Fig. 2.5 in the next section. The image was added by J.J. Thomson who had taken over from W.D. Niven as the editor for the *Treatise*'s third edition.[117] There is a much less extensive description accompanying this image, although it is once again identified as having been built for the Cavendish to illustrate the induction of currents.

Together, the images and descriptions of this flywheel demonstration device leave little doubt that it is the progeny of the Siemens governor.[118] Not only are their central mechanisms the same, the "fly-wheel" analogy given in "Dynamical Theory" performs some of the same work, albeit with more subtlety, as the mechanical model in "Physical Lines," which was itself built around the Siemens governor. Just as the content and concepts that make up Maxwell's electromagnetic theories evolved between 1862 and 1864 so too did his mechanical model/analogy; however, in both cases the core of his electromagnetic physics and his mechanical analogue remained the same. The relationship between these two realms of physical explanation did, however, change considerably between the two papers.

As stated above, the mechanical model in "Physical Lines," presented as a hypothetical microstructure of the ether, problematically tied Maxwell's novel electromagnetic results to particulars of the model itself. As Daniel Siegel has shown, the extent of ad hoc reasoning in "Physical Lines" has probably been overstated.[119] Nevertheless, examples like his account of the rotation of the plane of polarization of light by a magnetic field, i.e., the Faraday effect, are clear enough illustrations that the model had intruded uncomfortably into Maxwell's electromagnetic theory. In this case, the explanation of the Faraday effect depended on the radii of vortices, which could be larger or smaller to account for changes in the substance in which the phenomenon was occurring. That said, even this choice did not allow him to deal with paramagnetic and diamagnetic substances appropriately.[120] Ultimately, Maxwell had to assume that vortices in the two classes of substances rotated in opposite directions,

[115] Campbell and Garnett (1882, pp. 550–554).

[116] Maxwell (1892, Vol. 2, p. 228).

[117] Maxwell had died in 1879 before completing corrections on the second edition.

[118] There are additional fragments of evidence presented in the following section.

[119] Siegel (1991).

[120] There is a certain irony that the Faraday effect inspired Maxwell's approach in "Physical Lines" and yet his new theory was unable to provide a comprehensive explanation of the phenomenon.

not expanding on but rather contradicting his earlier elaborations of the model. As Knudsen points out, Maxwell's theory also assumed the existence of the phenomenon within a vacuum, despite empirical evidence to the contrary.[121] The displacement current was similarly entangled in mechanical particulars. Its existence as a separate component of the total current was defined by elements of the mechanical model.[122]

These issues, among others, left Maxwell searching for a new theory free of "hypothesis." "Dynamical Theory" largely delivered on this goal, or at least did so in regards to commitments to any particular mechanical components of a model. That said, as noted above, the paper did contain an analogy to a mechanical flywheel that was essentially a simplified version of the Siemens governor. This analogy was agnostic as to the specific microstructure of the ether. It was, however, still capable of clarifying vague electromagnetic concepts and suggesting paths forward for Maxwell's mathematical analysis. Maxwell's view on the role of analogies in science, such as the analogy to the flywheel/governor in "Dynamical Theory," is previewed in an unpublished essay that Maxwell wrote for the Apostles Club, "Analogies: Are There Real Analogies in Nature:"

> Before we can count any number of things we must pick them out of the universe, and give each of them a fictious unity by definition. . . The dimmed outlines of phenomenal things all merge into another unless we put on the focussing glass of theory and screw it up sometimes to one pitch of definition, and sometimes to another, so as to see down into different depths through the great millstone of the world.[123]

The analogy to a mechanical flywheel put into relief distinctions between electromagnetic phenomena and concepts by grounding them in a general set of mechanical analogues. Additionally, the analogy also suggested potential routes forward for Maxwell's mathematical analysis when clear pathways were either not to be found or the number of choices were overwhelming. In a posthumous essay on Maxwell's scientific methodology, James Jeans would describe essentially the same relationship: "From the very beginning his [Maxwell's] mathematical ideas were not only guided but controlled by a strong sense of physical reality."[124]

The shift from mechanical model to analogy may have relieved some embarrassing ontological commitments, however, the concepts of efficiency, precision, and divine perfection embodied by the governor were once again smuggled in with it, coloring the physics presented in "Dynamical Theory." Wherever the flywheel/governor shaped the content of physical theory it is appropriate to trace a further connection to the

[121] Knudsen (1976, pp. 225–261).
[122] This is recounted in the next chapter, Section 3.3, referencing Siegel (1991, pp. 85–119).
[123] Maxwell (1990, p. 377).
[124] Jeans (1931, p. 96).

web of concepts surrounding efficiency. The rest of this chapter will illustrate exactly how important the flywheel was in guiding the construction of "Dynamical Theory." At a large scale, however, the connection between these concepts and electromagnetic theory is much more immediate. Much like the honeycomb ether model represented the microstructure of the ether, the flywheel is analogous to the electromagnetic field and medium. The ether in "Dynamical Theory" remains in keeping with Maxwell's religious convictions as well as the epitome of efficiency and *near* perfection. The ether was perfectly continuous, uninterrupted by vacuum or matter:

> We have therefore some reason to believe, from the phenomena of light and heat, that there is an aethereal medium filling space and permeating bodies, capable of being set in motion and of transmitting that motion from one part to another, and of communicating that motion to gross matter so as to heat it and affect it in various ways.[125]

However, it was critically not a perfect medium transmitting motion in an instant, rather it was merely an extremely efficient one:

> the existence of a pervading medium, of small but real density, capable of being set in motion, and of transmitting motion from one part to another with great, but not infinite, velocity.
>
> Hence the parts of this medium must be so connected that the motion of one part depends in some way on the motion of the rest; and at the same time these connexions must be capable of a certain kind of elastic yielding, since the communication of motion is not instantaneous but occupies time.[126]

Maxwell's electromagnetic theory of light, first presented in "Physical Lines" and now refined in "Dynamical Theory," provided the clearest indication of the ether's exceptional efficiency and near perfection.

> If so, the agreement between the elasticity of the medium as calculated from the rapid alternations of luminous vibrations, and as found by the slow processes of electrical experiments, shews how perfect and regular the elastic properties of the medium must be when not encumbered with any matter denser than air.[127]

Maxwell's ether was a uniquely efficient elastic body capable of transmitting electric, magnetic, and optical effects nearly instantaneously and across great distances due

[125] Maxwell (1890a, p. 528).
[126] Maxwell (1890a, p. 528).
[127] Maxwell (1890a, p. 535).

to its continuity and perfection. What better device to embody the ether than the famously efficient Siemens governor?

Conceptualizing the ether and electromagnetic relations in terms of the flywheel/governor is not a choice that can be cordoned off from the electromagnetic theory that Maxwell presents in "Dynamical Theory." This approach had consequences for the content of Maxwell's electromagnetic theory. As I illustrate below, the mechanical analogy to the flywheel/governor clarified electromagnetic concepts and guided the development of his mathematical analysis in "Dynamical Theory." The Siemens governor and its connections to the rise of concepts of efficiency and precision, shifts from balance to engine models, work and waste, shaped Maxwell's "Dynamical Theory of the Electromagnetic Field" and remain embedded in its equations and attendant concepts.[128]

2.6 Flywheels and Bevel Gears

After an extended introduction, Maxwell's "A Dynamical Theory of the Electromagnetic Field"[129] moves to a general discussion of electromagnetic induction. The first part of this discussion is entitled "Electromagnetic Momentum of a Circuit" and it is here that Maxwell explicitly references a flywheel system as an analogue of the electromagnetic cases he will investigate:

> Now, if the magnetic state of the field depends on motions of the medium, a certain force must be exerted in order to increase or diminish these motions, and when the motions are excited they continue, so that the effect of the connexion between the current and the electromagnetic field surrounding it, is to endow the current with a kind of momentum, just as the connexion between the driving-point of a machine and a fly-wheel endows the driving-point with additional momentum, which may be called the momentum of the fly-wheel reduced to the driving-point.
>
> In the case of electric currents, the resistance to sudden increase or diminution of strength produces effects exactly like those of momentum, but the amount of this momentum depends on the shape of the conductor and the

[128]The following sections closely follow my earlier account of Maxwell's analogical reasoning in "Dynamical Theory" as presented in Lazaroff-Puck (2015).

[129]Equations that appear in Maxwell's original texts *and* are numbered (or lettered) therein are labeled in this chapter with their original number or letter within parentheses as well as a shorthand for the text from which they came. In this chapter, there are only equations from Maxwell's "A Dynamical Theory of the Electromagnetic Field" and thus each equation reproduced from the original text will be labeled "DT" in keeping with the style used in the following chapter which displays equations from a wider variety of Maxwell's published works. Beyond this, equations marked "DT" also show which part of the paper the equation is from, e.g., "P.3" for Part 3.

relative position of its different parts.[130]

This rhetoric is reminiscent of a discussion in Maxwell's "Physical Lines." A few pages after his citation of Goodeve and the Siemens governor, Maxwell spends a few paragraphs describing the relation between electromagnetic phenomena and the "axles," "driving wheels," and the "reduced momentum of the machine for that point."[131]

As stated above, there is no accompanying illustration of the flywheel system that Maxwell references in "Dynamical Theory;" however, the sketch of the flywheel designed by Maxwell printed in the third edition of Maxwell's *Treatise* is shown in Fig. 2.5.[132]

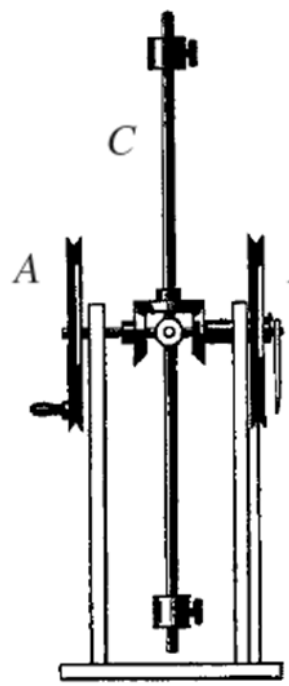


Figure 2.5: Maxwell's Flywheel[133]

The abstract of the 1864 paper as well as a deleted passage from the original manuscript, both submitted to the Royal Society in late October 1864, indicate that in addition to the flywheel, Maxwell began writing this paper with two more mechanical analogies in mind.[134] Another mechanical analogy could conceivably have

[130] Maxwell (1890a, pp. 536–537).
[131] Maxwell (1890h, pp. 478–479).
[132] Maxwell (1892, Vol. 2, p. 228).
[133] The labels in this image has been modified from those in the version shown in Maxwell (1892, Vol. 2, p. 228).
[134] Maxwell (1864b); Maxwell (1995, p. 191, 197).

done similar work, the flywheel analogy is after all meant to be illustrative and not a hypothetical model of reality. Maxwell was aware that "[t]he problem of determining the mechanism required to establish a given species of connexion between the motions of the parts of a system always admits of an infinite number of solutions."[135] The change from "a rod acted on by two forces perpendicular to its direction" and "two horses harnessed to a carriage by the intervention of a lever so that each horse pulls at its own arm of the lever while the lever is attached to the carriage by its fulcrum" to the flywheel was most likely a decision based simply on the respective clarity of each analogy as "some may be more clumsy or more complex than others" and perhaps in deference to the impression of efficiency conjured by the governor.[136] The elements of the rod and horse analogies seem ill-suited to embody the components of the dynamical equations with which Maxwell begins, while these analogies taken as a whole are clumsy illustrations of Maxwell's discussion of dynamics more generally. Ultimately, Maxwell saw an advantage in using only the flywheel as an analogue of electromagnetic phenomena in his 1864 paper. I can only speculate that his familiarity with it from "Physical Lines" and its reputation for efficiency were deciding factors. Evidently Maxwell's favorable impression of the flywheel survived "Dynamical Theory" because, as mentioned above, he had an example built (see Fig. 2.4) as a teaching aid for the Cavendish.[137] In what follows, the advantages of founding this paper on an analogy to a mechanical flywheel will become apparent.

First, the structure and operation of the flywheel must be understood to make sense of the analogy Maxwell exploits to construct his equations of electromagnetism. A close look at the flywheel's mechanism is also a good reminder of what it owes to the Siemens governor. The two driving-wheels A and B are supported by separate axles geared into the central flywheel C. Both driving-wheels A and B have a string hung over them attached to a weight acting as a friction break on each wheel. The flywheel is nothing but two rods arranged like a cross with weights on all four ends and a single gear. The two driving-wheels turn their respective axles, each connected on the opposite end to a bevel gear, which allows for the transmission of motion at right angles. The flywheel has its own bevel gear loosely affixed to it, geared into the bevel gears at A and B. There is no requirement that the gearing ratios of these independent bevel gears be equal. The weighted flywheel is set perpendicularly to the axles of the driving-wheels. The flywheel's primary axis of rotation is a line that passes through the axles of the driving-wheels. The bevel gear on the flywheel C is only loosely attached and is thus able to rotate around the long axis of the flywheel, perpendicular to the primary rotation of the flywheel.

As mentioned above, the gearing ratios of those bevel gears directly attached to

[135] Maxwell (1873b, Vol. 2, p. 417).
[136] Maxwell (1995, p. 191, 197); Maxwell (1873b, Vol. 2, p. 417).
[137] Maxwell (2002, p. 421); Maxwell (1892, Vol. 2, p. 228).

the driving-wheels may be different and it is in this way that both wheels might spin at different constant velocities without accelerating the flywheel. Assuming for the moment that the gearing ratios of A and B are equivalent, we see that if the driving-wheels A and B rotate with opposite angular velocities such that the linear speed at the rim of each wheel is of equal magnitude, v, then the intermediary bevel gear on the flywheel C rotates around the long axis of the flywheel with an angular speed vr, where r is the radius of the bevel gear on the flywheel C. If A and B are made to rotate at different speeds, then the entire flywheel C will rotate around an axis through the centers of A and B with an angular speed equal to half of the difference between the magnitudes of the linear speeds of A and B at their peripheries multiplied by the length of one arm of the flywheel (from one end to the axis through A and B). If there is an acceleration of the velocity of driving-wheel A while B is at rest, then the flywheel C will not move at first, but its loosely attached bevel gear will communicate a motion to the wheel B in the opposite direction of that at A. As this motion at B is resisted by its attached hanging weight, this reaction by B as well as the force imparted by A will cause the flywheel C to rotate around the axis through the centers of A and B in the same direction as A and with an angular speed equal to half of the magnitude of the linear speed of A at its periphery multiplied by the length of one arm of C. As long as the driving-wheel A remains at a constant velocity, C will remain at this speed, rolling around B, which will eventually come to rest due to the resistance of the weighted string. Any acceleration of A will again drive an opposite motion in B. This is illustrated in Fig. 2.6. As a consequence of the weights in the system, we see a transfer of momentum, first from the accelerated driving-wheel to the flywheel, and then from the flywheel to the other driving-wheel, making this system particularly suited for the application of Lagrangian dynamics.

On the page immediately following his discussion of the "fly-wheel," Maxwell provides a Lagrangian account of a mechanical system. Although Maxwell's discussion of the flywheel is limited to the brief given at the beginning of this section, his Lagrangian analysis comfortably describes just such a system. Indeed both the flywheel and the abstract Lagrangian system aim to illustrate the same concept, namely reduced momentum. Maxwell's general Lagrangian system introduces two "driving-points" A and B and a connected body C. In unifying the mechanical systems involved in both the prior discussion of the "fly-wheel" and the more general description that immediately precedes Maxwell's mathematical investigation, the only leaps necessary are to equate the central flywheel connected to driving-*wheels* with the generic "body C" similarly attached to driving-*points* A and B and thus to make a jump from rotational to linear velocities. In the case of the flywheel, we take the mass of the central flywheel to be C. Maxwell sets u as the linear velocity of A, v as that of B, and w as the linear velocity of C, a motion we take to be analogous to the flywheel's primary rotation around the axis through A and B. The system is geared such that the veloc-

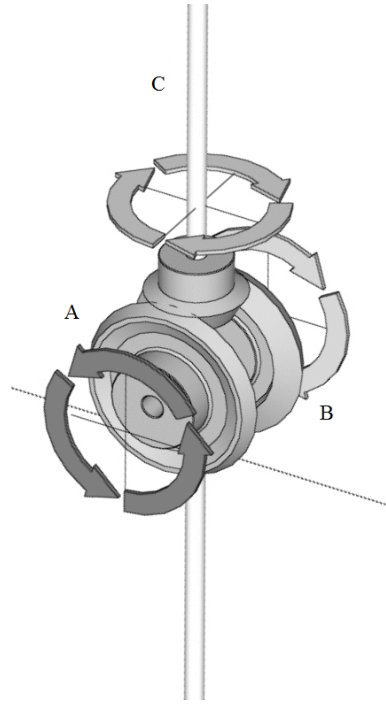


Figure 2.6: Mechanical Induction through the Flywheel

ity w of C is p times the velocity u of A and q times the velocity v of B. Using δx, δy, δz for the respective simultaneous displacements (δx and δy are independent) of A, B, and C, Maxwell obtains what he calls, citing Part II, Section 2, §5 of Lagrange's *Analytical Mechanics*, "the general equation of dynamics."[138] Lagrange's "general formula of dynamics for the motion of an arbitrary system of bodies" is represented as:[139]

$$\int \left(\frac{d^2x}{dt^2}\delta x + \frac{d^2y}{dt^2}\delta y + \frac{d^2z}{dt^2}\delta z \right) m + \int (P\delta p + Q\delta q + R\delta r + \ldots) \, m = 0. \tag{2.1}$$

Without parsing out Lagrange's more general dynamical equation, we can still recognize its paternity when we move back to Maxwell and his general equation of dynamics,

$$C\frac{dw}{dt}\delta z = X\delta x + Y\delta y, \tag{2.2}$$

which describes the balance of work in the system, where X and Y are the driving forces acting at A and B.

[138] Maxwell (1890a, p. 537).
[139] Lagrange (1997, p. 186).

Maxwell goes on to form two equations describing the relationship of linear velocities in parts of the system in terms of what amount to gearing ratios p and q. The first relates the accelerations at each of the points A, B, and C.

$$\frac{dw}{dt} = p\frac{du}{dt} + q\frac{dv}{dt}. \tag{2.3}$$

The second expresses the relation between their respective displacements.

$$\delta z = p\delta x + q\delta y. \tag{2.4}$$

Inserting Eqs. (2.3) and (2.4) into Eq. (2.2) and grouping δx and δy terms, Maxwell isolates X and Y, the forces at A and B.

$$\begin{aligned} X =& \frac{d}{dt}(Cp^2u + Cpqv), \\ Y =& \frac{d}{dt}(Cpqu + Cq^2v). \end{aligned} \tag{DT P.2 (1)}$$

In moving from Eqs. (2.2)–(2.4) to Eq. (DT P.2 (1)), Maxwell assumes that C, p, and q are constants. As we will see, Maxwell treats the electromagnetic analogues of these quantities as if they are time dependent. That Maxwell is willing to grant this latitude to quantities that would otherwise be treated as constants in a standard Lagrangian system suggests that he may be pursuing the physical analogy to the flywheel beyond what can be strictly justified by Lagrangian dynamics.

In Eq. (DT P.2 (1)), Maxwell arrives at a key concept that he will use to motivate his discussion of the electromagnetic field, namely the quantity he calls "reduced momentum." He defines the "momentum of C referred to A" as the momentum of C imparted by the force at the driving-point A, given by $(Cp^2u + Cpqv)$.[140] Similarly, the momentum of C referred to B is the momentum of C imparted by the force at the driving-point B and is given by $(Cpqu + Cq^2v)$. Reduced momentum is nothing but the momentum stemming from a particular force acting on the central body, C (or in the case of the flywheel, the central flywheel, C). Put another way, the effect of forces such as X and Y is to change the momentum of C in relation to the points A and B at which these forces are applied.

This simple system is generalized so that there may be an arbitrary number of bodies like C linked up to A and B, perhaps with different masses C and different gearing ratios p and q. That Maxwell appeared unconcerned with the potential mechanical difficulties of coupling an arbitrary number of these systems together demonstrates his move away from modeling electromagnetic phenomena and the ether itself, instead offering only a "dynamical illustration." The quantities Cp^2, Cpq, and Cq^2 in

[140] Maxwell (1890a, p. 537).

Eq. (DT P.2 (1)) then get replaced by sums over the different values of these three parameters

$$L = \sum(Cp^2) \quad M = \sum(Cpq) \quad N = \sum(Cq^2). \tag{2.5}$$

Note that L and N relate only to the driving force at their respective driving-point, A or B. In the electromagnetic case, L and N refer to the shapes of the circuits and act as coefficients of self-inductance. By contrast M, which in the electromagnetic case Maxwell refers to as the coefficient of mutual inductance, relates to the driving forces at both A and B. These quantities are loosely analogous to moments of inertia insofar as they measure resistance to rotational acceleration if we think in terms of an expanded flywheel system. The momentum referred to A is

$$Lu + Mv, \tag{2.6}$$

while the momentum referred to B is,

$$Mu + Nv. \tag{2.7}$$

The forces X and Y acting on A and B to drive the expanded system can then be written as before (cf. Eq. (DT P.2 (1))):

$$X = \frac{d}{dt}(Lu + Mv),$$
$$Y = \frac{d}{dt}(Mu + Nv). \qquad \text{DT P.2 (2)}$$

Resistance forces due to the weighted wires, which are also in reference to A or B and their respective velocities, take the form Ru and Sv as extra terms on the right-hand sides of these equations. The manner in which both resistance forces are incorporated in the electromagnetic case is demonstrated in Eqs. (DT P.2 (4))–(DT P.2 (5)) at the beginning of the next section.

Now is a convenient point to acknowledge yet another piece of evidence linking Maxwell's "fly-wheel" device and the Siemens governor. Although this Lagrangian analysis is supposedly general and does not immediately reference the flywheel within his "Dynamical Theory," very nearly the same equations of Lagrangian dynamics appear three years later in an investigation of differentially geared governors in his paper "On Governors."[141] As discussed above, this paper was already in progress *before* Maxwell began working on "Dynamical Theory." In "On Governors," Maxwell uses functionally identical mathematics, choosing many of the same of the same variable symbols, i.e., L, M, and N, to explore the Siemens governor (in the form employed at

[141] Maxwell (1890g, pp. 118–120).

the Greenwich Observatory) and produce a "Theory of Differential Gearing."[142] Just like the mathematics, Maxwell's description of the governor here would serve just as well as a description of his demonstration flywheel:

> In some contrivances the main shaft is connected with the governor by a wheel or system of wheels which are capable of rotation about the axis of the main shaft. These two axes may be at right angles, as in the ordinary system of differential bevel wheels; or they may be parallel, as in several contrivances adapted to clockwork.[143]

As Otto Mayr argues, this section of "On Governors" may have always been constructed in deference to the governor's dual role as a mechanical analogue of electromagnetic induction. The independence conditions worked out in the differential gearing section of "On Governors" were notably different from his concerns with stability earlier in the same paper. They appear to be Maxwell's effort to thoroughly check that the mechanical system could be trusted to illustrate electromagnetic induction (perhaps in preparation for building a physical model for the Cavendish).[144] The fact that Maxwell used nearly identical Lagrangian analysis in his 1864 paper and this later discussion of the Siemens governor also bolsters the claim that Maxwell conceived of the dynamical relations in his "Dynamical Theory" in terms of the flywheel/governor. Thus, while considering the nature of the flywheel in "Dynamical Theory," it is appropriate to keep in mind Maxwell's characterization of the differentially geared governor in "On Governors." When it is running well, the governor should be "in a proper state of efficiency."[145]

Returning to "Dynamical Theory," almost as an aside, Maxwell now makes a statement that finally leads us into his discussion of electromagnetism:

> If the velocity of A be increased at the rate du/dt, then in order to prevent B from moving a force, $\eta = d/dt(Mu)$ must be applied to it.[146]

This statement is key to understanding the connection between the mechanical illustration and electromagnetism. At the risk of belaboring the point, I will unpack this quotation to clarify the analogical relationship that Maxwell unveils. So that we might better understand what Maxwell had in mind, let us investigate how these relations are reflected in the operation of the flywheel. Consider the diagram in Fig. 2.6. As a result of the increase in velocity at A there is an indirect force on B, $-(d/dt)(Mu)$, that is to be canceled by η. Acceleration of the driving-wheel A causes

[142] See Fuller (1996) for a thorough account of this section of "On Governors."
[143] Maxwell (1890g, p. 118).
[144] Mayr (1971b, pp. 218–219).
[145] Maxwell (1890g, p. 120).
[146] Maxwell (1890a, p. 538).

an acceleration of the passive wheel B in the opposite direction. The force described that would "prevent B from moving" is then just the force we would have to apply to B to stop it accelerating as a result of the acceleration of A. The stopping force at B is the opposite of the force applied to B by our acceleration of the driving-wheel A.

The force on B as a result of action at A is mediated (hence the term indirect above) by the flywheel C, which Maxwell comes to see as the embodiment of the electromagnetic field. When a force is applied at A it leads to an increase in the momentum $Lu + Mv$ of the flywheel (cf. Eq. (DT P.2 (2))). This increase in the flywheel's momentum is defined as the reduced momentum of A. The flywheel's momentum then decreases over time as it acts on the passive wheel B. Fig. 2.6 illustrates how motion is transferred from A to B through the flywheel C. The force on B takes the form of a decrease in momentum of the flywheel in time, $-(d/dt)(Mu)$. This process of force transferal through the flywheel is the mechanical analogue of electromagnetic induction; in the electromagnetic case, the field moderates the transferal of forces between circuits. Maxwell goes on to say that this effect on B, $-(d/dt)(Mu)$, is consistent with the electromotive force on a circuit which arises from the increase in strength of a nearby circuit, namely it is the induced electromotive force. Just as the flywheel's momentum decreases as it acts on B, the electromagnetic momentum of the field decreases as a result of its action on a circuit. The induced current is such that it produces a force which acts counter to the change in current at A that produced the induced electromotive force. This is Lenz's law.

Naturally there are some similarities between the flywheel analogy and the honeycomb model presented in "Physical Lines." Both are capable of giving a mechanical account of electromagnetic induction; however, while this feature is the primary function of the flywheel analogy, it was merely an extension of the earlier model.[147] Nevertheless, the mechanical analogy in the 1864 paper is significantly more general, providing an illustration of connections between the field, represented by the central body or flywheel, and objects in it, represented as driving-points, not a hypothetical mechanical model of the microstructure of the electromagnetic ether. Additionally, while the specific flywheel analogy deals with rotations, Maxwell's Lagrangian dynamics is concerned exclusively with linear velocities. The mechanically grounded concept of electromagnetic momentum that is central to Maxwell's "Dynamical Theory" does not explicitly require considerations of rotation, in contrast to the crucial role played by torques in modeling electromagnetic induction in "Physical Lines."[148]

Maxwell concludes his dynamical illustration with a warning. Nevertheless, this should not be taken as a threat to the project of elevating the relative status of flywheel analogy in the historical literature that surrounds "Dynamical Theory."

[147] Siegel (1991, p. 71).
[148] Siegel (1991, p. 73).

> This dynamical illustration is to be considered merely as assisting the reader to understand what is meant in mechanics by Reduced Momentum. The facts of the induction of currents as depending on the variations of the quantity called Electromagnetic Momentum, or Electrotonic State, rest on the experiments of Faraday, Felici, &c.[149]

As will be made clear in the following sections, the concept of electromagnetic momentum which is so central to Maxwell's "Dynamical Theory" is itself grounded in the mechanical concept of reduced momentum, and its role in guiding Maxwell's mathematical analysis is governed by his exploitation of analogical links to the flywheel that suggest particular derivations of certain electromagnetic expressions. The facts of electromagnetic phenomena supplied by "the experiments of Faraday, Felici, &c" are necessary for the mechanical analogy to hold; without electromagnetic phenomena similar in action to the mechanical processes there would be no analogical link through which the flywheel or even his abstract Lagrangian dynamics could affect Maxwell's investigation of electromagnetism, no "partial similarity between the laws of one science and those of another which makes each of them illustrate the other."[150] The accounts of Maxwell's mathematical analysis that follow serve to highlight the importance of the flywheel/governor to his "Dynamical Theory" and the analogically grounded concept of electromagnetic momentum, a role that had previously been obscured in the literature by the choice to substitute electromagnetic momentum for the vector potential. Working within Maxwell's original formalism makes it much easier to appreciate the significance of the mechanical analogy that guided his analysis.

2.7 Mobilizing the Mechanical Analogy to Analyze the Effects of Circuits through the Field

Before examining the specific electromagnetic examples that Maxwell lays out, it is critical to understand the basic connections between the mechanical flywheel and electromagnetism that constitute the analogical link. Maxwell begins anew with two conducting circuits A and B instead of driving-points, while keeping in mind the lessons laid out in the preceding section. The currents x and y in A and B take the place of the velocities at the driving-points, a reasonable substitution as currents also represent a change in time. L, M, and N now represent quantities that depend on the form and relative position of the circuits, L describing the form of circuit A, N of circuit B, and M the relative position of A and B. Insofar as these quantities were

[149] Maxwell (1890a, p. 538).
[150] Maxwell (1890f, p. 156).

originally made up of gearing ratios and the summed weights of the central flywheels in the flywheel system, together expressing the driving-wheels' moments of inertia, a strong analogy holds between their use in the mechanical and electromagnetic case. Lenz's law in the electromagnetic case is drawn directly from the construction of the mechanical example and the way motion is transferred from one driving-wheel, through the gears and flywheels to the other driving-wheel, always resulting in an acceleration opposed to that which initially drove the system. If we continue to think in terms of the flywheel analogy, the C's of our expanded mechanical system, the weighted flywheels being acted on by the driving-wheels, can now be thought of as expanding into all space and representing the field. The quantity for which Maxwell coined the term electromagnetic momentum is analogous to the reduced momentum that existed in the flywheel or system of flywheels. If the analogy holds, then electromagnetic momentum extends from the wires throughout the unbounded field. As such, in accordance with the mechanical illustration, the reduced electromagnetic momentum of A is

$$Lx + My, \tag{2.8}$$

and that of B is

$$Mx + Ny. \tag{2.9}$$

ξ, the electromotive force due to changes in A, be they changes in the strength of the current, the form of the circuit, or its relative position with respect to another circuit of current y, is given by

$$\xi = Rx + \frac{d}{dt}(Lx + My), \qquad \text{DT P.2 (4)}$$

and the force, η, which arises from changes at B, by

$$\eta = Sy + \frac{d}{dt}(Mx + Ny), \qquad \text{DT P.2 (5)}$$

where R and S are coefficients of resistance.

In the sections that follow, I investigate Maxwell's approach to more specific cases of circuits acting on passive circuits by way of the field. It will be helpful to keep in mind not only the basic electromagnetic properties discussed above, but also the analogous mechanical operations that underpin them.

2.7.1 Induction of a Current by Another Through the Field[151]

It is not trivial to grasp the idea that a current in one circuit should induce a current in some other passive circuit in the field. The mechanical analogy grounds current-

[151] Section titles closely resemble Maxwell's own titles and proceed in the order given in Maxwell's "Dynamical Theory."

current interactions in clear physical concepts, illustrating the dynamical connection between components in the electromagnetic case. The flywheel analogy elucidates Maxwell's statement that "since the two currents are in connexion with every point of the field, they will be in connexion with each other."[152] Just as the driving-wheels are geared into the flywheel, the circuit should be imagined as being "geared into" the electromagnetic field. The continuity of the ether as well as its efficiency, which Maxwell emphasized when writing generally about the ether, are here emphasized by the structure and flywheel/governor and the analogy linking it with electromagnetism.

Consider the induction of a current in the passive circuit B by that of the active circuit A.[153] We are told that N remains constant, which is to say that circuit B is rigid. Additionally, without some initial current driving B (B is a passive circuit), the equation describing the electromotive force due to B vanishes, i.e., $\eta = 0$. The product Ny vanishes as B does not impress a force on A through the field, nor can it initially self-induce a force. Thus, Eq. (DT P.2 (5)) reduces to

$$Sy + \frac{d}{dt}(Mx) = 0. \tag{2.10}$$

As we can see from this equation describing the process of induction of B by A, there are two distinct ways in which this phenomenon can arise, depending on which variable is held constant, M or x. If M is held constant and x is allowed to vary, then a current y in B will be induced by the variation of the current in A, while both circuits remain fixed with respect to their relative positions. If we allow M to vary and hold x constant, then a current y in B will be induced by a change in the relative position of the two circuits, the current in A remaining constant. If we think in terms of the flywheel analogy, the distinction between these two types of induction becomes immediately apparent. The latter case, where M is said to vary, is analogous to a manipulation of both gearing ratios in the flywheel system, while the former is analogous to the acceleration of the driving-wheel A. The flywheel/governor suggests an inherent physical difference between these two causes of induction. One arises from a change in the free variable of the system (velocity of a driving-wheel), while the other requires a physical alteration of the setup of the system itself (altering gearing ratios). We will follow Maxwell's lead and analyze these two possible causes for induction separately.

Induction of a Current by the Variation of Another

Consider the case that the only electromotive force acting on B is due to the increase in the current in A from 0 to x. In that case M is constant, meaning the circuits

[152] Maxwell (1890a, p. 537).
[153] Maxwell (1890a, p. 540).

will not move relative to one another, and they will not change shape, otherwise this motion would produce an additional electromotive force.

As M is constant, Eq. (2.10) gives

$$Sy + M\frac{dx}{dt} = 0 \quad \longrightarrow \quad y = -\frac{M}{S}\left(\frac{dx}{dt}\right). \tag{2.11}$$

A force arising from the change, dx/dt, in the current at A affects the field, and then acts on the current y through the coefficient of mutual inductance M that relates the relative positions of the two circuits. The electromagnetic momentum of the field is exhausted as its electromagnetic momentum is transferred to B. The analogous mechanical case has already been laid out by Maxwell in his stopping force example. If we again take refuge in the flywheel analogy, an increase in the velocity of A acts through the central flywheel to transfer momentum to B in accordance with the coefficient M. The negative sign is indicative of Lenz's law, such that the induced electromotive force produces a current which will oppose the change that produced it. Maxwell goes on to integrate Eq. (2.11) getting what he calls the "total induced current," or the total charge passing through B due to the increase in current at A from 0 to x.[154]

Induction of a Current by the Motion of the Circuit

Next Maxwell investigates the induced electromotive force on B due to the two circuits A and B approaching one another. Such a motion will be represented by a change in the coefficient of mutual inductance, M. In this case, Eq. (2.10) gives

$$Sy + x\frac{dM}{dt} = 0 \quad \longrightarrow \quad y = -\frac{x}{S}\frac{dM}{dt}. \tag{2.12}$$

Again Maxwell finds that the induced electromotive force on B follows from a reduction of electromagnetic momentum in the field through its transfer to B, producing a current opposed to the change which produced it, in agreement with Lenz's law. Here the analogous mechanical effect would involve the increase of both gearing ratios which make up the M term, causing an increase in the momentum of the flywheel by the action of A, and subsequently a decrease in the momentum of the flywheel as this momentum is received by B.

The work done by viewing both of these cases of induction through the lens of the flywheel is twofold. First, it clearly delineates the two cases of induction by reference to specific elements in the mechanical case, as they "resemble[ ] rather the reduced momentum of a driving-point of a machine influenced by its mechanical

[154] Maxwell (1890a, p. 540).

connexions."[155] Second, it provides clear physical concepts through which we may come to terms with these electromagnetic phenomena: "L, M, N correspond to the same quantities in the dynamical illustration, except they are supposed to be capable of variation when the conductors A or B are moved."[156]

2.7.2 Equation of Work and Energy

To form the equation of total work in unit time (power) done by both circuits A and B, Maxwell proceeds analogously to a mechanical system, multiplying the electromotive forces ξ and η (from Eq. (DT P.2 (4)) and (DT P.2 (5))) by the currents x and y respectively (in the mechanical case, the power, P, is given by the inner product, $\mathbf{F} \cdot \mathbf{v}$)[157]

$$\xi x + \eta y = Rx^2 + Sy^2 + x\frac{d}{dt}(Lx + My) + y\frac{d}{dt}(Mx + Ny). \qquad \text{DT P.2 (8)}$$

After dropping the terms Rx^2 and Sy^2, the energy lost as heat due to resistance, we can rewrite the right-hand side of Eq. (DT P.2 (8)) as:

$$\frac{1}{2}\frac{d}{dt}\left(Lx^2 + 2Mxy + Ny^2\right) + \frac{1}{2}\frac{dL}{dt}x^2 + \frac{dM}{dt}xy + \frac{1}{2}\frac{dN}{dt}y^2. \qquad (2.13)$$

When L, M, and N are constant, the last three terms in Eq. (2.13) vanish. What is left is "the whole intrinsic energy of the currents" or the change in the energy contained within the field due to the currents x and y. Maxwell makes a prescient but guarded follow-up point, noting that as the currents are time derivatives, this energy "probably exists as actual motion, the seat of this motion being not merely the conducting circuits, but the space surrounding them." This motion and the energy is in the field, although it is "in a form imperceptible to our senses."[158] While the dynamical theory will make no specific claims about the field, Maxwell's analogical reasoning has effectively physicalized empty space. As Simpson puts it, "*space* is not an empty geometrical container but a coherent, connected physical system bearing the energy of motion."[159] By analogy to the flywheel, the properties of the field resemble those of a moment of inertia, a physical concept adapted to the field, but stripped of the immediate perceptibility it had in the earlier mechanical illustration.

The last three terms in Eq. (2.13) in which L, M, and N are variable describe the work done in unit time by the "alterations in the form and position of the conducting

[155] Maxwell (1890a, p. 539).
[156] Maxwell (1890a, p. 539).
[157] Maxwell (1890a, p. 541).
[158] Maxwell (1890a, p. 541).
[159] Simpson (1997, p. 312).

circuits A and B."[160] Maxwell goes on to note that this impressed force must in fact be a simple mechanical force acting on a body, such as a conductor in one of the circuits, a very tangible action with electromagnetic consequences in the field. This equation then is taken to be the work done during these mechanical alterations of the circuit.[161]

Maxwell concludes this section with a justification of the dynamical project which will follow in the next section on the "General Equations of the Electromagnetic Field." If the unresisted part of an acting electromotive force generates

> a self-persistent state of the current, which we may call (from mechanical analogy) its electromagnetic momentum, and [if] this momentum depends on circumstances external to the conductor, then both induction of currents and electromagnetic attractions may be proved by mechanical reasoning.[162]

Essentially Maxwell is outlining his plan of attack for the next section. If he has been justified in using the mechanical illustration and thus, as we have suggested, the flywheel to investigate how electromotive forces arising from changes in circuits affect the electromagnetic field, then such reasoning should work equally well in reverse. In the "General Equations" section, Maxwell will draw on his mechanical analogy to the flywheel to inform his investigation of induced electromotive forces, i.e., his investigation of how electromotive forces arising from changes in the electromagnetic field "due to any system of magnets or currents" affect circuits.[163]

2.8 General Equations of the Electromagnetic Field: Constructing a Generalized Induced Electromotive Force[164]

As noted at the conclusion of the preceding section, the equations that Maxwell derives in the rest of "Dynamical Theory" are no longer from the point of view of driving-wheels or circuits. Rather, they are primarily equations of induction, describing the action of the electromagnetic field on circuits. The primary focus of this

[160] Maxwell (1890a, p. 542).

[161] Maxwell's comment that this mechanical force acts to maximize L, M, and N remains puzzling. Maxwell (1890a, p. 542).

[162] Maxwell (1890a, p. 542).

[163] Maxwell (1890a, p. 555).

[164] I am skipping Maxwell's extended attempt to "bring these results within the range of experimental verification" and picking up again at the beginning of Part III, "General Equations of the Electromagnetic Field."

section is to reconstruct Maxwell's approach to deriving a fully generalized equation for the induced electromotive force on a conductor. Although there will be additional applications of the flywheel analogy within specific subsections, the most striking example of the way in which the flywheel guides Maxwell's mathematics can be seen in the specific choices he makes in breaking up the analysis of induced electromotive force in a circuit. Maxwell builds the fully generalized induced electromotive force from two constituent parts, the induced electromotive force due to changes in the electromagnetic momentum of the field and the induced electromotive force due to a motion of the circuit through the field. Dividing the analysis of the electromotive force in such a way is suggested by analogy to the flywheel itself and the distinct physical difference it draws between the effects of the acceleration of a driving-wheel (changes in currents, which define the electromagnetic momentum of the field in most examples) and changes in gearing ratios (changes in the form and/or position of a circuit). This physical distinction between two different origins of the same force in the flywheel carries over into the general equations section of this paper and ultimately guides Maxwell's analysis and assembly of the fully general equation for induced electromotive force on a moving conductor.

In his 1864 paper, Maxwell did not yet use the elements of vector calculus that later appear in his *Treatise on Electricity and Magnetism*. To save ourselves from rewriting each equation for each component while at the same time maintaining the ease of comparison between our reconstruction and Maxwell's text, we will write vectors by putting their three components in parentheses, (x, y, z).

2.8.1 Electromotive Force (P, Q, R) and Electromagnetic Momentum (F, G, H)

Analogous to Newtonian mechanics whereby the force is equal to the time derivative of momentum,

$$\mathbf{F} = \frac{d\mathbf{p}}{dt}, \quad \text{or} \quad (F_x, F_y, F_z) = \frac{d}{dt}(p_x, p_y, p_z), \tag{2.14}$$

the electromotive force at an arbitrary point in the field will be equal to a change in momentum, albeit with a negative sign to denote that it is an induced electromotive force which arises through a decrease in electromagnetic momentum in the field in accordance with Lenz's law.[165] Unlike what we have seen from Maxwell before, electromagnetic momentum expressed in this relation is localized at a point in the field and entirely general, insofar as it does not refer to any specific driving-points which create the field.

$$(P, Q, R) = -\frac{\partial}{\partial t}(F, G, H) \qquad \text{DT P.3 (29)}$$

[165] See the ends of Section 2.6 and Section 2.7 for more detailed discussions of this relation.

In modern notation this equation may be rewritten:

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial \mathbf{t}}. \tag{2.15}$$

where **A**, now called the "vector potential," plays the role of Maxwell's electromagnetic momentum.

2.8.2 Electromagnetic Momentum of a Circuit

Returning to his concept of reduced momentum, Maxwell's mechanical analogy informs his definition of the total electromagnetic momentum referred to the circuit. The total electromagnetic momentum referred to the circuit is represented by a line integral of the electromagnetic momentum (F, G, H) over the circuit. Although it may initially appear unjustified, this expression is a natural consequence of his mechanical analogy to the flywheel. The circuit should be thought of as "geared into" the field at every point around its entire length:

> In the case of electric currents, the force in action is not ordinary mechanical force... but something outside the conductor, and capable of being affected by other conductors in the neighbourhood carrying currents. In this it resembles rather the reduced momentum of a driving-point of a machine as influenced by its mechanical connexions, than that of a simple moving body like a cannon ball, or water in a tube.[166]

Based on the mechanical presumptions that ground Maxwell's approach, the circuits, like the analogous driving-wheels in the flywheel analogue, must be in dynamical connection with other structures through the field, in which case "currents are in connexion with every point of the field" and the line integral of electromagnetic momentum around the circuit is the correct representation of the circuit's total electromagnetic momentum.[167] While Maxwell does expect this continuity from the ether, having already provided much of the foundation for this theory, the flywheel provides another justification and some further evidentiary support for this property of the ether.

$$\oint_{\text{circuit}} (F, G, H) \cdot d\mathbf{l}. \tag{2.16}$$

Using Stokes' theorem, we can rewrite this as,

$$\oint_{\partial \mathbf{S}} (F, G, H) \cdot d\mathbf{l} = \iint_{\mathbf{S}} \text{curl}(F, G, H) \cdot d\mathbf{S} \qquad \text{DT P.3 (30)}$$

[166] Maxwell (1890a, p. 539).
[167] Maxwell (1890a, p. 537).

$$\text{curl}(F, G, H) = \left(\frac{\partial H}{\partial y} - \frac{\partial G}{\partial z}, \frac{\partial F}{\partial z} - \frac{\partial H}{\partial x}, \frac{\partial G}{\partial x} - \frac{\partial F}{\partial y} \right), \tag{2.17}$$

where $\mathbf{S}$ is a surface and $\partial\mathbf{S}$ is the edge of the surface, coinciding with the circuit.

As Maxwell's quantity of total reduced electromagnetic momentum is equivalent to Faraday's "Electro-tonic State," it is ostensibly a measure of the strength of the field, or "the number of lines of magnetic force which pass through it [the circuit]."[168] Thus Maxwell is able to find support for his mathematical representation of the electromagnetic momentum of the circuit not only from his flywheel analogy but also from the physical geometry he had developed in "On Faraday's Lines of Force."[169]

Magnetic Force (α, β, γ)

Maxwell's investigation of electromagnetic momentum of a circuit yielded a measure of the strength of the magnetic field passing through the circuit. The magnetic force per unit area is thus the integrand of the surface integral on the right-hand side of Eq. (DT P.3 (30))

$$\mu\,(\alpha, \beta, \gamma) = \text{curl}(F, G, H), \qquad \text{DT P.3 (B)}$$

where μ is "the ratio of magnetic induction in a given medium to that in air under an equal magnetizing force."[170] In modern notation,

$$\mathbf{B} = \text{curl}\,\mathbf{A}. \tag{2.18}$$

2.8.3 Electromotive Force in a Circuit

The role of the flywheel in the case of induced electromotive force in a circuit mirrors its use in the case of the reduced electromagnetic momentum of the circuit. Again we should think in terms of the flywheel: the electromagnetic momentum referred to the circuit is related to the form and relative position of the circuit (gearing ratios in the mechanical case). Maxwell founds his construction of an equation for electromotive force on the expression for the total electromagnetic momentum in the circuit, a line integral of electromagnetic momentum over the circuit, set equal to another expression of total momentum,

$$\oint_{\partial\mathbf{S}} (F, G, H) \cdot d\mathbf{l} = Lu + Mv. \qquad \text{DT P.3 (33)}$$

This other expression of total momentum, $Lu+Mv$, is just the expression for reduced momentum in the mechanical case that Maxwell derived in conjunction with the

[168] Maxwell (1890a, p. 556).
[169] Maxwell (1890f).
[170] Maxwell (1890a, p. 556).

flywheel analogy. In the equation above, the total momentum referred to the driving-point A (cf. Eq. (2.6)) is set equal to the total electromagnetic momentum of the field referred to the circuit A (cf. Eq. (DT P.3 (30))).

Note that Maxwell is mixing electromagnetic and mechanical terms in this equation. He forgoes including the equivalent electromagnetic quantities, choosing the velocities u and v instead of the currents x and y. In this first step towards constructing a generalized equation of electromotive force, consciously or not, Maxwell ultimately grounds his analysis in the relations obtained through his mechanical analogy to the flywheel.

It follows that ξ, the complete induced electromotive force on A arising from both self and mutual induction (the opposite of Eq. (DT P.2 (2)), in the mechanical analogue and the opposite of Eq. (DT P.2 (4)) without resistance forces in the electromagnetic case), is given in terms of the total momentum by:

$$\xi = -\frac{d}{dt}(Lu + Mv), \qquad \text{DT P.3 (34)}$$

where the right-hand side is again expressed as a mechanically derived quantity. Using Eq. (DT P.3 (33)), we can also write the right-hand side in explicitly electromagnetic terms,

$$-\frac{d}{dt}\oint_{\partial \mathbf{S}} (F, G, H) \cdot d\mathbf{l}. \tag{2.19}$$

With the help of Stokes' theorem, the line integral above can be rewritten as

$$-\frac{d}{dt}\iint\limits_{\mathbf{S}} \text{curl}(F, G, H) \cdot d\mathbf{S} = -\iint\limits_{\mathbf{S}} \frac{\partial}{\partial t}\text{curl}(F, G, H) \cdot d\mathbf{S} = -\iint\limits_{\mathbf{S}} \text{curl}\,\frac{\partial}{\partial t}(F, G, H) \cdot d\mathbf{S}. \tag{2.20}$$

The circuit should still be thought of as "geared into" the field at every point around its entire length justifying the use of another line integral to describe the total induced electromotive force "in a circuit." Thus, the left-hand side of Eq. (DT P.3 (34)) becomes

$$\oint_{\partial \mathbf{S}} (P, Q, R) \cdot d\mathbf{l}. \qquad \text{DT P.3 (32)}$$

Using Stokes' theorem again, we can rewrite this integral as

$$\iint\limits_{\mathbf{S}} \text{curl}(P, Q, R) \cdot d\mathbf{S}. \tag{2.21}$$

Substituting expressions (2.21) and (2.20) for the left and right-hand sides of Eq. (DT P.3 (34)), respectively, we find:

$$\iint\limits_{\mathbf{S}} \text{curl}(P, Q, R) \cdot d\mathbf{S} = -\iint\limits_{\mathbf{S}} \text{curl}\,\frac{\partial}{\partial t}(F, G, H) \cdot d\mathbf{S}. \tag{2.22}$$

It follows from this equation that (P, Q, R) should be equal to $-\frac{\partial}{\partial t}(F, G, H)$ *modulo* a term $\nabla\psi$, since $\mathrm{curl}(\nabla\psi) = 0$ for any ψ. Therefore,

$$(P, Q, R) = -\frac{\partial}{\partial t}(F, G, H) - \nabla\psi, \qquad \text{DT P.3 (35)}$$

or in modern terms

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} - \nabla\varphi. \qquad (2.23)$$

And thus we have recovered Maxwell's "indeterminate" electric potential, the gradient of ψ. While ψ cannot effect a current in a circuit, it is supposed to indicate "the existence of a force urging the electricity to or from certain definite points in the field."[171] Factoring in circuits and currents and looking at the induced electromotive force around the length of the circuit A, as opposed to dealing with electromotive force at some arbitrary point in the field, changes Eq. (2.15), $\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t}$, to Eq. (2.23), $\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} - \nabla\varphi$ (where φ is the electric potential).

2.8.4 Electromotive Force on a Moving Conductor

Finally, to complete his project of constructing a generalized equation of induced electromotive force on an element in the field, Maxwell considers the effect of changes to the form and position of a circuit on the electromagnetic momentum of that circuit. Maxwell aims to find the induced electromotive force on a moving conductor by introducing correction terms for the expression of induced electromotive force on a rigid and stationary circuit given in Eq. (DT P.3 (35)). It may appear odd that Maxwell was driven to complicate this demonstration of the electromotive force on a moving conductor by also considering a change in form of the circuit. A modern course on electricity and magnetism and even the reconstruction of this paper in Simpson's guided study involve only the motion of a rigid circuit through the field or deal exclusively with the moving conductor and the field. Simpson's modernized derivation of $\mathbf{v} \times \mathbf{B}$ describes it as merely as "the expression for the electromotive force $\mathbf{E}$ induced in a conductor moving in a field of magnetic flux $\mathbf{B}$ with a velocity $\mathbf{v}$."[172] Why divide this analysis of a moving conductor up into elements "due to the motion of [the] conductor" and others "due to the lengthening of [the] circuit," and why begin with the total electromagnetic momentum of the circuit at all?[173] Would it not be much simpler to just start with a rigid circuit moving through the field and then analyze the force on it by the field, or perhaps analyze the force on the moving conductor directly?

[171] Maxwell (1890a, p. 558).
[172] Simpson (1997, p. 380).
[173] Maxwell (1890a, p. 559).

To understand Maxwell's reasoning for complicating this problem, we must take a closer look at the system Maxwell investigates and the specific question he seeks to answer. A conductor which makes up the circuit and the circuit itself are allowed to move, putting not only the entire circuit in motion through the field, but lengthening the circuit as well (as pictured in Fig. 2.7).

> Let a short straight conductor of length a, parallel to the axis of x, move with a velocity whose components are dx/dt, dy/dt, dz/dt, and let its extremities slide along two parallel conductors with a velocity ds/dt. Let us find the alteration of the electromagnetic momentum of the circuit of which this arrangement forms a part.[174]

The motion of the short straight conductor, dx/dt, dy/dt, dz/dt, is an absolute motion in all directions simultaneously. The wires that make up the whole circuit are also in motion; however, Maxwell only provides the relative velocity of the conductor with regard to the circuit, ds/dt. Thus, the whole circuit not only possesses some absolute motion, it also expands in all directions as the conductor rolls along its wires, due to the difference between the circuit's motion and the motion of the short straight conductor. Initially at least, Maxwell is purely concerned with deriving the change in the total electromagnetic momentum (cf. Eq. (DT P.3 (30))) of the circuit as a result of the absolute motion of the circuit, only later will he use this expression to determine the electromotive force on a moving conductor.

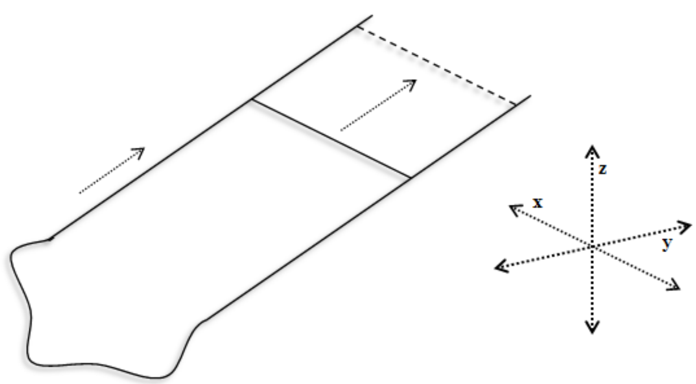


Figure 2.7: Total Motion of the Conductor and Circuit

From Maxwell's description of electromotive force, in this case the P-component, "represent[ing] the difference of potential per unit of length in a conductor placed in the direction of x at the given point," we gather that a straight conductor parallel to

[174]Maxwell (1890a, p. 558).

an axis may only change the component of electromagnetic momentum corresponding to the axis to which it lies parallel. Using this, we consider a few special cases.[175]

First, as shown in Fig. 2.8, we examine the case of the short straight conductor moving along the axis of y with velocity dy/dt. The rest of the circuit is also moving in the y-direction and the relative velocity of the short straight conductor with regard to the circuit is ds/dt.

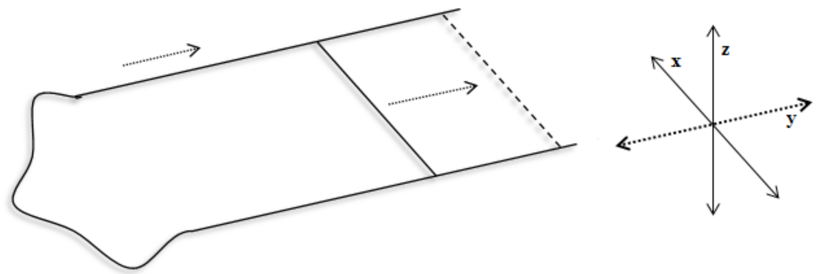


Figure 2.8: Motion of the Conductor and Circuit in the y-direction

Due to its orientation, the conductor is only able to affect the x-component of electromagnetic momentum, F. The conductor will produce a change in electromagnetic momentum that corresponds to its changing position on the y axis.

$$a\frac{\partial F}{\partial y}\frac{dy}{dt} \tag{2.24}$$

The relative motion of the conductor along the y axis with regard to the circuit, ds/dt, will naturally cause an expansion of the circuit. The wires of the circuit which lie parallel to the y axis will lengthen, dy/ds, altering the y-component of electromagnetic momentum G, per unit length in x,[176] resulting in the expression:

$$a\frac{ds}{dt}\frac{\partial G}{\partial x}\frac{dy}{ds} = a\frac{\partial G}{\partial x}\frac{dy}{dt}. \tag{2.25}$$

Maxwell is interested in the change in electromagnetic momentum of the circuit as a result of the absolute motion of the circuit through the field. To transform these changes in electromagnetic momentum due to the motion of the conductor and due

[175] Maxwell (1890a, p. 555).

[176] Here we are looking at the electromagnetic momentum of a circuit (not a single conductor as before) from a perspective such that the circuit is defined as the boundary of the area $dydx$. As the circuit lengthens in the y-direction, the area increases per unit length in x. As such, the number of lines of magnetic force that pass through the circuit will also increase per unit length in x. If we remember that the number of these lines is a measure of electromagnetic momentum, the fact that the expansion is in the y-direction entails a change in G, the y-component of electromagnetic momentum, per unit length in x (cf. p. 65).

to the change in configuration of the circuit into the expression for the motion circuit as a whole, we must subtract Eq. (2.25) from Eq. (2.24), the terms which result from the relative motion of the conductor with regard to the circuit from those which stem from the absolute motion of the conductor. This gives the change in electromagnetic momentum due to the total absolute change in position of the circuit:

$$a\frac{\partial F}{\partial y}\frac{dy}{dt} - a\frac{\partial G}{\partial x}\frac{dy}{dt} = a\left(\frac{\partial F}{\partial y} - \frac{\partial G}{\partial x}\right)\frac{dy}{dt}. \tag{2.26}$$

The factor in parentheses is just minus the z-component of curl(F, G, H), which by Eq. (DT P.3 (B)) is equal to the z-component of the magnetic field, $\mu\,(\alpha, \beta, \gamma)$; hence, the right-hand side of Eq. (2.26) can be written as

$$-a\mu\gamma\frac{dy}{dt}. \tag{2.27}$$

Now consider the case of motion in the z-direction. To imagine this we may simply switch the labeling of the axes in Fig. 2.8 to obtain Fig. 2.9 below.

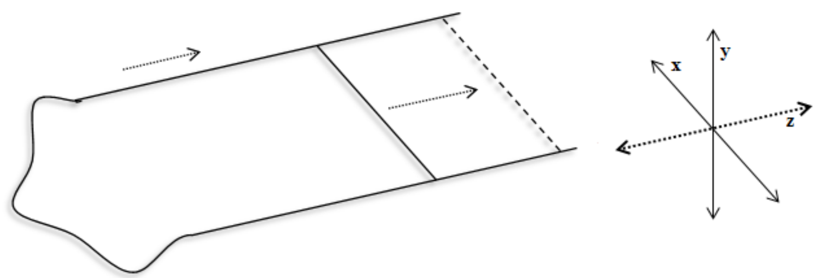


Figure 2.9: Motion of the Conductor and Circuit in the z-direction

Working similarly with this orthogonal case of motion and expansion along the z axis, we find

$$a\frac{dF}{dz}\frac{dz}{dt} - a\frac{dH}{dx}\frac{dz}{dt} = a\left(\frac{dF}{dz} - \frac{dH}{dx}\right)\frac{dz}{dt} = a\mu\beta\frac{dz}{dt}, \tag{2.28}$$

where in the last step we used that the expression in parentheses is the y-component of curl(F, G, H), which by Eq. (DT P.3 (B)) is equal to $\mu\beta$.

Finally, if we follow these same steps but for a motion of the conductor parallel to x and an expansion of the circuit along the x axis, there will be no change in the electromagnetic momentum of the circuit:

$$a\frac{\partial F}{\partial x}\frac{dx}{dt} - a\frac{\partial F}{\partial x}\frac{dx}{dt} = 0. \tag{2.29}$$

To find the total change in electromagnetic momentum in the case of a simultaneous motion of the conductor parallel to the x axis in all three directions we add up the terms from Eq. (2.27) and Eq. (2.28)

$$-a\mu\gamma\frac{dy}{dt} + a\mu\beta\frac{dz}{dt} = a\mu\left(\beta\frac{dz}{dt} - \gamma\frac{dy}{dt}\right). \tag{2.30}$$

As Maxwell has been interested in determining the induced electromotive force (P, Q, R), or the decrease over time of the electromagnetic momentum of the field which is to be transferred to the circuit due to its motion (cf. Eq. (DT P.3 (29))), he must use the opposite of Eq. (2.30), the total change in the electromagnetic momentum of the circuit, to form P. Although Maxwell began this investigation looking at changes to the electromagnetic momentum of the circuit due to the motion of the circuit, by definition the components of electromotive force (P, Q, R) only affect conductors lying parallel to the relevant axes, and thus P is the electromotive force on the moving conductor parallel to the x axis. Additionally, as (P, Q, R) is measured in unit length, we find that the x-component of the electromotive force on the conductor is given by

$$P = \mu\gamma\frac{dy}{dt} - \mu\beta\frac{dz}{dt}. \qquad \text{DT P.3 (36)}$$

This is the x-component of the cross-product of the velocity $(\dot{x}, \dot{y}, \dot{z})$ and the $\mathbf{B}$-field $\mu(\alpha, \beta, \gamma)$.

In the cases of the conductor lying parallel to the y or z axes, minor variations yield results for Q and R. Eq. (DT P.3 (36)) is a correction to Eq. (DT P.3 (35)) to account for the effects due to the motion of a conductor. The completed generalized equation of induced electromotive force (P, Q, R) is then

$$\begin{aligned} P &= \mu\left(\gamma\frac{dy}{dt} - \beta\frac{dz}{dt}\right) - \frac{\partial F}{\partial t} - \frac{\partial \psi}{\partial x} \\ Q &= \mu\left(\alpha\frac{dz}{dt} - \gamma\frac{dx}{dt}\right) - \frac{\partial G}{\partial t} - \frac{\partial \psi}{\partial y} \\ R &= \mu\left(\beta\frac{dx}{dt} - \alpha\frac{dy}{dt}\right) - \frac{\partial H}{\partial t} - \frac{\partial \psi}{\partial z}. \end{aligned} \qquad \text{DT P.3 (D)}$$

In terms we recognize it is[177]

$$\mathbf{F} = \mathbf{v} \times \mathbf{B} - \frac{\partial \mathbf{A}}{\partial t} - \nabla\varphi. \tag{2.31}$$

[177]We might also recognize that $-\partial\mathbf{A}/\partial t - \nabla\varphi = \mathbf{E}$ and thus Eq. (2.31) is essentially the Lorentz Force.

Substituting in the relation between **B** and **A** that Maxwell established in his discussion of magnetic force, we may rewrite the equation:[178]

$$\mathbf{F} = \mathbf{v} \times (\text{curl}\mathbf{A}) - \frac{\partial \mathbf{A}}{\partial t} - \nabla\varphi. \tag{2.32}$$

Returning to the question with which we began this discussion, why then did Maxwell complicate this derivation by changing the shape of the circuit and beginning with the total electromagnetic momentum of the circuit if he ends up with the same equations for induced electromotive force as the much simpler alternatives? The answer to our question is that the machine underpinning Maxwell's "Dynamical Theory" suggests this more convoluted analytical route. The concept of electromagnetic momentum is at the heart of the flywheel analogy and although the line integral of electromagnetic momentum around the circuit has replaced the more evidently mechanical quantity of reduced/electromagnetic momentum, $Lu + Mv$, Maxwell's analysis still follows the path suggested by the dynamical analogy and describes the initial system in terms of the total electromagnetic momentum of a circuit. For a passive or driving-wheel the expression describing its total induced force from the flywheel contains both terms L (or N) and M, which in the case of the flywheel contains the gearing ratios of both wheels. In electromagnetism, L refers to the form of the circuit and M to its relative position. The flywheel itself suggests the grouping of analysis by types which are mechanically defined, but also indicates that changes in M necessarily impact L or N. Having already covered induced electromotive forces due to changes in the electromagnetic momentum of the field (in the mechanical case changes in the velocity of driving-wheels), the final step is to cover induced electromotive forces due to motion of a circuit through the field (changes in gearing ratios). In deriving the effect of the field on a moving circuit, the technological foundations of this paper demand an analysis of a change in form of the circuit in motion so that its effect on the electromagnetic momentum of the circuit can be removed, isolating the change due to the absolute motion of the circuit itself. After a careful setup and analysis, Maxwell is able to remove the change in electromagnetic momentum due the alteration of the circuit's configuration and isolate the change due to the motion of the circuit (the same result as starting with a moving rigid circuit). Nonetheless, it is the analogy to the flywheel that suggests this roundabout approach to deriving the generalized equation for the induced electromotive force on a moving conductor.

2.9 Legacy of the Flywheel and Governor

Maxwell's flywheel/governor continued to be used as a mechanical illustration of electromagnetic induction by theoreticians across Europe as well as electrical engineers in

[178]Darrigol (2000, p. 160).

Britain, "throw[ing] light upon some scientific idea so that the student may be enabled to grasp it."[179] At the Cavendish, both J.J. Thomson and John Henry Poynting seem to have encountered the flywheel that Maxwell commissioned. J.J. Thomson not only added an illustration and explanation of the flywheel and the analogy connecting it to electromagnetism to the third edition of Maxwell's *Treatise*, he and Poynting also intended to include a similar account of the flywheel in the planned second volume of their *Text-Book of Physics: Electricity and Magnetism*. A surviving final draft of a chapter entitled "Electromagnetic Induction" includes what appears to be very nearly the same description of the flywheel as appears in the Thomson edited third edition of Maxwell's *Treatise*.[180] The most significant difference is the draft expands upon the manner in which the flywheel illustrates "the effect of an iron core in increasing induction."[181]

> These effects depend upon the motion of the intermediate fly wheel they are much more marked when the movable weights are placed out as far as possible from the axis of rotation than when there [*sic*] are moved in close to the axis; this corresponds to the increase in Electromagnetic induction produced by inserting an iron in the coils.[182]

As late as 1914, J.J. Thomson and Poynting evidently still thought the flywheel/governor was a useful tool for illustrating electromagnetic induction to students. Thomson even felt strongly enough to expand upon his original description. Whether due to Poynting's death that same year or some other unsaid circumstance the volume was never published.

Although Maxwell was judicious in his use of an analogy between mechanics and electromagnetism in the *Treatise*, certain English electrical engineers shared Maxwell's opinion that

> [i]t is difficult, however, for the mind which has once recognized the analogy between phenomena of self-induction and those of the motion of material bodies, to abandon altogether the help of this analogy, or to admit that it is entirely superficial and misleading.[183]

One of those engineers, John Hopkinson, appealed explicitly to Maxwell's flywheel in his lecture "On Some Points in Electric Lighting," delivered in 1883 to the Institution

[179] Maxwell (1890b, p. 242).

[180] The two "disks," i.e., driving wheels, are referenced as P and Q in the draft, just as they were in the *Treatise*, which suggests that they also intended to reuse the same image of the flywheel for the not pictured but referenced figure. Thomson and Poynting (nd, pp. 21–22).

[181] Maxwell (1892, Vol. 2, p. 228).

[182] Thomson and Poynting (nd, p. 22).

[183] Maxwell (1873b, Vol. 2, p. 181); discussed in Gooday (2004, p. 180).

of Civil Engineers.[184] In trying to give a theoretical account of the possibilities for alternating current machines, Hopkinson used the flywheel to illustrate that electrical circuits acted as if they had inertia.[185]

In 1890, Lord Rayleigh reimagined Maxwell's flywheel as a system of weights and pulleys due to an engineering problem even more fundamental than the one that had motivated Maxwell's to involve the Siemens governor in the first place. Rayleigh lacked access to differential gears.[186] Although Ludwig Boltzmann knew of the existence of *Maxwell's* flywheel through Rayleigh, he admitted, "unfortunately, I am not familiar with [it]."[187] Thus when imagining his own system to illustrate electromagnetic induction, Boltzmann based his design on Rayleigh's "very simple apparatus."[188] Nevertheless, Boltzmann's device remains tied to Maxwell's flywheel not only through their shared purpose, but also through a shared mechanical lineage joined by Rayleigh, a connection through a machine book subculture hidden within theoretical physics. Boltzmann not only included an illustration of a significantly more complicated apparatus or *Bizykel* in his 1891 "Lectures on Maxwell's Theory of Electricity and Light," he also had a physical model built, one which he treasured and often brought along on trips.[189]

The relation of the components and operation of flywheel to electromagnetic phenomena mirrors those described by Rayleigh and can be translated into the same differential gear relations first noticed by Maxwell in the Siemens governor. The added complications were inspired by a major flaw Boltzmann had made note of in Rayleigh's design (one common to Maxwell's flywheel), namely that "the parameters can not be changed in it which for us is rather essential."[191] Boltzmann's additions only deepened the connection to electromagnetism, allowing him to easily change the terms L, M, and N, and thus provide a powerful mechanical demonstration of the effects of moving and morphing circuits.[192]

What began as a concrete and practical device, the Siemens chronometric/differential governor, was transformed by Maxwell into an idealized mechanism suited to guiding his development of electromagnetic theory. When Maxwell, Rayleigh, and Boltzmann all built their own "flywheels," they completed this cycle and rematerialized the idealized machinery. In the case of Rayleigh and Boltzmann's devices, the physical objects that resulted from this process of translation did not much resemble the origi-

[184]Hopkinson (1901).
[185]Hopkinson (1901, p. 60); discussed in Gooday (2004, pp. 186–188).
[186]Rayleigh (1890, p. 434).
[187]Boltzmann (1891, p. 45).
[188]Boltzmann (1891, p. 45).
[189]Boltzmann (1891, p. 21, Fig. 15); Eckert (2001).
[190]Boltzmann (1891, Fig. 15); reprinted and discussed in Eckert (2001) and Harman (1982, p. 150).
[191]Boltzmann (1891, p. 45).
[192]Boltzmann (1891, pp. 27–28, 45).

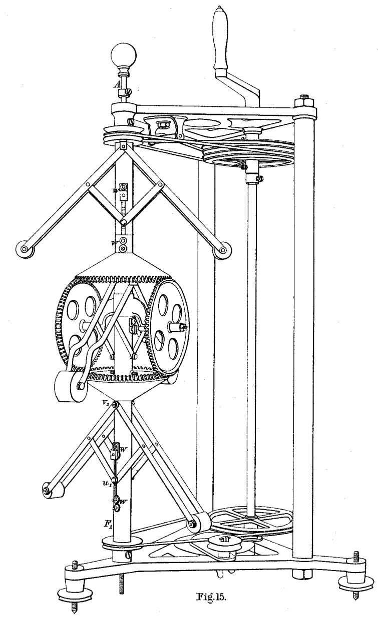


Figure 2.10: Boltzmann's *Bizykel*[190]

nal Siemens governor. Although mostly inspired by Rayleigh's lack of adequate parts to recreate Maxwell's design, the Rayleigh and Boltzmann demonstration devices also illustrate their different priorities. Neither shared Maxwell's same extended personal history with the governor and without the connections to efficiency, religion, and prior hard won theories they were likely less attached to any specific design. Boltzmann in particular was clearly most concerned with capturing as much of the phenomena of electromagnetic induction in his device's machinery as possible.

Boltzmann also lent his model out to Arnold Sommerfeld and an image of the central mechanism of a differentially geared flywheel made an appearance in Sommerfeld's textbook on mechanics.[193] There, it was again distinguished as an illustrative analogy through which students could conceptualize electromagnetic induction, although by this time Sommerfeld already thought the flywheel was "much more complicated than Maxwell's theory which it was intended to illustrate" and better served as "an exercise on the differential of an automobile."[194] Through the end of the 19th century the flywheel (and its reengineered progeny) remained an important teaching tool, entrenched by the underlying connections between the construction and operation of the mechanical device and Maxwell's formulation of his equations for electrodynamics.

J.J. Thomson and Poynting's enduring loyalty aside, Sommerfeld's comments re-

[193]Sommerfeld (1952, p. 255); Eckert (2001).
[194]Sommerfeld (1952, p. 225).
[195]Sommerfeld (1952, p. 255).

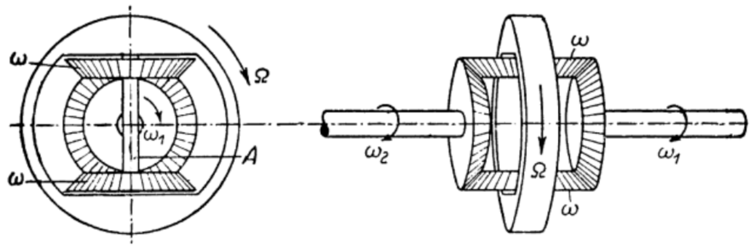


Figure 2.11: Differential Governor in Sommerfeld's Textbook on Mechanics[195]

flect a sentiment that had become common in the physics community by the end of the 19th century. Understanding this sentiment helps explain the rapid loss of interest in the flywheel as a tool for teaching electromagnetism. In 1895, H. A. Lorentz's electron theory included the controversial step of rejecting the universality of Newton's 3rd Law, the equality of action and reaction. Lorentz had accepted that the ether was immobile, creating a natural contradiction: the ether could exert a force on regular matter, but the ether itself was not perturbed by matter passing through it. Max Abraham's invention of a new explicitly non-mechanical conception of electromagnetic momentum in 1903 (see footnote 6) may have rescued the action-reaction principle, but it could not save the mechanical conception of the ether and the accompanying cottage-industry of mechanical models and analogies that came with it.[196] Instead, Abraham and some of his contemporaries (including, much to his regret, Sommerfeld[197]) undertook a project to reestablish physics upon a foundation of electromagnetism. With the rise of what came to be known as the Electromagnetic Worldview, the role of mechanics in relation to electromagnetism was not just diminished, rather it was entirely inverted:

> The opposite attempt seems to me much more promising as the foundation for further theoretical work, i.e., to consider the fundamental electromagnetic equations as the more general ones, from which the mechanical ones have to be derived.[198]

As a brief aside, it is worth mentioning that Maxwell was not the only eminent physicist at work in the late-19th century who concerned himself with mechanical governors. In addition to Maxwell, Siemens, and Airy, Otto Mayr describes how

[196] Janssen (2003, pp. 34–36).
[197] Much later Sommerfeld reflected on his trilogy of papers in support of the burgeoning Electromagnetic Worldview as works to which he "originally attached great value, [but] were therefore condemned to fruitlessness." Sommerfeld (1968, p. 667); discussed in Janssen and Mecklenburg (2006, p. 113).
[198] Wien (1901, p. 502).

William Thomson, Léon Foucault and Josiah Willard Gibbs[199] were all in one way or another concerned with mechanical governors. While their more modest scientific goals were achieved, none of them produced a practical design and their mathematical analyses of governors, e.g., Maxwell's "On Governors," were similarly ignored by industry.[200] Maxwell's "On Governors" was eventually resurrected by Norbert Wiener when naming his nascent field of control and communication theory. "Cybernetics" was coined as a roundabout reference to governors made through Greek, an homage to "On Governors" which Wiener considered "the first significant paper on feedback mechanisms."[201] Although it was a product of enterprising brothers in the infancy of their business and engineering careers, the Siemens' governor, remained a commercial failure; however, reimagined as the "fly-wheel" by Maxwell, nearly the same device has carved out a lasting career within the academy.

2.10 Conclusion

The shadow of massive cultural change is cast even on the finest details of abstract physics. The early-19th century witnessed a rapid and all-encompassing intellectual shift from models of balance to engine models. This included a focus on temporality across a wide range of subjects, from thermodynamics to political economy. Concern over waste followed and helped mold recognizable conceptions of efficiency. Through William Rankine's struggle for legitimacy, efficiency would become fully modern, incorporating economic and mechanical factors into a single quantitative metric. I have argued that this conceptual development up to but *not* including Rankine is embodied by the differential governor designed by the elder Siemens brothers. Designed as a paragon of mechanical efficiency, the Siemens chronometric governor was an ideal analogue for the electromagnetic ether in Maxwell's electromagnetic theories. Maxwell's comments in both "Physical Lines" and "Dynamical Theory" as well as his

[199]Gibbs, known for his immense contributions to statistical mechanics (a name which he coined) and correspondent of Maxwell, designed his governor in the early 1870s just before his earliest work on thermodynamics. Much like I have emphasized the role played by the Siemens governor in guiding or supporting Maxwell's work in electrodynamics, L. P. Wheeler insisted that Gibbs' own governor demonstrates "the earliest example of Gibbs' use of that powerful process of generalization which underlies the enduring quality of his great contributions to our understanding of the properties of matter," premiering "the same process [generalizing equilibrium principles] followed in the monumental work on the Equilibrium of Heterogeneous Substances. . . and thus was born the science of Physical Chemistry." Otto Mayr is somewhat less convinced: "it would not support a claim that the governor experience was a prerequisite or even a contributing factor to Gibbs's success in the treatment of thermal equilibria, or that whatever the two contributions have in common (mainly the number *three*) is in any deeper sense characteristic of Gibbs's work." Gibbs and Wheeler (1947, p. 78); Mayr (1971b, p. 221).

[200]Mayr (1971b).

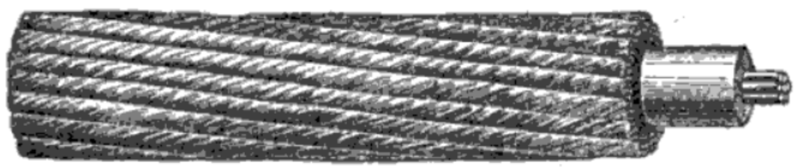
[201]Wiener (1948, p. 11–12); discussed in Mayr (1971a).

personal faith demanded an uniquely efficient model for the ether (as well as one that could properly account for various electromagnetic phenomena). At the intersection of Maxwell's personal Christian faith and his physics, the divinely perfect order and continuity of the ether required a similarly efficient model, a role that the Siemens governor filled much more easily than its industrial opportunities.

But this connection between the Siemens governor and Maxwell's theory was not purely illustrative. The governor played an integral part in the development of Maxwell's honeycomb model in 1861–1862 and in 1864 stripped down and reconstituted as a flywheel, it, by analogy, clarified electromagnetic concepts and shaped Maxwell's approach to rederiving his general equations of the electromagnetic field. This narrative of intellectual change, work and waste, and the maturation of efficiency is encoded in the design of the Siemens governor, and thus this base industrial object helped to mold elegant details of Maxwell's equations of electromagnetism. Had the Siemens governor been a commercial success, i.e., if it had made sacrifices in pure mechanical efficiency in an effort to make it cheaper or more reliable or otherwise more economical, it would have made for a less appealing choice as a mechanical analogue of electromagnetic phenomena. This imagined success may have encouraged a different choice of device as model or analogue, altering the path to and presentation of Maxwell's electromagnetic theory.

This technology, the Siemens governor, has a past spelled out not only in prototypes and incremental innovations but also in the culture that made its development possible and desirable. Consequently, Maxwell's electromagnetic theories share these same origins. So too do they possess linked futures, as a teaching tool and the subject to be learned. Maxwell's electromagnetic theory *is* the legacy of the Siemens chronometric governor and the revolutionary reconceptualization of human thought that birthed that technology.

Chapter 3



The Cable and the Capacitor: Submarine Telegraphy and its Influence on Maxwell's Electromagnetic Theory

3.1 Introduction

This history of physical theory is a story of failed undersea telegraph cables and fundamental equations of electromagnetism; committee reports and an ecological disaster; capacitors[1] and British colonialism. It covers how James Clerk Maxwell's electromag-

[1]A note on terminology: In 1782, about two short decades after steam power was revolutionized by James Watt's invention of the separate condenser, Alessandro Volta introduced a "condenser" of his own. Much like Watt's steam condenser condensed water vapor into liquid water ultimately improving the steam engine's efficiency, Volta's condenser of electricity condensed electrical fluid, i.e., increased the density of charge, so that it could "collect and render sensible that small quantity of electricity, which would otherwise remain imperceptible and unobserved." Volta (1782, p. xi). In the early-20th century, the English-speaking-world came to call electrical condensers "capacitors." "Condenser" remains the preferred term in most languages, e.g. *condensateur* in French, *Kondensator* in German, and *condensator* in Dutch. The time period and resultant quotations referenced in this chapter predate this shift in vocabulary and thus use the term "condenser;" however, my own comments will follow modern convention and use the term capacitor to refer to these same devices. The one exception to this rule is my use of the phrase "leaky condenser," which is a major feature of Section 3.5. Despite the shift from condenser to capacitor in English, "leaky condenser"

netic theory emerged from the failures of the early submarine telegraph industry and became close kin of its later successes. In concert with technological idealizations, submarine telegraphy shaped the content of Maxwell's electromagnetic theories and the theories of the British physicists who followed in his footsteps (before the rise of electron theory).[2] This technological influence bridges the gap between Maxwell's abstract theoretical physics and the political, economic, colonial, and ecological forces tied to the rise to the telegraph industry in the British Empire of the late-19th century. Maxwell's theory and submarine telegraphy are connected through the same committees that helped to rescue the industry after a string of costly public failures. The same political and economic forces that drove these early failed cable attempts and made necessary the industry's rescue by committee remain causally connected to particular details of Maxwell's physical theory, albeit through a connection mediated by the technology of submarine telegraph cables. As regards the health of submarine telegraphy, these committees were wildly successful in repairing not only the industry's reputation but also its practices. Thus, this shared technological and bureaucratic ancestry also bonds together Maxwell's electromagnetic theory and the consequences of the ascendency of a global British submarine telegraph cable network.

Within the Maxwell historiography, Bruce Hunt and Daniel Jon Mitchell are nearly alone in investigating technology and engineering's role in shaping Maxwell's theorizing.[3] Both focus on Maxwell's work to define a system of absolute electrical measurement with the British Association for the Advancement of Science (BAAS) Committee on Electrical Standards as their fount of engineering knowledge. In Maxwell's experiments with the BAAS, Hunt locates the origins of a new more operationalist, i.e., more engineering-esque, methodology that would power Maxwell's "Dynamical Theory of the Electromagnetic Field." Mitchell meanwhile finds the source for Maxwell's invention of dimensional formulae, "devised... as mathematical tools for unit conversion, which eventually led him... to treat them as analytic forms for absolute units."[4] While Mitchell undoubtedly locates a much more tangible product and path of inspiration from Maxwell's BAAS work, neither Mitchell nor Hunt describe any direct impact on the content of any of Maxwell's electromagnetic theories. Electromagnetic concepts and relations in Maxwell's electromagnetic theories are not *immediately* shaped by the Standards work in either Mitchell or Hunt's narratives. Additionally, neither Hunt nor Mitchell's narratives are concerned with material technologies. These are histories of the influence of engineering work, not machines. Consequently, although the Committee's precision measurements were intended in part to aid the telegraph industry, standardizing measurements across firms and countries and crucially be-

has remained the preferred nomenclature within the history of physics.

[2]Buchwald (1985).

[3]Hunt (2014); Mitchell (2017); Crosbie Smith covers similar ground in Smith (1998).

[4]Mitchell (2017, p. 64).

tween industry and the academy, they were initiated by the BAAS. The Committee had to abide the practical concerns of the telegraph industry and offer units that were of such a magnitude as to be relevant by the average engineer, but beyond this, the construction of a system of absolute electrical measures was a goal set by the scientifically and philosophically minded Standards Committee members. Indeed a good part of the appeal of the absolute system to cable engineering was the corresponding accumulation of credibility through association with advanced sciences. The connection then between Maxwell and submarine telegraphy through the Standards Committee is quite loose.

There are no narratives connecting Maxwell and submarine telegraphy as intimately as those assembled for Thomson in Smith and Wise's biography of Thomson, *Energy & Empire*.[5] These historians find sources for Thomson's electromagnetic theories in not only the technology of submarine telegraphy, but also in his personal faith, and the political and economic context of his times. The link between Thomson's electrical theory and his own work on submarine telegraphs is clear and unobstructed by intermediaries. Meanwhile, as one of Maxwell's British successors in the physics of electromagnetism, Joseph Larmor, recalled: "Maxwell steers clear of submarine telegraphy, which in its long-distance domain had then the prominence that now attaches to the domain of wireless waves."[6] And yet, Maxwell was eventually made a member of the Society of Telegraph Engineers.[7] Maxwell was not Thomson and I cannot claim to have constructed a narrative for Maxwell that rivals Thomson's connection to submarine telegraphy. Nevertheless, I do believe I have closed the gap. I will show that Larmor's confident statement is not just hyperbole, but demonstrably false.

A close look at Maxwell's letters and papers reveals that outside of his work with the Standards Committee, he had a remarkably limited interaction with *the* premier electrical technology of the late-19th century, telegraphy. In November, 1857 Maxwell wrote to Thomson with an idea for submarine cable "kites," which Maxwell hoped could alleviate stress on the line at the surface and reduce wasteful folding of it on the ocean floor. While these comments were merely an addendum to a longer letter (the letter was mostly about his work on the stability of Saturn's rings), they did at least demonstrate some passing interest in practical matters. Maxwell's knowledge of the circumstances of the 1857 Atlantic cable's failure also show he was keeping up with the news of the expedition.[8] Otherwise, Maxwell only poked fun at Thomson's participation with the first Atlantic telegraph to his lifelong friend Lewis Campbell. He wryly commented that while "a-laying of the telegraph which was to go to America," Thomson was "bringing his obtrusive science to bear upon the

[5]Smith and Wise (1989).
[6]Larmor (1936, p. 695).
[7]Schaffer (1995, p. 155).
[8]Maxwell (1990, pp. 555–556).

engineers, so that they broke the cable with not following (it appears) his advice." He followed this up with four humorous verses of song parody he had just composed, "The Song of the Atlantic Telegraph Company."[9] While this chapter will make use

[9]Campbell and Garnett (1882, pp. 278–280).

In reproducing Maxwell's song, I have taken the liberty of substituting in for "(U)" according to Maxwell's equation "(U) = 'Under the sea,"'

The Song of the Atlantic Telegraph Company

I.
Under the sea, Under the sea,
Mark how the telegraph motions to me,
Under the sea, Under the sea,
Signals are coming along,
With a wag, wag, wag;
The telegraph needle is vibrating free,
And every vibration is telling to me
How they drag, drag, drag,
The telegraph cable along,

II.
Under the sea, Under the sea,
No little signals are coming to me,
Under the sea, Under the sea,
Something has surely gone wrong,
And it's broke, broke, broke;
What is the cause of it does not transpire,
But something has broken the telegraph wire
With a stroke, stroke, stroke,
Or else they've been pulling too strong.

III.
Under the sea, Under the sea,
Fishes are whispering. What can it be,
Under the sea, Under the sea,
So many hundred miles long?
For it's strange, strange, strange,
How they could spin out such durable stuff,
Lying all wiry, elastic, and tough,
Without change, change, change,
In the salt water so strong.

IV.
Under the sea, Under the sea,
There let us leave it for fishes to see;
Under the sea, Under the sea,
They'll see lots of cables ere long,
For we'll twine, twine, twine,
And spin a new cable, and try it again,
And settle our bargains of cotton and grain,
With a line, line, line,—
A line that will never go wrong.

of Maxwell's Standards work, it will also demonstrate that Maxwell's science was influenced by additional sources of technological knowledge, some of which originated in submarine telegraphy.

Specifically, I argue that the stability of Maxwell's electromagnetic theory as presented in "A Dynamical Theory of the Electromagnetic Field" is contingent upon concepts and phenomena drawn from the submarine telegraph industry. In the aftermath of highly publicized failures of multiple long distance submarine telegraph lines to overseas British colonial territories, most notably the two early Atlantic cables and the Red Sea cable, the British government in cooperation with industry formed the Joint Committee on the Construction of Submarine Telegraphs. Maxwell draws heavily on the work of the engineer Henry Charles Fleeming Jenkin, his colleague on the Standards Committee, directly citing Jenkin's published testimony and report to the Joint Committee. Maxwell's citation of Jenkin's Joint Committee contribution report not only connects the former's scientific work to the technology of submarine telegraphy (and its failure), but also to the politics of the British Empire embodied by the technology. Jenkin's work on cable insulation and his ideas about the confounding new phenomena of electric absorption, combined with Maxwell's preexisting idealized capacitor, shaped Maxwell's concept of electric displacement and opened a new path for empirical confirmation of his broader theory. Maxwell's concern with appropriately modeling the phenomena of electric absorption *as described by Jenkin* allowed this technological influence to bleed out into his broader theory, infecting a fundamental equation of electromagnetism, Ohm's law. This moment of intrusion by submarine telegraphy into theoretical physics was later reconstituted within Maxwell's 1873 textbook, *A Treatise on Electricity and Magnetism*. There similar equations were derived but through a deeply divergent process that suggested a completely new understanding of electrical phenomena within a dielectric. Until the rise of electron theory, this new understanding continued to haunt followers of Maxwellian theory in the form of the "leaky condenser." Consequently, I can trace the historical lineage of Maxwellians' concepts of conduction back to the failures of early submarine telegraphy.

But it wasn't only Maxwell learning from the Joint Committee. The Committee, the testimony it received, and the report it produced were intended to help the struggling submarine telegraph industry right itself. Ultimately, the Committee succeeded in this regard, healing the industry's wounded reputation and establishing better procedures for cable construction and laying. The last few decades of the 19th century saw a submarine cable boom and by the turn of the century, Britain's submarine cable network spanned the globe. This vast network remade the politics, economics, and societies of Britain and its expanding empire at great environmental cost. These political effects and costs of the successful cable network are, like elements of Maxwell's theory, contingent on the Joint Committee report. Maxwell's theory and the reshaped politics of a wired-up Imperial Britain are twins.

To be clear, this chapter contains two separate narratives tying submarine telegraphy and the political context surrounding the industry to Maxwellian electromagnetic theory; the first is causal, the second is not. In both, British submarine telegraphy is understood as having been consciously designed and used to "constitute, embody, [and] enact political goals," the lines have *technopolitics* in the sense outlined by Gabrielle Hecht in *The Radiance of France*.[10] British cables acted as tools of colonial control, aiding economic and military imperialism along carefully planned routes along the seafloor. From the failures of long distance submarine telegraph lines and the economics and politics wrapped up in these ventures, to the Joint Committee, and finally to Maxwell's electromagnetic theory and eventually the theories of his intellectual successors runs a continuous causal chain. The architecture of these physical theories is contingent upon testimony and reports of the Joint Committee which in turn was itself contingent upon the failures of the telegraphy industry and the wider historical forces which both contributed to these failures and elevated them to issues of national importance. The second narrative, which connects the later successes of submarine telegraphy and the resulting consequences to Maxwellian theory, is explicitly non-causal. I aim merely to illustrate the close kinship between the world-shaping effects of the wild successes of the British undersea cable network and Maxwellian theory, bonded by their shared parentage via the Joint Committee. Maxwellian theory did not save the submarine telegraph industry, nor was it responsible for either the fortunes or violence that were made possible by a British global cable network. But theory was also not isolated from these effects. Maxwellian theory is wrapped up in this context, if not always causally. This was an imperial science.[11]

That Maxwellian theory is deeply tied to practical elements of submarine telegraphy is not such a historiographical about-face when considering the model set by Cardwell, and the work of Smith and Wise, Mitchell, and especially Hunt. That the link is to Jenkin's work with the Joint Committee, however, connects perhaps the shining achievement of 19th-century theoretical physics with the repeated failures of the early submarine telegraph industry. The Joint Committee was established to

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[10] Hecht (1998, p. 25).

[11] Obviously Maxwell is not the first scientist whose work has deep ties to imperialism. William Thomson's lifelong involvement in industry is inseparable from his more "pure" scientific pursuits. Just as I argue that Maxwell's connection to submarine telegraphy shaped his physics and connected him to the imperial context surrounding the cables, so too do Crosbie Smith and Norton Wise argue for Thomson, not just with submarine telegraphy, but steam engines and turbines as well. In many ways Thomson's connections were not particularly subtle. By the end of his life, Thomson's work had made him a rich man and gotten him elevated to Lord Kelvin of Largs. Smith and Wise (1989, pp. xx–xxi). Stepping outside of the history of physics, Charles Darwin's voyage aboard HMS *Beagle* was famously driven by imperial concerns and inspired a complicated attitude in Darwin, at times paternalistically sympathetic towards Indigenous peoples but still largely supportive of British colonialism. Desmond and Moore (1991, pp. 105–106, 176–177, 266–267).

figure out why expensive long distance submarine cables had failed so spectacularly, notably the two initial Atlantic cable attempts and the Red Sea cable, and to lay out a comprehensive account of best practices so such failures could be avoided in the future. Ultimately, Maxwell's wellspring of technological knowledge, i.e., Jenkin's report, is a product of the failure not the success of British submarine telegraphy. First, it is prudent to ask in what way or to what extent these earlier attempts to span the Atlantic or run a cable to India were failures?

While the first Atlantic cable did not make it to North American soil, the second worked for about a month before going dead.[12] Is this a complete failure? As has been pointed out, it did show that an Atlantic cable could work. Failure (and success) as a historical category is at best unstable across time and in hindsight, failures are easily recast as pioneering technological innovation. We might next ask: what exactly failed? In the case of the Atlantic cables, much of the blame for the failure was placed (somewhat unfairly) in the lap of the company electrician, Wildman Whitehouse. Assigning Whitehouse the blame for the cable's failure was a deliberate attempt to rescue submarine telegraphy from an onslaught of bad publicity following the loss of signal.[13] Ultimately, failure is less about the material object itself, instead, as Graeme Gooday puts it, "what 'fails' is *human expectations* of hardware performance and distribution—or rather a 'failure' of socio-technical relations."[14] The failure of the second Atlantic cable was a failure to meet expectations for performance embedded in the cable's design (as well as Whitehouse's expectation that it should hold-up to enormous applied voltages). This failure (among others) was eventually transformed into an incredible success by the work of the Joint Committee, a learning opportunity that the telegraph industry gladly accepted and profited from. Indeed, this reversal of failure is the point of this entire chapter. Thanks to the Joint Committee, these "failed" submarine telegraph lines not only made possible the rapid expansion of the British undersea cable network, but, as we shall see, these 'failures' also helped to shape Maxwell's mature electromagnetic theory. These 'failed' cables were even more successful than historians have yet appreciated.

And yet, failure remains a critical component of this chapter's historical narratives. Without the shared understanding amongst the majority of the public, the engineers, investors, and the British government that these long distance submarine

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[12]Similarly, sections of the doomed Red Sea cable to India did work for a short period, even if the entire line was never functional at the same time. These failed long distance cables will be discussed in more depth in Section 3.2.

[13]Gooday (1998, p. 275).

[14]Gooday (1998, p. 286). That said, even if we can trace a tortured line of misunderstanding or misapplication back from a 'failed' technology to an appropriately responsible human, it seems worthwhile to preserve some of our more common ways of speaking, occasionally laying the blame for failure on the object itself, particularly in those instances when it appears farfetched for any designer or engineer or user to have anticipated the mode of failure.

cables had failed, the British government's Board of Trade and the Atlantic Telegraph Company would not have created the Joint Committee on the Construction of Submarine Telegraphs. Enumerating reasons for past failures and methods to avoid future failure, understood at the time as principally failures of and by humans not failures of technology, motivated the founding of the Joint Committee. The failure of so many expensive individual cables had planted seeds of doubt that submarine telegraphy as a whole might be a failed technology. Understanding possible (and realized) modes of cable failure *localized* each failure, thereby preventing the agglomeration of unique cable failures into an indictment of submarine telegraphy as a failed class of technology.[15] The Joint Committee's members made as much clear in the final words of their report summary:

> We desire, however, in conclusion, to observe that we are clearly of opinion that the failures of the existing submarine lines which we have described have been due to causes which might have been guarded against had adequate preliminary investigation been made into the question. And we are convinced that if regard be had to the principles we have enunciated in devising, manufacturing, laying, and maintaining submarine cables, this class of enterprise may prove as successful as it has hitherto been disastrous.[16]

This commonly felt sense of failure is responsible for the Joint Committee, this chapter's central point of narrative connection.

Section 3.2 begins with a description of the failures of early long distance submarine telegraphy, particularly the failed Atlantic cables of 1857 and 1858, and the creation of the Joint Committee on the Construction of Submarine Telegraphs in an attempt to salvage the industry. Special attention is paid to Fleeming Jenkin's discussion of the phenomenon that came to be known as "electric absorption," not only the discussion in his testimony before the Joint Committee but also that in some of his later work, most notably in collaboration with James Clerk Maxwell on the BAAS Committee on Electrical Standards. Finally, the political and economic forces behind submarine telegraphy, its failures, and the Joint Committee are discussed. In this way, concern over the phenomenon of electric absorption, itself a product of Jenkin's work for the Joint Committee and Standards Committee and consequently a product of the failure of submarine telegraphy and the economic and political forces behind the industry, found its way into Maxwell's orbit.

Section 3.3 deals with the period immediately before Maxwell joined the Standards Committee, examining the roles played by capacitors in his pioneering contribution to electromagnetic theory, "On Physical Lines of Force." These roles range from

[15] Jones-Imhotep (2017, pp. 10–11).

[16] Council Committee For Trade and Atlantic Telegraph Company (1861, p. xxxvi).

implicit to explicit, helping to construct the displacement current to providing a new experimental prospect for verifying his electromagnetic theory of light.

Section 3.4 is split into two subsections with a short introduction. In Subsection 3.4.1, I analyze the often ignored "Theory of the Condenser" from Maxwell's "Dynamical Theory of the Electromagnetic Field." The capacitor and Jenkin's telegraph inspired description of electric absorption are shown to combine (with help from Faraday) in the form of a stratified capacitor that models electric absorption. In this capacity, the stratified capacitor serves a lynchpin of Maxwell's broader electromagnetic theory, becoming important enough to warrant a change to a central equation so that it could adequately model electric absorption. Following this, in Subsection 3.4.2, I argue that in his *Treatise on Electricity and Magnetism* Maxwell reimagines his analysis of the stratified capacitor and electric absorption avoiding the major pitfall in the version in "Dynamical Theory." In doing so, he makes fundamental changes to his conception of electrical actions within a dielectric. In the discussions of both theories, I also examine the empirical significance of electric absorption for his electromagnetic theory of light within the experimental program that Maxwell first outlined in "Physical Lines."

Section 3.5 traces the influence of this new conceptual picture of the dielectric on the work of some "Maxwellians" in the form of the "leaky condenser," noting their modifications and its importance to their understanding of conduction and consequently, its close connection to the demise of Maxwellian theory with the arrival of electron theory. These Maxwellians' theories are the final resting place of the concepts spawned by the combination of Maxwell's idealizations of capacitors and the concerns of the submarine telegraphy industry, in particular Jenkin's report to the Joint Committee.

Section 3.6 discusses the rapid expansion of submarine cables across the British Empire, reshaping global markets and politics in favor of imperial stability, despite the staggering environmental cost paid. These effects of the successfully expanding cable network are to be interpreted not as a direct causal legacy of Maxwell's theories, but instead a close sibling, having been born from the same events and indeed many of the same individuals.

Finally, Section 3.7 summarizes the central arguments of this case study and concludes with some brief historiographical remarks.

3.2 Fleeming Jenkin and the Failures of Submarine Telegraphy

Anchored offshore in Valentia Bay, Ireland on August 5th, 1857, four steam powered ships of the American and British Navies floated together waiting for the day's festivities to end. This multinational armada included the world's largest steam frigate, the USS *Niagara*, and HMS *Agamemnon*, the first purpose built steam battleship in the British fleet, a Crimean War veteran, flagship during the siege of Sevastopol, both of which had been retrofitted to house the 2500 mile length of submarine telegraph cable built to span the Atlantic Ocean.[17] Accompanied by two additional steamships, the USS *Susquehanna* and HMS *Leopard*, the vessels idled as the cable was landed and secured. Overseeing the festivities onshore, the Lord Lieutenant of Ireland, the Earl of Carlisle, cheered this first victory of the Atlantic Telegraph cable and wished for continued successes, with the hope that "this Atlantic Cable will, in all future time, serve as an emblem of that strong cord of love which I trust will always unite the British islands to the great continent of America."[18]

Beginning the next morning the ships set sail from Valentia Bay to lay the telegraph cable across the ocean to Newfoundland. They would follow a path along a relatively shallow and flat portion of the Atlantic, the so-called "Atlantic Telegraph Plateau," discovered through depth soundings made in preparation for the expedition.[19] With the cable split between two ships, the winning plan was for the *Niagara* to lay the first half of the cable from Valentia to the mid-Atlantic and then splice the end into the cable carried by the *Agamemnon* to finish the second half of the journey to Newfoundland. After only five miles the cable snapped. *Niagara* was forced to unceremoniously return, fish the cable out of the water, splice it back into the rest of the cable in the hold, and continue onwards. After this first hiccup things went smoothly for the next two hundred miles. There were no breaks and the electric contact with shore remained constant. Eventually, however, after a mysterious electrical disconnect seemingly righted itself (or as Samuel Morse surmised the overstretched cable's insulation was righted by the crushing ocean depths), the cable snapped again under excessive braking. This time the break had occurred in over two miles of water. The cable was unrecoverable and what cable was left was now not long enough to span the Atlantic. The *Niagara* and soon after the *Agamemnon* returned to Britain to store their cables and try again the following year. The total loss amounted to approximately £100,000 and much of the initial enthusiasm.[20]

This failed attempt at laying a submarine telegraph cable across the Atlantic Ocean began in early 1854 in the mind of New York businessman Cyrus Field. Presented with the opportunity of rescuing a bankrupt telegraph operation attempting to connect St. John's, Newfoundland to mainland Canada, Field found himself exploring the possibility of a much more daring connection across the Atlantic Ocean. After acquiring the charter of the failed Newfoundland Electric Telegraph Company

[17] Dibner (1964, pp. 30–31).
[18] Dibner (1964, p. 35).
[19] Bright (2014, pp. 29–30).
[20] Dibner (1964, pp. 36–39); Bright (2014, pp. 34–40).

and a group of wealthy partners, Field's New York, Newfoundland, and London Telegraph Company was in business with a subscribed share capital of $ 1,500,000.[21] The company's first task was to lay a cable across the Gulf of St. Lawrence to connect Newfoundland to the mainland telegraph network (starting the cable from St. John's Newfoundland would allow for the shortest Atlantic crossing).[22]

The first effort at laying this cable across the gulf ended in failure as the cable had to be cut in bad weather; however, the company learned a valuable lesson about the necessity of steam powered ships for submarine cable laying. By 1855 a new cable was successfully laid across the gulf by steamship and by the following year the submarine cable was connected to St. John's by an overland line. The company could then turn its attention to spanning the Atlantic. Field went to both Washington D.C. and London to ask the respective governments to perform additional soundings to confirm the existence of the Atlantic plateau. With new depth data confirming a reasonable seabed upon which the cable could rest, Field raised an additional £350,000 in subscribed shares and obtained matching yearly government subsidies from the British and American governments as well as an allowance to borrow ships from the nations' navies. With this newly collected capital, the firm was reorganized and remade into the Atlantic Telegraph Company.[23] Now, all that was left was to obtain 2,500 miles of submarine telegraph cable and lay it successfully.

The new submarine cable was to be an order of magnitude longer and on its trip to the bottom of the Atlantic, would end up subjected to far harsher conditions than any cable previously constructed. With reassurances from experts no less eminent than Samuel Morse and Michael Faraday that electrical signals across such a long underwater cable would be practical, the Atlantic Telegraph Company's engineers set about rapidly designing a strong, but lightweight and flexible cable. The cable's core of seven-stranded copper wires was sheathed in three layers of gutta-percha insulation. Gutta-percha is a natural latex with good electrical insulating properties and largely impermeable to seawater. It is derived from the sap of gutta-percha trees, which luckily for British cable concerns were relatively abundant upon its discovery in the colonies of British Malaya.[24] While the core was manufactured by the Gutta Percha Company, the finalized cable covered in hemp, pitch tar, linseed oil, wax, and finally a protective shell of iron wires was assembled in two parts by Glass, Elliot and Company of London and R. S. Newall and Company of Birkenhead.[25] Designed and constructed at breakneck pace to meet the Atlantic Telegraph Company's goal of summer 1857, this was the 2500 mile cable bound for the holds of the *Niagara* and *Agamemnon*, and which doomed that first expedition.

[21]Dibner (1964, p. 11).
[22]Bright (2014, p. 27).
[23]Dibner (1964, pp. 22–23); Bright (2014, pp. 31–32).
[24]Gutta-percha will be discussed in more detail at the end of Section 3.6.
[25]Dibner (1964, pp. 24–25); Bright (2014, pp. 33–35).

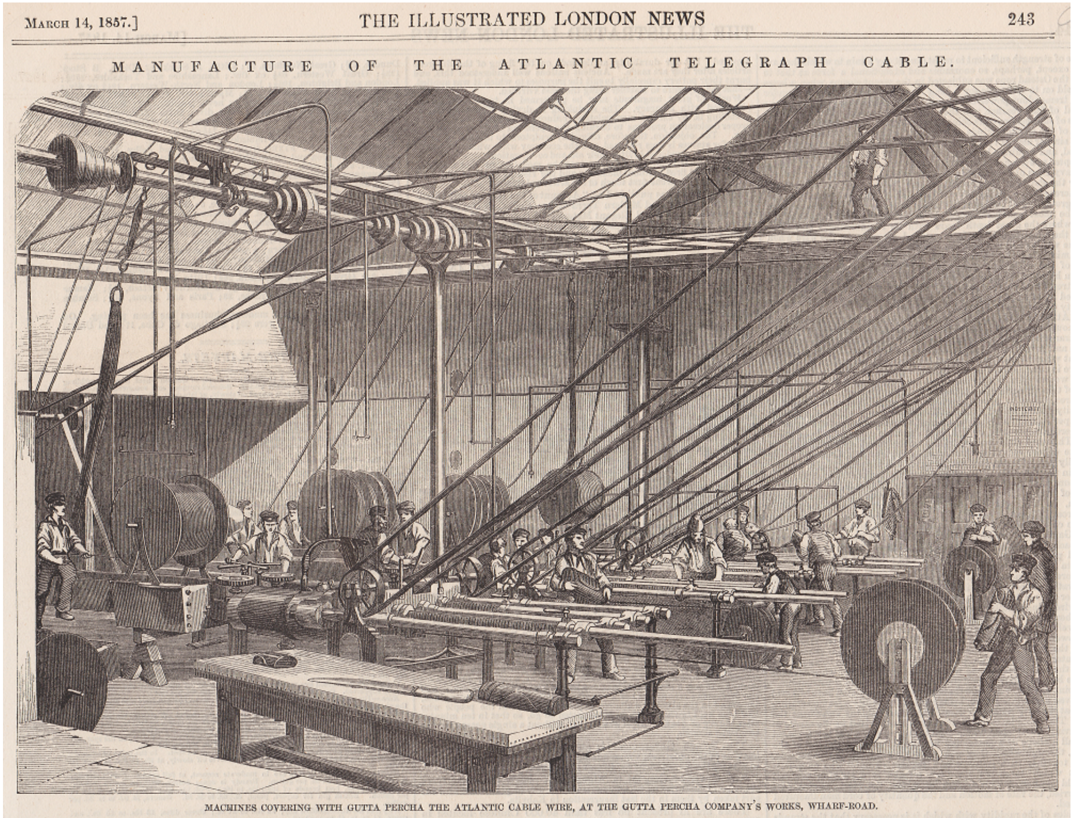

Figure 3.1: Applying Gutta-Percha to the Copper Core at the Gutta Percha Company's Cable Factory

Nevertheless, by mid-1858 the cable dispensing equipment had been improved and more than enough replacement cable produced to set out for a second attempt. *Niagara* and *Agamemnon* were once again loaded with cable and set out together; however, this time they were to rendezvous mid-ocean, splice their cables together, sink the cable, and then slowly steam off in opposite directions. After two restarts demanded by quick cable breaks, the spectacular failure of a third attempt and the accompanying loss of hundreds of miles of cable heralded the end of the expedition. And yet, with enough cable left to finish the job, within a month the ships were headed back to the mid-Atlantic. This time the cable remained intact. Occasional repairs were made to sections in the ships' holds as they gradually made their ways across the Atlantic and the two ships remained in contact through the cable for nearly their entire journey with some mysterious exceptions that terrified those onboard. The *Niagara* would arrive first in Newfoundland followed soon after by the *Agamemnon* in Valentia, both would successfully land their cables. This third attempt had succeeded, the Atlantic telegraph cable was working.[26]

Figure 3.2: *Agamemnon* and *Niagara* Meet Mid-Ocean to Lay the Atlantic Cable

Celebrations on both sides of the Atlantic were somewhat muted as the cable's telegraphic ability was tested for nearly two weeks before Queen Victoria's congratulatory telegraph and President Buchanan's reply made their ways across the line. The symbolic meaning of a telegraphic link uniting Britain and the United States was not lost on either party, although President Buchanan's proclamation was more grandiose:

> May the Atlantic telegraph, under the blessing of Heaven, prove to be a bond of perpetual peace and friendship between the kindred nations, and an instrument destined by Divine Providence to diffuse religion, civilization, liberty and law throughout the world.[27]

These messages were further delayed by the shoddy performance of the cable. It took between twenty-six and twenty-seven hours to relay the 247 words exchanged by the heads of state.[28] Delays aside, these official communications kicked off celebrations

[26]Dibner (1964, pp. 55–63); Bright (2014, pp. 44–51).
[27]Spencer (1866, p. 542).
[28]Coates and Finn (1979, p. 16).

across the United States, particularly of course in Cyrus Field's home of New York where New York City hall nearly burned in the revelry.[29] And yet, while the celebrations were still ongoing, messages along the line ceased. The cable had failed a mere four weeks into its operation. The cable was unrecoverable, the massive investments both private and government had returned nothing, and public enthusiasm for an Atlantic telegraph was at an all-time low.[30]

Ultimately, the financial losses suffered by the British government due to the repeated failures to lay a submarine telegraph cable across the Atlantic were not too onerous, continued payment was contingent on the cable continuing to work. Nevertheless, the failure of the Atlantic cable was followed soon after by the failure of the planned Red Sea cable. The Red Sea cable was meant to link Britain with its Indian colony without the political trouble of an overland route through the Ottoman Empire. In the immediate aftermath of the Indian Rebellion of 1857, the government overlooked concerns raised by the failure of the first Atlantic cable expedition and signed a contract with the Red Sea and India Telegraph Company to connect Suez to Karachi (by way of Aden). Before the failure of the short lived 1858 Atlantic cable, one of the few communications that did cross the ocean was a cost saving cancellation of orders to move British troops from Canada to India following the end of the Indian Rebellion of 1857.[31] The desperation to shore up its control over the Indian subcontinent through rapid telegraphic communication[32] led the British government to make financial promises that would prove disastrous. Even though cable sections failed before the complete line was even laid, enough stipulations had been met such that the government remained on the hook for yearly payments of £36,000 per year for 50 years, eventually totaling £1.8 million (split equally between the British and colonial Indian governments).[33] The line had been doomed from the start. Foolishly agreed upon financial incentives to lay as little cable as possible predictably created an incentive to lay a "taut" line. The cable's components were stretched beyond their

[29]Dibner (1964, p. 67).

[30]Hunt (1997, pp. 317–318); Coates and Finn (1979, pp. 17–19). In an odd turn of events, Tiffany & Company of New York *may* have been one of the only entities to profit from the failure of the 1858 cable. After the cable fleet docked, Tiffany purchased leftover cable from the holds of the *Niagra*, sliced it up, and sold thousands of short cable sections for 50¢ each as well as various souvenirs made from the cable. Nevertheless, the initial cable-mania inspired buying spree did not exhaust Tiffany's stocks and after the cable failed within a month, the retailer was left with numerous unsold sections. Burns (2017); Burns (2019).

[31]Headrick (1991, p. 18).

[32]Even after steamships became common, mail still took 6 weeks to travel from Britain to India (and another 6 weeks to return). Within living memory of the era, mail times between 5 and 8 months could be expected. Headrick Tentacles of Progress 97

[33]Hunt (1997, p. 318); Headrick (1991, p. 20). After the Red Sea cable failed, additional capital was invested in an attempt to repair the line. In 1862, an expedition set out only to return with news that the line was permanently dead. Cell (1970, pp. 229–234, 248–251).

limits, undoubtedly contributing to the numerous failures along the line's sections.[34]

The negative public perception and financial losses engendered by these repeated failures inspired the British government's Board of Trade, in collaboration with the Atlantic Telegraph Company, to set up the Joint Committee on the Construction of Submarine Telegraphs to investigate and improve the viability of submarine telegraphy. The Committee was chaired by Captain Douglas Galton of the Royal Engineers and included experts such as the engineers Latimer and Edwin Clark, Cromwell Fleetwood Varley, and George Parker Bidder, Professor Charles Wheatstone, and the secretary and Chairman of the Atlantic Telegraph Company, George Saward and James Stuart-Wortley.[35] In twenty-two sessions between from December 1859 until September 1860, the Committee listened to equally expert testimony from scientists, engineers, and promoters involved in submarine telegraphy.[36]

One matter to be settled was what or who was at fault for the failure of the Atlantic telegraph cable. Wildman Whitehouse, formerly the chief electrician of the Atlantic Telegraph Company, was quickly saddled with the blame. Initially, Whitehouse had been indispensable to those hoping to lay a cable across the Atlantic. He had allayed fears that signal retardation across such a long cable would render it impractical, fending off a sophisticated attack on such a cable's viability by William Thomson and his "Law of Squares."[37] Thomson's Law of Squares indicated that the signal retardation was proportional to resistance and capacitance of a cable. The "square" came about as both of these properties were themselves proportional to the length of the cable, such that the retardation was itself proportional to the square of length for a given width of wire. This relationship had the potential to sink the practicality of long distance submarine telegraphy. Despite his amateur standing in electrical science and telegraphy, Whitehouse overwhelmed Thomson's lofty scientific authority with a deluge of measurements supposedly contradicting the Law of Squares.

After the failures of the Atlantic cable, for which he was ostensibly head electrician, Whitehouse's outsider status made him an easy target for the Joint Committee.[38] It came out that while the cable was still in operation, Whitehouse had lied about the effectiveness of his own relays and begun to use Thomson's mirror galvanometer in secret. Whitehouse's decision to apply high voltage induction coils to the line in hopes of improving signaling has often been labeled the death blow for the cable and applying approximately 2000 volts to the Atlantic telegraph undoubtedly did harm

[34]Bright (2014, p. 57); Headrick (1988, p. 100).

[35]Coates and Finn (1979, p. 18).

[36]Bright (2014, p. 61).

[37]Thomson's broader theory of electric telegraphs was centered on Fourier's "heat equation" and in keeping with Thomson's methodological preferences, made use of a suggestive mechanical analogy. Thomson's initial criticism was somewhat over-aggressive. Hunt (1996, pp. 160–162).

[38]Whitehouse was not present on any of the voyages. Thomson meanwhile dutifully accompanied each expedition.

to the cable's insulation.[39] However, this was insulation that had been manufactured under extreme time pressures without testing, allowed to deteriorate in the hot sun in improper storage between expeditions, and surrounding copper that Thomson himself had complained was wildly variable in quality. The Committee did acknowledge and appropriately single out these issues as responsible for the fate of the cable. Their aggressive questioning of Whitehouse and in particular its focus on his amateurism was nevertheless a striking contrast to its praise of Thomson's practical and theoretical contributions. Cable engineer Fleeming Jenkin's expansive experimental vindication of Thomson's signaling theory was certainly of no help to Whitehouse.[40] With Whitehouse filling the role of blameworthy scapegoat, the future of submarine telegraphy was reborn by taking refuge in scientific authority, both as a means of repairing the industry's reputation and to build a more secure technical foundation of best practices.[41]

Nevertheless, finding scapegoats for failures, be they people, materials, or techniques, did not encompass the entirety of the Joint Committee report. Assigning blame for past failure might have helped to rehabilitate the perception of submarine telegraphy, but a clearly outlined set of best practices would be at least as important in restoring confidence in the industry. The Board of Trade's initial instruction to the Committee was to elucidate the "best form for the composition and outer covering of submarine telegraph cables."[42] The Committee took this appeal seriously. While they still regularly asked effectively rhetorical questions regarding the basic viability of submarine telegraphy, the Committee also commissioned experiments and asked genuinely probing questions of their expert witnesses in an attempt to generate a summary of the best procedures for building and laying submarine telegraph cables.[43] With testimony from forty-three engineers and scientists, each with a particular set of expertise relevant to submarine cables, and eighteen technical appendices, the Joint Committee was able to put together a comprehensive summary: "principles which we consider should govern these undertakings [the construction and laying of submarine telegraph cables] in future."[44] The report itself became a standard reference in the industry, reprinted in full in the technical journal *The Electrician*: "the most valuable collection of facts, warnings, and evidence ever compiled concerning submarine cables."[45]

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[39] Bright (2014, pp. 52–53).

[40] Council Committee For Trade and Atlantic Telegraph Company (1861, p. 142).

[41] Hunt (1996); Smith and Wise (1989, pp. 675–677).

[42] Council Committee For Trade and Atlantic Telegraph Company (1861, p. v).

[43] With few exceptions, most of experts who testified were asked variations of the same question: whether or not there were any physical or engineering reasons that rendered long distance, deep water submarine telegraphy impossible.

[44] Council Committee For Trade and Atlantic Telegraph Company (1861, p. v).

[45] Electrician (1899, p. 725); discussed in Cookson and Hempstead (2000, p. 50); Bright (2014,

For the purposes of what follows however, I will concentrate on the testimony and submitted studies of Fleeming Jenkin, ignoring those more infamous parts that helped to end Wildman Whitehouse's career. Amongst all of the exceptional engineers interviewed for the report, Jenkin remains particularly remarkable.[46] At the time of his interview (22nd of December 1859), he had been employed at R. S. Newell and Company for two years, arriving while the company was already in the process of armoring their half of the first Atlantic cable. Eminently practical, as his time onboard cable laying ships attests,[47] Jenkin was also a gifted experimenter and electrical mind. As his frequent correspondent and future business partner William Thomson put it, "I was much struck, not only with his brightness and ability, but with his resolution to understand everything spoken of, to see if possible thoroughly through every difficult question, and (no *if* about this!) to slur over nothing."[48] Jenkin comfortably straddled the territory between engineering and science, as did Thomson and other contemporaries.[49] Jenkin was unquestionably, however, an engineer first, albeit a pioneer in the still developing field of engineering science as well as an instructor in it (as he saw it), holding the first Regius Chair of Engineering at Edinburgh University between 1868 and 1885.[50]

The bulk of Jenkin's testimony before the Committee and the paper he submitted (which appears as Appendix 14 of the report) concerned experiments he performed on the insulation of Gutta Percha Works cable sections at Newell's Birkenhead factory.[51] The most famous product of this work, more so even than his empirical vindication of Thomson's telegraph theory, 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 magnitude, establishing the first "absolute measurement of the electric resistance of an insulating material," and breaking down the conceptual barrier between conductors and insulators.[52]

I am interested in something much more mundane. Jenkin begins his testimony

p. 61).

[46]Jenkin may be better remembered in certain circles for his racist critique of Charles Darwin's views on the heredity of favorable traits, a point which Darwin conceded in the fifth edition of the *Origin of Species*. While his chosen example is repulsive, we should be careful not to understate the bite of Jenkin's arguments, some of which retained relevance even after the rediscovery of Mendel. Jenkin also enjoys limited recognition as one of the first to draw supply and demand curves. Gould (1992).

[47]Cookson and Hempstead (2000, p. 39).

[48]Jenkin (1887b, p. clv); discussed in Cookson and Hempstead (2000, p. 37).

[49]Layton (1971, pp. 578–579).

[50]Immediately prior to his post at Edinburgh University, Jenkin was a professor of engineering at University College, London beginning in 1866. Marsden (1992, p. 320); Cookson and Hempstead (2000, p. 94).

[51]Council Committee For Trade and Atlantic Telegraph Company (1861, pp. 135–148, 464–481).

[52]Jenkin (1887b, p. clvi); discussed in Hunt (1998, pp. 96–97).

examining the relationship between the temperature of a submerged cable and its resistance and then compares effects across two cables with different insulating materials. The insulated cable was submerged in a bath of water with one end insulated (thus grounded through the water) and the other connected with a sensitive Siemens and Halske sine galvanometer and then a pole of the battery, the other pole of the battery having been connected with earth. The leakage or "loss" of current through the gutta-percha could thus be read on the galvanometer, i.e., "any current which passed between the internal surface of the gutta-percha and the external surface of the gutta-percha which was in water in connexion with earth, was shown by the galvanometer."[53] By heating the bath water and allowing the temperature of the cable to reach equilibrium, Jenkin was able to obtain a range of measurements of current leakage for various temperatures.

In the pure gutta-percha cable, he noted "the great increase of loss, or diminution of resistance in the gutta-percha at those temperatures," while the second cable made of layers of gutta-percha and Chatterton's compound was

> more perfectly insulated than that prepared with gutta percha at high temperatures; but, on the other hand, and this is a point of immense importance, at low temperatures the gutta-percha is actually the better insulator of the two materials.[54]

There is some controversy as to whether the cable prepared with Chatterton's compound was correctly described. During the course of his testimony to the Committee, Willoughby Smith of the Gutta Percha Company (from which the cables were sourced) claims that the cable Jenkin insists is insulated with Chatterton's compound and gutta-percha is in fact made from the company's "special mixture." Council Committee For Trade and Atlantic Telegraph Company (1861, pp. 30–31, 137). Jenkin supplemented this testimony with charts, clearly illustrating a linear relationship between temperature and resistance.[55] A comparison between the charts for the two cables also furnished his "point of immense importance," namely that pure gutta-percha outperformed Chatterton's compound as an insulator (although the latter could still be useful providing better adherence between the gutta-percha insulation and the copper core). A more general point was suggested, given that Chatterton's compound itself is merely a "mixture of Stockholm tar, resin, and gutta percha in the ratio 1:1:3" and the particular cable Jenkin experimented on utilized four alternating layers of the compound and pure gutta-percha in its insulating coating.[56] Put another way, Jenkin had shown the importance of the purity of a submarine cable's insulating

[53]Council Committee For Trade and Atlantic Telegraph Company (1861, p. 136).
[54]Council Committee For Trade and Atlantic Telegraph Company (1861, pp. 136–137).
[55]Council Committee For Trade and Atlantic Telegraph Company (1861, pp. 464–468).
[56]Cookson and Hempstead (2000, p. 51).

coating; there was less electrical loss with pure gutta-percha as the insulator than when using what was essentially adulterated gutta-percha.

While chasing this temperature-resistance relationship, Jenkin also happened to encounter another peculiar phenomenon that he reported to the Committee:

> You will, however, observe that there are two curves in each diagram. To account for that, I must mention a phenomenon which I observed, and which I have never seen noticed anywhere else, namely, the change in the resistance of the gutta-percha due to continued electrification, or continued contact with one pole of a battery. The increase of the resistance of the gutta-percha is very considerable for the first five minutes. It is difficult to ascertain what the increase of resistance is during the first minute, because the observation being made upon a galvanometer, the needle of the galvanometer takes some time to come to rest, and during its oscillations no observations can be made. But seeing that there was a continued and very considerable change, I made, in each case, five different observations ; the first, one minute after the battery was connected with the coil ; the second, two minutes ; the third, three minutes ; the fourth, four minutes ; and the fifth, five minutes after the connexion of the battery with the coil. I invariably got a very much larger resistance after the fifth minute than after the first minute.[57]

At the prompting of the Committee, Jenkin clarified that the increase in resistance over time is actually measured by the decreasing electrical loss from the cable: "less loss, which indicated increased resistance."[58] Jenkin's cables seemed to become less leaky the longer they were charged. In the back and forth testimony that followed, he revealed the rest of the complications surrounding this phenomenon. Reversing the current (from positive to negative or vice versa) temporarily destroys the effect in "pure gutta-percha exactly," although not completely in impure gutta-percha.[59] If the cable was left to charge for some time, rapidly reversing the current and then quickly reverting to the original current direction had only a minor effect on the built-up resistance, i.e., it does not increase the loss from the cable significantly. If rapid current reversals occur without an extended initial charging then little to no effect is seen. Experiments on much longer cables revealed that the phenomenon was not unique to short sections.

Impurities in gutta-percha coatings seemingly increased electrical loss. Longer charging times (up to 5min) seemed to have the opposite effect, loss decreased and resistance increased. The phenomena nevertheless seemed connected in some sense as

[57]Council Committee For Trade and Atlantic Telegraph Company (1861, p. 136).
[58]Council Committee For Trade and Atlantic Telegraph Company (1861, p. 136).
[59]Council Committee For Trade and Atlantic Telegraph Company (1861, p. 136).

impurities in the insulation made the latter "charging" effect more robust when opposite currents were applied. While the general idea that purer insulation performed better was not especially shocking, Jenkin was impressed with the degree to which it affected performance: "it is very remarkable that so small a quantity of varnish as is employed, should so materially alter the insulating qualities of the coating."[60] Even the relatively small layers of tar and resin adulterated gutta-percha inserted between layers of pure gutta-percha in the cable's insulation apparently affected performance and this new anomalous phenomenon significantly. As regarded the relationship between loss/resistance and charging time revealed by his experiments, Jenkin proudly stated that "[t]he extra resistance due to continued electrification has been fully described, as the author believes, for the first time."[61]

As for what exactly was the physical cause behind the phenomena of "extra resistance," Jenkin did cautiously offer some ideas when pressed by the Committee.

> I have not yet formed any very decided opinion upon that point. I am inclined to believe that it is really owing to a change in the body of the gutta-percha itself. Whether that change is due to the moisture which may be contained in the pores of the gutta-percha, or whether there is some change in the nature of the gutta-percha itself, I cannot decide as yet. I have reason to believe that it does not depend upon the contact of the copper with the gutta-percha, because I have found a very marked increase in the effect whenever the mass of gutta-percha has been increased; and this leads me to believe that it is in the body of the gutta-percha that the change takes place. It is just possible that it may arise from the polarization of the moisture in the molecules of the gutta-percha and not from the resistance of the gutta-percha.[62]

These early thoughts on the underlying nature of this phenomenon are unsurprisingly noncommittal. Essentially all Jenkin was comfortable asserting was that the effect took place within the gutta-percha insulation as opposed to on the boundary layer between the insulation and the copper core. Nevertheless, while the variation of the phenomenon according to the quantity of gutta-percha insulation suggested the general location of the effect (within the insulation), it did not rule out absorbed water as a potential cause. Gutta-percha was well known to take on water and it was entirely possible that this extra resistance in the submerged test cables was thanks to some action of the water absorbed by the cable's insulation. Specifically, Jenkin pointed to polarization of the absorbed water as a potential solution, a possibility he followed up

[60] Council Committee For Trade and Atlantic Telegraph Company (1861, p. 467).

[61] Council Committee For Trade and Atlantic Telegraph Company (1861, pp. 467–468). As it would turn out, Jenkin was only the first to document this phenomenon in telegraph cables.

[62] Council Committee For Trade and Atlantic Telegraph Company (1861, p. 136).

on in the "On the Insulating Properties of Gutta-Percha" that formed Appendix 14 of the report, and in a condensed form under the same title in *Proceedings of the Royal Society*.[63] In the version of the paper that appears in *Proceedings*, Jenkin directly acknowledges that polarization of either the water trapped within the gutta-percha or the gutta-percha itself could explain the observed phenomena: "a phenomenon, which the author thinks may be due to the polarization of the molecules of gutta percha, or of the moisture contained in the pores of the gutta percha."[64] Within Appendix 14 of the report, Jenkin again leaves open whether it is the polarization of the water within the gutta-percha or the gutta-percha itself that acts (he is certain only that the action occurs within the gutta-percha). However, this indecision aside, Jenkin does more explicitly describe the mechanism by which polarization produces 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."[65]

In 1862, Jenkin published a substantial follow-up in Philosophical Transactions, "Experimental Researches on the Transmission of Electric Signals through Submarine Cables. Part I. Laws of Transmission through various lengths of one Cable." At this point, the phenomenon of extra resistance represented the sole objection to the agreement between William Thomson's mathematical theory of submarine telegraph signaling and observations of time sequences of received pulses, referred to by Thomson and Jenkin as "arrival curves."[66] Accounting for the varying resistance finally brought theory and observation into exceptionally close agreement.[67] Ultimately, the effect was of little consequence for day to day telegraphic operations, the resistance was unlikely to vary much as lines were generally kept constantly electrified. As far as any new revelations regarding the causes of the phenomena, Jenkin was struck by the close resemblance between plots of resistance increasing in the cable as a current flowed through it and those for its decrease while a reversed current was applied.

> The identity of the curve of increase with the curve of decrease seems to show that the apparent increase of the resistance of the gutta is rather due to an absorption of electricity which is again given out, than to a real change in the conductivity material.[68]

The idea that cable insulation might in some sense "absorb" electricity was not new. Thomson may have been the first to mathematically express the relationship

[63] Jenkin (1860).
[64] Jenkin (1860, p. 410).
[65] Council Committee For Trade and Atlantic Telegraph Company (1861, p. 471).
[66] Jenkin (1862, p. 1000).
[67] Jenkin (1862, p. 1001).
[68] Jenkin (1862, p. 1001).

between the conductivity of a cable's copper core, the specific inductive capacity of the insulation, and the cable's overall length to its potential signaling speed, but the general phenomena had long since been identified by Michael Faraday. His realization that submarine cables act as capacitors provided an explanation for signal retardation. Electrical signals were responsible for a buildup of charge in the cable's insulation as if the cable was a (massive) capacitor. In this cable-capacitor, the copper core served as one conductive plate, the insulation as the dielectric, and the ocean as the other plate. Signals were thereby slowed and elongated, muddling messages and confusing telegraph operators. Although the name seemingly did not catch on, the cable engineer Cromwell Fleetwood Varley referred to these phenomena as "inductive absorption."[69] Absorption reconceptualized the phenomenon of extra resistance. While Jenkin had already identified the seat of the phenomenon as within the insulating layer, he now asserted that the insulation was storing electricity and that this electricity was recoverable.

The year before he published "Experimental Researches," Jenkin had become an inaugural member of William Thomson's BAAS Committee on Electrical Standards. Given his pioneering experimental work at Newell and Company and his close ties to Thomson, Jenkin was a natural choice. The Committee initially aimed to establish an absolute scale of electrical resistance that, unlike Weber's system, was of more utilitarian magnitudes amenable to the needs of telegraph engineers.[70] A standardized and accessible electrical measure of resistance would help engineers assure the quality of their own conducting and insulating materials and evaluate the suppliers.[71] The official unit resistance coils were not released until 1865 but quickly became an indispensable piece of equipment for telegraph engineers and research scientists. The careful precision and years of expertise that had built the "ohm" was then available for purchase.[72]

In his capacity as a member of this committee, Jenkin found himself working closely with James Clerk Maxwell, after the latter joined the Committee to work on their second report, issued in 1863.[73] During their time working together, Jenkin and Maxwell were frequent coauthors and became close friends.[74] Thus it was, that

[69]Council Committee For Trade and Atlantic Telegraph Company (1861, p. 228). Varley was eventually business partners with both Jenkin and Thomson, realizing profits from patents on novel electric devices as well as telegraph consultancy services. Cookson and Hempstead (2000, p. 67).

[70]Another product of the Standards Committee's work was the dimensional formula introduced by Maxwell. For more on how Jenkin, Thomson, and the needs of practical engineering shaped its interpretation, see Mitchell (2017).

[71]With the release of their official standard resistance unit, the Standards Committee had made good on the recommendation of the Joint Committee's call to establish a standard measure of resistance. Council Committee For Trade and Atlantic Telegraph Company (1861, pp xvi–xvii).

[72]Hunt (1994).

[73]Maxwell had not been involved with the earlier Joint Committee report.

[74]Maxwell even served as godfather to Jenkin's youngest son, Bernard Maxwell Jenkin. Cookson

in 1863, Jenkin and Maxwell coauthored Appendix C to the Second Report, "On the Elementary Relations between Electrical Measurements." Within Part IV of this appendix we find, under the subsection "45. Practical Measurement of Electric Resistance:"

> 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 phenomenon 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.[75]

Although precision 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 in to signal retardation but as we shall see, became increasingly important within electromagnetic field theory.[76] As he had noted in his initial Joint Committee paper, "[t]his phenomenon has great influence on all tests of insulation."[77]

Speculation about the potential causes of electric absorption is absent from Standards reports. Other than some slightly more precise language there is nothing resembling a breakthrough. Rather, the text embodies a passing of the baton from Jenkin to his Standards Committee colleague and coauthor Maxwell. Jenkin and other members of the Standards Committee would continue to discuss electric absorption and related issues on occasion, but among the members of the Standards Committee none except Maxwell would make any advancements beyond what Jenkin had already achieved. Indeed, the final line of the quote above reads like a challenge, "the laws of the variation are very imperfectly known"; electric absorption had been described by Jenkin, but it awaited a complete theory.

The path by which the phenomenon of electric absorption found its way into James Clerk Maxwell's notice weaves its way through the heart of the history of submarine telegraphy and consequently through the history of the Victorian British Empire. While the phenomenon itself was not at all responsible for complications experienced by engineers working on long undersea telegraph lines,[78] it was described and brought to (relatively) wide attention as a result of the repeated failures of costly long distance submarine lines. The failed 1857 and 1858 attempts to lay an Atlantic cable cost

and Hempstead (2000, p. 17).

75 Jenkin et al. (1873, p. 84).

76 Jenkin et al. (1873, p. 242); Jenkin (1887a, pp. 97–99).

77 Council Committee For Trade and Atlantic Telegraph Company (1861, p. 468).

78 Lines were generally constantly charged and electric absorption did not affect signal retardation nor would it cause complete failures.

investors millions of dollars while the British government escaped mostly unscathed (having only guaranteed money for a working cable) . The failure of the Red Sea cable cost the British government nearly two million pounds and was a millstone around the neck of the treasury for decades.[79] Of course, the money lost on the Red Sea cable was painful for the British government, but it had agreed to the absolute guarantee in hopes of establishing rapid communication with India and consolidating its colonial power in London. Britain had hoped to command more direct control over its colony and react more immediately to issues that threatened its rule over India, lessons gleaned from the confusion and delays in responding to the Indian Rebellion of 1857.[80] Even the Atlantic telegraph, with its board of investors headlined by New York financier Cyrus Field and other wealthy American businessmen, was ultimately to establish a link between Britain and its colonies. The western terminus of the cable came ashore in what was then still the British colony of Canada while its eastern terminus, landed in Valentia, Ireland, was a part of the United Kingdom itself.

For its part the submarine telegraph industry was itself also battered by these failures, beyond the loss of initial capital. In light of the high-profile nature of the Atlantic and Red Sea cables, their failures destroyed confidence in the feasibility of submarine telegraphy and cooled off investment in new undersea lines. The Joint Committee on the Construction of Submarine Telegraph Cables formed by the coming together of the Atlantic Telegraph Company and the British government aimed to bolster the reputation of the industry and secure its future. To do so would require not only uncovering the causes (or at least scapegoats) behind past failures, but also outlining a set of best practices to be followed by future telegraphic enterprises so that they might prove economical. It was in the course of the Joint Committee's investigation that Jenkin first described the phenomena of electric absorption (then referred to as extra resistance) and its relation to the purity of the cable's insula-

[79] Cell (1970, pp. 229–234, 248–251).

[80] Outside of telegraphy itself, Maxwell has another connection to India and the Indian "Mutiny" of 1857. Maxwell's close friend Robert Henry Pomeroy had been appointed assistant magistrate at "Azinghur," i.e., Azimghur (now Azamgarh) after which he died from a fever caught while fighting "insurgents" at Ghazeepore (now Ghazipur). This death affected Maxwell immensely, surpassed only by the death of his father the year before. Maxwell mourned Pomeroy's death not only as a loss for those who knew him, but for India itself. Maxwell considered Pomeroy the man "most likely to have done something for India." Maxwell's discussions of Pomeroy's exploits and death are one of the few instances where we get any hints as to Maxwell's attitude towards British colonialism and non-white subjects of the Empire. Maxwell, seemingly taking his cues on British India from Pomeroy, had no sympathy for the "Mutiny" and demonstrated a caring but overall paternalistic attitude towards the colony: "We seem to be in the position of having undertaken the management of India at the most critical period, when all the old institutions and religions must break up, and yet it is by no means plain how new civilisation and self-government among people so different from us is to be introduced. One thing is clear, that if we neglect them, or turn them adrift again, or simply make money of them, then we must look to Spain and the Americans for our examples of wicked management and consequent ruin." Campbell and Garnett (1882, pp. 219–220, 282, 285–286).

tion. Never suspected as a culprit for past failure or a risk for future ones, electric absorption did nonetheless present a practical hurdle for the study of the insulation of submarine telegraphs. Given the Committee on Electrical Standards' formative purpose of assisting the telegraph industry in establishing measurement standards to assure reliable, uniform material quality and better communication between practitioners (and scientists), it is unsurprising then that during Jenkin and Maxwell's work as central figures on the Committee electric absorption would appear again. By the time Maxwell had encountered the phenomenon, electric absorption had become deeply entangled with the uncertain fortunes of submarine telegraphy and thus Britain's drive to fortify its overseas empire that had given the telegraph industry its impetus and financial backing.

3.3 James Clerk Maxwell, Capacitors, and his "Physical Lines of Force"

Before he joined the Standards Committee, James Clerk Maxwell was engaged in the most creative period of his scientific career. In 1860 he moved to King's College, London[81] and in the time before he retired his position in 1865, Maxwell made pioneering contributions to the kinetic theory of gases, color theory (including the first color photograph), and published his two most significant papers on electricity and magnetism. The first of these papers, "On Physical Lines of Force," was published in Philosophical Magazine across four parts between 1861 and 1862.[82]

"Physical Lines" introduces two of Maxwell's most conspicuous additions to electromagnetic theory, the displacement current and his electromagnetic theory of light. The honeycomb-like model of the micro-structure of the ether that guided these innovations, growing in complication as the paper grew in parts, has spawned a cottage industry in the history and philosophy of science, full of discussions of Maxwell's methodological commitment to his model and the extent to which it was responsible for his theoretical innovations.[83] Although the theory hinges upon the particulars of Maxwell's mechanical model, its industrial appearance masks the paper's rather minimal connections to technology. Unsurprisingly, the model itself, specifically the differential action of the small "idle" wheels, had ties to contemporaneous technology. Maxwell acknowledged this chain of inspiration, citing a particular differentially geared, Siemens designed governor from an introductory book of mechanisms and machinery.[84]

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[81] He also contracted smallpox and had to be nursed back to health by his wife Katherine.

[82] Maxwell (1890h).

[83] Siegel (1991); Morrison (1992); Everitt (1975); Darrigol (2000); Harman (2001); Knudsen (1976).

[84] See Section 2.4. For the story of the Siemens governor itself see Section 2.3.

The other wellspring of technological influence in "Physical Lines" is Maxwell's treatment of capacitors. Within the paper, capacitors play both an implicit and explicit role in the construction of the electromagnetic theory. As described by Daniel Siegel, capacitors are implicitly called upon as a critical step in the model-reasoning that culminates in the displacement current. Explicitly they (in the form of a Leyden jar) serve as an object of study with outsized empirical significance for Maxwell's electromagnetic theory. Both the implicit and explicit invocations of capacitors appear in the third part of the paper, "The Theory of Molecular Vortices Applied to Statical Electricity," published in January, 1862.

The displacement current arrived within "Physical Lines" as Maxwell strove to create a unified field theory of electromagnetism. In an attempt to extend the mathematical and mechanical frameworks established in the first two parts of the paper to include electrostatics, Maxwell found it necessary to remake his magnetic vortices as elastic and to modify Ampère's Law.[85]

$$(p, q, r) = \frac{1}{4\pi} \nabla \times (\alpha, \beta, \gamma) \qquad \text{PL P.1 (9)}$$

to

$$(p, q, r) = \frac{1}{4\pi} \left(\nabla \times (\alpha, \beta, \gamma) - \frac{1}{E^2} \frac{d}{dt} (P, Q, R) \right) \qquad \text{PL P.3 (112)}$$

or in modern nomenclature[86]

$$\mathbf{J} = \frac{1}{4\pi} \nabla \times \mathbf{H} \tag{3.1}$$

to

$$\mathbf{J} = \frac{1}{4\pi} \left(\nabla \times \mathbf{H} - \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t} \right) \tag{3.2}$$

Physical reasoning stemming from Maxwell's obsessively field-first approach to electromagnetism, borrowed from Faraday, as well as from his newly elasticized mechanical model aligned to suggest the path forward. The paradigmatic, albeit unspoken, case to be considered in both analyses was that of a charging capacitor.

[85]Two notes on equations in this chapter:

First, to avoid rewriting each equation for each component while still allowing for easy comparison with Maxwell's text, vectors are written by putting their three components in parentheses, (x, y, z).

Second, equations that appear in Maxwell's original texts *and* are numbered (or lettered) therein are labeled in this chapter with their original number or letter within parentheses as well as a shorthand for the text from which they came. "PL" stands for "On Physical Lines of Force," "DT" for "A Dynamical Theory of the Electromagnetic Field," and "Treatise" for Maxwell's *Treatise on Electricity and Magnetism: Volume 1.* Beyond this equations marked "PL" or "DT" also show which part of the paper the equation is from, e.g., "P.5" for Part 5. Equations from the *Treatise* are marked with a corresponding article number, e.g., "Art. 329" for Article 329.

[86]Siegel (1991, pp. 92–97).

The field-first approach originated with Faraday: the forces in the space around electrical objects were the true causal seat of power. In direct opposition to the continental electrical tradition exemplified by Ampère, Faraday regarded the field as "primary,"[87] while currents and charges were simply epiphenomena. From Maxwell field-first approach, the capacitor plates "served merely as the bounding surfaces where the chain of polarized particles in the dielectric was terminated."[88] The dielectric sandwiched between capacitor plates is what bore induction. Chains of polarized molecules stretched across the charged capacitor's dielectric and while adjacent molecules canceled the charge of one another within the dielectric, at the dielectric-plate interface these chains end and leave unequalized charge on the surface of the dielectric. The original, unmodified Ampère's law had demonstrated the flow of an electric current in a closed circuit and could not contribute to any accumulation of charge. Upon opening the circuit, as in the case of a charging capacitor, charges appear on the plate-dielectric interfaces and do so in such a manner as to indicate a reverse polarization, i.e., in the opposite direction as would result from the electric field associated with the unmodified current. Let us imagine a straight-line element of a closed current loop, with the electric field and current passing from left to right. Now let us break this wire and attach a capacitor plate to each end. According to the field-first view, if, as we expect, we see the build up of positive charge on the left plate and negative on the right, these charges, which in actuality exist on the extreme surfaces of the dielectric, are an epiphenomenal manifestation of a polarization that runs counter to the left to right direction of the electric field. As such, the effect of this polarization, "a general displacement of the electricity in a certain direction," what Maxwell dubs the displacement current, should be interpreted as a subtraction from a fictional closed circuit, canceling out the contribution within the opened space occupied by the dielectric.[89]

The explanatory power of this field-first explanation is nonetheless limited. It was within Maxwell's elastic-mechanical ether model that the displacement current was initially conceptualized and physicalized and thus, if we want to understand the physical reasoning behind the displacement current, we would be foolish to avoid Maxwell's model.[90] First, a quick overview of how Maxwell's ether model functions, both literally as a mechanical device and as an analogue of electromagnetic phenomena. The hexagons represent molecular vortices the rotation of which describes a magnetic field. Whether or not Maxwell added the smaller idle wheels interspersed between the hexagons simply to solve an engineering problem (how to get adjacent

[87] Siegel (1991, p. 9).

[88] Siegel (1991, p. 104).

[89] Maxwell (1890h, p. 491); Siegel (1991, pp. 100–105). Maxwell explicitly cited Ottaviano Mossotti's mathematical treatment of polarized media. Mossotti (1847).

[90] To be clear, I am following Siegel's analysis of the working of Maxwell's model (one generally shared by Boltzmann). Others, e.g., Bromberg, disagree. Bromberg (1967).

hexagons spinning in the same direction) and then found himself with room to extend his model's explanatory reach, the addition of these idle wheels succeeded in both respects.[91] If within some region, the hexagonal vortices were to rotate with equal velocities, a homogenous magnetic field, the idle wheels between them would simply spin in place. However, if these vortices were to rotate with unequal velocities, the idle wheels would begin to move between the vortices. Within the model, this flow of the small idle wheel particles through channels between the hexagonal magnetic vortices (as a result of the vortices' rotations) represents an electric current, one described by the unmodified form of Ampère's Law.

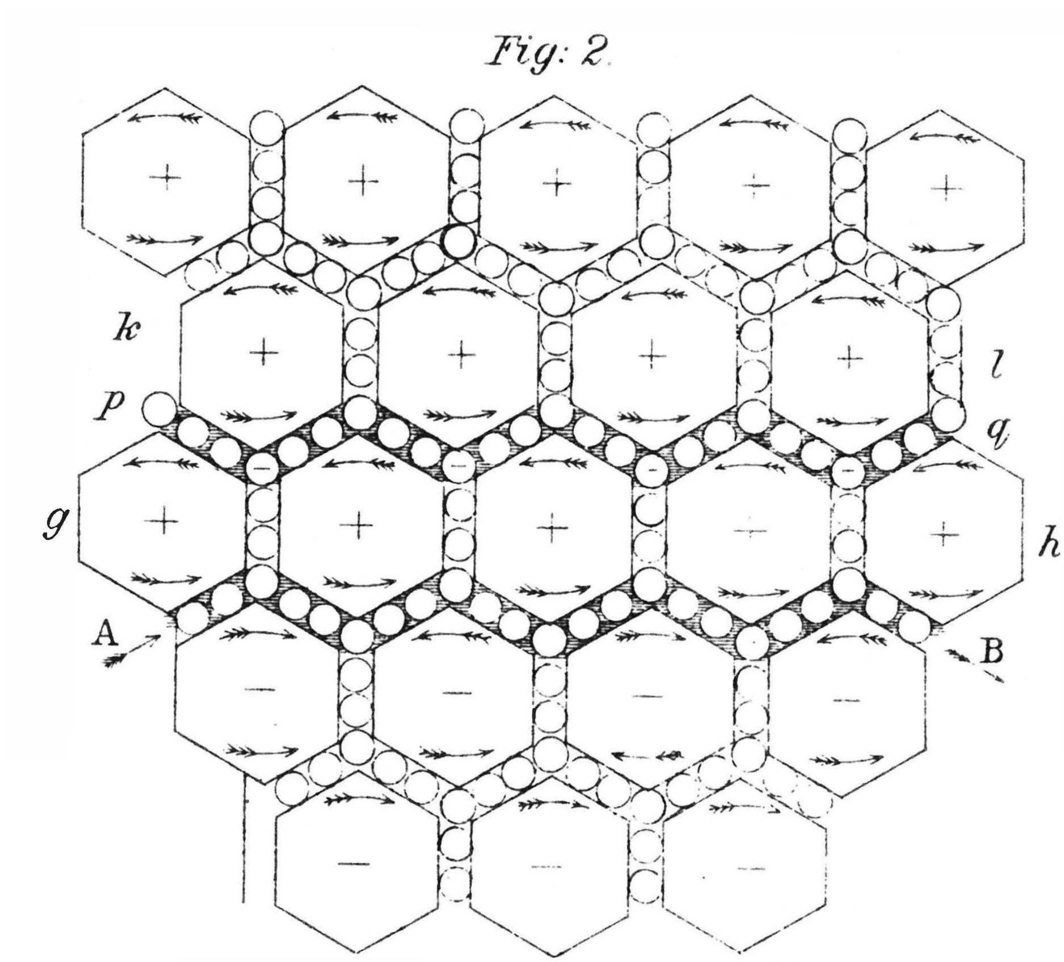

Figure 3.3: Mechanical Model of the Electromagnetic Ether

[91] Maxwell presents the added explanatory power offered by the idle wheels as a happy accident of what began as an engineering solution. As noted in Section 2.4, whether Maxwell's account of his work is accurate is an open (but minor) question.

The formerly rigid vortices having become elastic in Part III made necessary a correction to the relationship between vortex rotation and particle motion: "To correct the equations…of electric currents for the effect due to the elasticity of the medium."[92] Deformation of the vortices displaces not only points along the surface of the vortices themselves, but also displaces adjacent idle wheels/electrical particles. As such, this elastic displacement contributes to particle motion and thus to the electric current and must be accounted for in addition to the effects of vortex rotation.[93] In the case of a charging capacitor, the dielectric will not permit the translational motion of the particles; they can only rotate in place.[94] Therefore, if we imagine a cross section of Maxwell's model representing the plates and dielectric of a capacitor, we should expect particles to build up on the boundary of one plate as they cannot continue through the dielectric, generating a positive charge, while particles move away from the edge of the other plate, the resulting shortage indicating a negative charge. Within the dielectric, the fixing of the particles between vortices means that unequal forces along surfaces of the vortices will cause vortices to distort in addition to rotating. Thus, the model provides a physical distinction between the two contributing current elements of Maxwell's revised Ampère's Law.

Rotation and distortion act as analogues for the conduction current and displacement current. In the case of the charging capacitor, the vortices in the dielectric rotate as if they were within the plate or wires of the circuit; however, as this rotation would normally cause the particles to move as they do outside of the dielectric, i.e., as an electric current, fixing these particles constrains the rotation of the vortices in the dielectric. These dielectric vortices are distorted by the immobile particles, their surfaces are displaced in the opposite direction of rotation, in such a way as would move the fixed particles opposite to the predicted motion due to rotation. This is the mechanical analogue of the displacement current. Thus, we see that in the case of the charging capacitor, the displacement current, represented in the model by the distortion of the dielectric vortices, acts counter to the standard current described by the vortices' rotations. The equal and opposite displacement and conduction currents within the dielectric are each defined by unique mechanical motions, vortex distortion and rotation respectively. Of course, helpful physical distinctions aside, this perfect canceling of contributions within the dielectric is not miraculous, it was already preordained. By fixing the particles within the dielectric there could be no current there. Nevertheless, the case of the charging capacitor treated within the context of the ether model (and even with only the field-first approach) fundamentally embodies Maxwell's generalization of Ampère's Law from closed to both closed and

[92] Maxwell (1890h, p. 496).
[93] Siegel (1991, p. 107).
[94] Maxwell (1890h, p. 487); Siegel (1991, p. 108).
[95] Siegel (1991, p. 109).

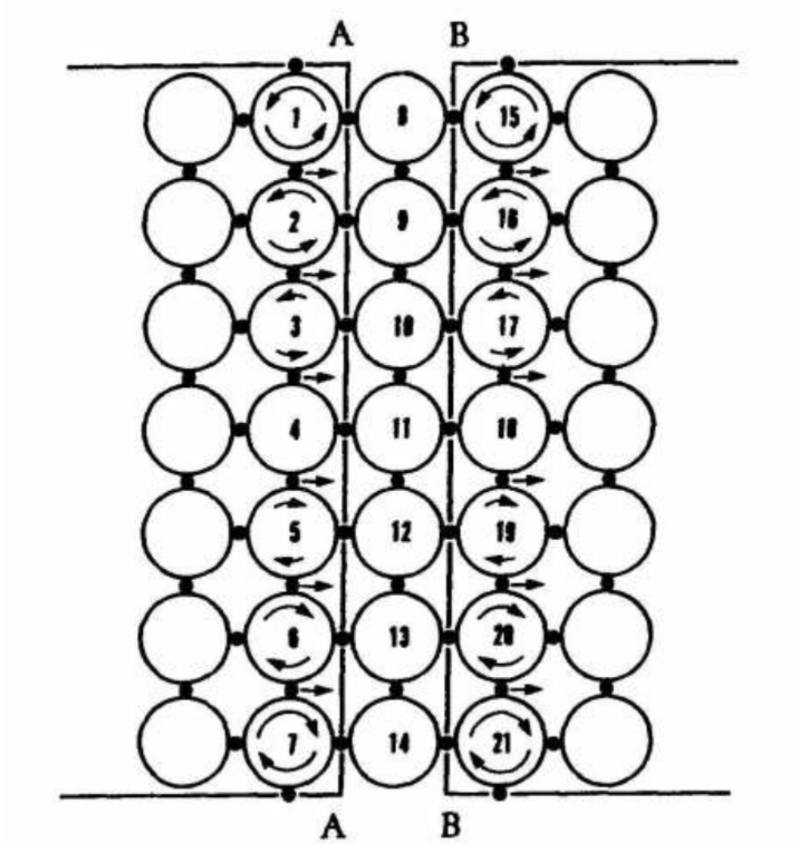

Figure 3.4: Mechanical Model of the Electromagnetic Ether between Capacitor Plates A and B[95]

open circuits. The charging capacitor is the open circuit. Ampère's Law is generalized via the addition of the displacement current through the consideration of an idealized but otherwise immediately familiar technology.

The elasticity of the medium also allowed for the propagation of transverse waves and Part III of "Physical Lines" accordingly heralded the first incarnation of Maxwell's electromagnetic theory of light. The close agreement between the calculated (from the ratio of electrostatic and electromagnetic forces and in mechanical analogue from the medium density and elastic constant) velocity of these transverse waves 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."[96] Resting upon the close agreement of these two velocities was the unification of electromagnetism and optics. Immediately following this conclusion and

[96] Maxwell (1890h, p. 500).

rounding out Part III was a discussion of the capacity of Leyden jars and a novel empirical prediction that if confirmed could offer further (perhaps more direct) support for his electromagnetic theory of light. After noting the close agreement between the speed of light and his calculated wave velocity, the following proposition, Prop. XVII, aims "[t]o find the electric capacity of a Leyden jar composed of any given dielectric placed between two conducting surfaces."[97] Maxwell labels the potentials of the two surfaces ψ_1 and ψ_2, the area of these surfaces S, the distance between them θ, and the quantity of electricity on each surface as e and $-e$. The capacity is then by definition

$$C = \frac{e}{\psi_1 - \psi_2} \qquad \text{PL P.3 (138)}$$

an equation more recognizable to modern readers written:

$$C = \frac{Q}{V} \tag{3.3}$$

where Q is the charge on the plates and V is the voltage between the plates.

Ultimately, Maxwell arrives at the following equation for the capacity of a Leyden jar

$$C = \frac{S}{4\pi E^2 \theta} \qquad \text{PL P.3 (140)}$$

where E is "a coefficient depending on the nature of the dielectric" and in the mechanical case depends on the elastic constant.[98] In modern notation the expression $1/4\pi E^2$ is encapsulated within the single term ϵ_0, the permittivity of free space. The above equation can then be represented more familiarly as

$$C = \epsilon_0 \frac{S}{\theta} \tag{3.4}$$

Maxwell continues, deducing the "coefficient of induction of dielectrics" D, i.e., specific inductive capacity, from the ratio of the capacity of a Leyden jar containing some particular dielectric material to one of equal size containing only air.[99]

$$D = \frac{C_1}{C_{\text{air}}} \tag{3.5}$$

$$D = \frac{{E_{\text{air}}}^2}{{E_1}^2} \tag{3.6}$$

[97] Maxwell (1890h, p. 500).
[98] Maxwell (1890h, p. 491).
[99] Maxwell (1890h, p. 501).

Given then that

$$E = V\sqrt{\mu} \qquad \text{PL P.3 (135)}$$

$$D = \frac{{V_{\mathrm{air}}}^2}{{V_1}^2\mu} \qquad \text{PL P.3 (141)}$$

and the index of refraction i is defined as the ratio of the velocity of light in common air (not vacuum) to its velocity in a some given medium

$$\frac{V_{\mathrm{air}}}{V_1} = i \qquad (3.7)$$

then

$$D = \frac{i^2}{\mu} \qquad \text{PL P.3 (142)}$$

As such, Maxwell arrived at an empirical prediction with the potential to provide solid backing for his unification of electromagnetism and optics.[100] There was, at the time of publication, no data against which to test this predicted this relation; however, it did illustrate the possibility of an experimental research program that could validate Maxwell's electro-optical theory, long before there were any whispers of actually producing and detecting electromagnetic waves. He said as much to Faraday in an October, 1861 letter:

> The conception I have hit on has led, when worked out mathematically to some very interesting results, capable of testing my theory, and exhibiting numerical relations between optical, electric and electromagnetic phenomena, which I hope soon to verify more completely. What I now wish to ascertain is whether the measures of the capacity for electric induction of dielectric bodies with reference to air have been modified materially since your estimates of them in 'Series XI', either by yourself or others.[101]

Two months later in December, Maxwell wrote to William Thomson with a similar request:

> If there is in all media, in spite of the disturbing influence of gross matter, the same relation between the velocity of light and the statical action of electricity, then the 'dielectric capacity', that is, the capacity of a Leyden jar of given thickness formed of it, is proportional to the square of the index of refraction. Do you know any good measures of dielectric capacity of

[100] An account of Maxwell's derivation of the relationship between D and i in the context of his mechanical ether model can be found in Siegel (1991, pp. 141–142).

[101] Maxwell (1990, p. 683).

> 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.[102]

These letters to Faraday and Thomson reveal Maxwell's belief in the power his predicted electro-optical relationship could wield in bolstering his electromagnetic theory of light.[103] The capacitor, or more specifically a Leyden jar, had provided a second crucial empirical link between electromagnetism and optics and Maxwell was eager to find the data to back it up.[104] This second experimental avenue would become increasingly relevant as none other than William Thomson began to cast doubt on the complete equality of the ratio of electrostatic and electromagnetic forces and the speed of light and thus on Maxwell's electromagnetic theory of light itself.[105] In "Physical Lines," the capacitor served not only as a critical guide to Maxwell's novel theoretical developments but also promised a path forward for experimental confirmation of these same developments.

The letter to Thomson also marks Maxwell's first mention of Jenkin in any surviving letter or paper. Given Thomson and Jenkin's close association Maxwell likely received a strong sense of Thomson's appreciation for Jenkin's technical and scientific aptitude. In any case, this letter and its concern with the properties of dielectrics marks the beginning of Maxwell and Jenkin's scientific relationship.

After the publication of the fourth and final installment of "Physical Lines" in February, 1862, Maxwell joined the Standards Committee. In the laboratory at King's College, he initially worked with his countryman and fellow physicist Balfour Stewart as well as Jenkin. When their measurements recommenced the following year, Stewart was replaced by Charles Hockin, who had just graduated that same year as 3rd Wrangler and would go on to become a remarkably successful telegraph engineer.[106] The work of these men was ultimately compiled into the Committee report discussed above. Although the Standards Committee did produce a standardized, practical resistance coil, electric absorption continued to plague the Committee's precision measurements involving insulators and capacitors in reports for the rest of

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[102]Maxwell (1990, p. 696).

[103]Maxwell also wrote to Cecil James Monro in February, 1862 detailing his own plans for "measuring electrical effects through different media, and comparing those media with air." Maxwell (1990, p. 710).

[104]The capacitor was also in part responsible for the first, more famous link between electromagnetism and optics, the close agreement between the wave velocity in Maxwell's medium and the speed of light. To obtain the values that Maxwell's wave velocity is ultimately derived from, Kohlrausch and Weber had made multiple electrostatic and electromagnetic measurements on a capacitor.

[105]Smith (1998, p. 235); Schaffer (1995, p. 148, 154).

[106]The Electrician (1882).

the 1860s.[107] Maxwell's electromagnetic theory of light stood on unsteady empirical grounds as methods for determining the ratio of electrostatic to electromagnetic units were undermined by electric absorption. Capacitors constructed with solid dielectrics were so plagued by absorption that discharging could "continue for hours, if not for days." Unable to obtain a "definite measurable capacity," the methods of obtaining the ratio of units (which assumed such values for capacity) could only provide skewed values.[108] And yet, these were hardly Maxwell's most pressing electromagnetic issues. The conceptual novelties introduced in "Physical Lines" were still precariously perched atop his speculative ether model. A new electromagnetic theory was needed, so much the better if it could deal with electric absorption. In 1864, the year after his first Standards report and while still a member of the Committee, Maxwell set to work constructing another new theory of electromagnetism.

3.4 Laying the Line from "A Dynamical Theory" to the *Treatise*

The development of Maxwell's 1864 paper "A Dynamical Theory of the Electromagnetic Field" is shrouded in some mystery. There are very few surviving early drafts or relevant letters from the period that elucidate Maxwell's process. What draft fragments do exist suggest that Maxwell devised the bulk of the paper during the summer of 1864, ultimately completing it by October.[109] Even before the paper was finalized for publication in 1865, Maxwell was famously confident in his new theory, writing his cousin Charles Hope Cay, "I have also a paper afloat, with an electromagnetic theory of light, which, till I am convinced to the contrary, I hold to be great guns."[110] And Maxwell did genuinely have a lot to be excited about.

The time between "Physical Lines" and "Dynamical Theory" saw Maxwell strip away most of the commitments to mechanical particulars in his electromagnetic theory while preserving its most novel elements. Maxwell recovered (and modernized) his general field equations, his concept of displacement and the displacement current, and reconstructed his electromagnetic theory of light all without delving into specifics of the ether's structure. He was proud to report to George Stokes that he had reconceived his electromagnetic theory of light "without any hypothesis about the structure of the medium."[111] Even if the extent to which, as Whittaker put it, "the architecture of his system was displayed, stripped of the scaffolding by aid of which it

[107] Jenkin et al. (1873).

[108] Maxwell (1890d, p. 136); Jenkin et al. (1873, p. 139, 190).

[109] The paper was submitted on October 27, 1864 and read December 8, 1864. Maxwell (1995, p. 189).

[110] Maxwell (1995, p. 203).

[111] Maxwell (1995, pp. 187–188).

had been first erected" may be somewhat overblown, the size of hypothetical ethereal wheels was absent from the calculation of the Faraday effect.[112] Put more judiciously, the dramatic determinative role played by Maxwell's mechanical model in identifying electromagnetic concepts that characterizes "Physical Lines" was excised by 1864. The displacement current was no longer built up from the intricate double motion of the wheels of a mechanical model. Instead the mechanical analogy behind Maxwell's "Dynamical Theory" realized a softer touch. Physical analogy, specifically to a differentially geared flywheel system, occasionally guided his mathematical analysis, but there was no budding mechanism that could purport to explain the phenomena of electromagnetism.[113] His new theory was "not wise about vortices."[114]

Would it be fair then to suggest, as Hunt has, 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?"[115] Certainly in "Dynamical Theory" Maxwell's theorizing had been stripped of its most fanciful speculations, and the paper was constructed as he was still making theory relevant measures with Jenkin.[116] I can accept Hunt's conclusion that Maxwell's measurement work collaborating with engineers led him to reconsider his microstructural approach, choosing instead to focus on constructing relations between measurable quantities.[117] However, we should be careful not to over index on the drama of Maxwell doing away with his hypothetical ether model. Significant continuity was preserved between "Physical Lines" and "Dynamical Theory" that extended beyond mathematics.

An element that did remain across the two papers was Maxwell's commitment to the elasticity of the electromagnetic medium and its fundamental connection to his concept of displacement. In 1862, reimagining magnetic vortices as elastic birthed the corrective term that Maxwell dubbed the "displacement current." Within "Dynamical Theory" the vortices disappeared, but the elasticity of the medium and its association with displacement were preserved:

> electric displacement, which according to our theory is a kind of elastic yielding to the action of the [electromotive] force, similar to that which takes place in structures and machines owing to the want of perfect rigidity

[112] Whittaker (1987, p. 255); Lazaroff-Puck (2015).

[113] See Chapter 2 or for an account of how the flywheel fits into Maxwell's evolving scientific methodology see Lazaroff-Puck (2015).

[114] Maxwell (1995, p. 337).

[115] Hunt (2014, p. 305).

[116] Hunt (2014, p. 288).

[117] Hunt (2014, p. 337). Maxwell's analogy to a flywheel in "Dynamical Theory" does avoid delving into the ether's microstructure. This reaction against unobservables and adoption of something like a positivist/engineering science methodology was to become increasingly widespread in late-19th-century physics.

of the connexions.[118]

The initial connection between elasticity and displacement had been generated within the context of Maxwell's mechanical model; however, the model proved superfluous to the relationship.

Judging by what we have seen of Jenkin's causal speculations regarding electric absorption (Jenkin who as Hunt acknowledges embodied both sides of Edwin Layton's engineer-physicist methodological divide), we might consider what conceptual elements Maxwell borrowed from Jenkin.[119] In this regard, Maxwell and Jenkin's hypothesis-free joint effort "On the Elementary Relations between Electrical Measurements," cited by Hunt as embodying the "engineering approach" Maxwell chased in "Dynamical Theory" and discussed above as a moment of "baton passing," may be less instructive than Jenkin's earlier, less spartan work.

3.4.1 Cables and Capacitors in "Dynamical Theory"

In "Dynamical Theory," Maxwell once again relied heavily upon capacitors to construct his new theory of electromagnetism.[120] Where much of Maxwell's use of capacitors as theoretical guides had been either not explicitly mentioned but ever-present (at least in Part III) or placed awkwardly (following up the bombshell that was his electromagnetic theory of light), Maxwell allotted capacitors prime real estate in 1864. There Maxwell reserved "Part V" of his 7-part paper for his "Theory of the Condenser."[121] Now arriving right before his reformulated electromagnetic theory of

[118] Maxwell (1890a, p. 531).

[119] Hunt (2014, pp. 323–324); Layton (1971).

[120] This chapter and Chapter 2 both examine technological influences in Maxwell's "Dynamical Theory," a mechanical flywheel/governor in the proceeding chapter and the capacitor (and submarine telegraph cables) in this one. Given the discussion in Section 3.3, it should come as no surprise that there is a notable point of overlap between these technologies. According to William Garnett, demonstrator under Maxwell at the Cavendish Laboratory, the flywheel was used to illustrate the charging, discharging, and even spark/disruptive discharges of a Leyden jar. Campbell and Garnett (1882, p. 554).

[121] Maxwell (1890a, pp. 572–576). Part V of Maxwell's "Dynamical Theory" has been repeatedly passed over in the historical literature, even a notably comprehensive introduction to Maxwell's electromagnetic papers like Thomas K. Simpson's *Maxwell on the Electromagnetic Field: A Guided Study* completely skips over this section of Maxwell's "Dynamical Theory." Simpson (1997, p. 291, 335). Perhaps the most comprehensive account of this section is two sentences from Malcolm Longair's commentary on the paper: "This section is concerned with the determination of the capacity and absorption of capacitors of various construction. This was an issue of considerable importance for the laying of long lengths of submarine telegraph cables, highlighted by the failure of the project to lay the first transatlantic telegraph cable in 1858." Longair (2015, p. 15). Notably, Longair recognizes the connection to submarine telegraphy that I argue for in this chapter. He does, however, overstate the practical significance of Maxwell's "Theory of the Condenser." Other than a single footnote in Olivier Darrigol's *Electrodynamics from Ampère to Einstein*, which will be discussed later, I have

light (Part VI), Maxwell's "Theory of the Condenser" begins mostly as a retread of what he had published in 1862. Immediately following this, however, is an account of charge dissipation, residual charge, and secondary discharge built up from Maxwell's concept of displacement. After his brief qualitative description, Maxwell notes that "[t]hese 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.'"[122] In Part I of "Dynamical Theory," Maxwell is even more explicit, noting that "[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."[123] 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, wherein Faraday, working with a spherical capacitor, had identified residual charge and secondary discharge in various solid dielectrics two decades before Jenkin's cable experiments. Faraday's qualitative account would conclude that the phenomena resulted from the conductive properties of imperfect insulators, allowing charge to penetrate within these dielectrics such that "the electric forces sustaining the induction are not upon the metallic surfaces only, but upon and within the dielectric also..."[124] At no point does Faraday refer to the phenomena by the name "electric absorption." As shown in Section 3.2, Jenkin had already referred to the phenomenon as a kind of absorption in 1862. By the time of his collaboration with Maxwell on the Standards Committee, Jenkin was already using the name "electric absorption."

There does appear to be a discrepancy between Maxwell's description of electric absorption in Part I, the introduction to "Dynamical Theory," and in Part V. Whereas, in the introduction the conductivity of the dielectric is set apart from electric absorption as a separate "disturbing phenomena" affecting the measurement of specific inductive capacity, in Part V it is, together with residual charge a constituent phenomenon of electric absorption.[125] The section in Part I that appears to contradict Part V merely diagnoses the practical difficulties of measuring specific inductive capacity and would be entirely at home within that section even if the "Theory of the Condenser" had never been added.[126] As we shall see, drafts and letters show that Part V was added after the bulk of the paper had already been completed, thus it

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not found any other discussions of this section in the historiography. Darrigol (2000, p. 162 n60).

[122] Maxwell (1890a, p. 573).

[123] Maxwell (1890a, p. 532).

[124] Faraday (1838, p. 23).

[125] Maxwell (1890a, pp. 531–532, 573–576).

[126] As Maxwell's letter to Hockin (see page 122) reveals, the "Theory of the Condenser" was likely developed in the fall of 1864, after most of the paper had already been worked out over the summer.

is likely that the discussion in Part I was simply never updated to reflect Maxwell's new theory.

Maxwell's "Theory of the Condenser" is just as much a theory of the submarine telegraph as it is about capacitors. As concerns relevant electrical phenomena, capacitors and submarine telegraphs are effectively one and the same. Faraday described a submerged telegraph cable as:

> a Leyden arrangement…produced upon a large scale; the copper wire becomes charged statically with that electricity which the pole of the battery connected with it can supply; it acts by induction through the gutta percha…Producing the opposite state on the surface of the water touching the gutta percha, which forms the outer coating of this curious arrangement.[127]

Jenkin's cable experiments detailing electric absorption are relevant to Maxwell's burgeoning "Theory of the Condenser" in just the same way Maxwell's theory was to be relevant not only to capacitors but to submarine cables as well.

The theory that follows is a product of the repeated failure of submarine telegraphy, failures so costly that they made necessary the Joint Committee or else risk the collapse of the entire industry. Jenkin's empirical description of electric absorption in varying purities of cable insulation that Maxwell cited only existed because of the needs of the telegraph industry (or at least R. S. Newell and Company) and was made famous because of their failures. Maxwell's connection to Jenkin and electric absorption came through his work on the Standards Committee, again in service of the needs of the telegraph industry. All of the economic and political pressures, the concerns of international private industry, as well as the imperial concerns of the British Empire that drove early submarine telegraphy, and the committees that rescued it are embedded in the theory Maxwell developed. The transitive relationship between the Victorian economic and political context and Maxwell's theory of electric absorption, passing as it does through the technology of submarine telegraphy, may at first appear contained; however, it found its way to the very heart of Maxwellian electromagnetic theory.

To begin Part V, Maxwell again constructs an expression for capacity of "[t]he simplest form of condenser consist[ing] of a uniform layer of insulating matter bounded by two conducting surfaces."[128] He had specifically used a Leyden jar as his reference device in 1862, but as he makes clear in what follows, he is now thinking in terms of parallel plate capacitors. Regardless of what device Maxwell is picturing, his derivation of capacity does not change substantially from the one he presented in 1862. The lone exception is that Maxwell's efforts in 1864 consistently utilize electromagnetic as

[127] Faraday (1854, p. 200).

[128] Maxwell (1890a, p. 572).

opposed to electrostatic units and thus in place of $4\pi E^2$ he has the constant k, what he calls "electric elasticity."[129]

Immediately following his derivation of capacity, Maxwell goes on to define "Specific Capacity of Electric Induction (D)," i.e., specific inductive capacity, albeit in a much clearer manner than in 1862.[130] He needlessly converts k into electrostatic units and then back again to obtain $D = k_o/k$, where k_o is the value in air. As was discussed above, what immediately follows this in "Physical Lines" is Maxwell's attempt to use the relationship between D and the index of refraction to set up an experimental program testing his electromagnetic theory of light. What was the capstone of Part III of his 1862 paper, accompanied by significant commentary, is absent from Maxwell's "Theory of Condensers" in 1864.

This relation between optical and electromagnetic properties of media does appear halfway through "Part VI: Electromagnetic Theory of Light;" however, in a much reduced form, lacking the expansive discussion provided in 1862.[131] Moving this discussion of the relation between D and the index of refraction to accompany the rest of his electromagnetic theory of light is entirely unsurprising. "Dynamical Theory" was published all at once, and thus he was free to organize his theory topically rather than split into four parts published in the sequence they were developed. Nevertheless, the newly abbreviated section suggests Maxwell's chastening towards what he once believed a promising route towards the empirical confirmation of his theory. Through his work with the Standards Committee, Maxwell had experienced firsthand that electric absorption complicated all precision measurements of solid dielectrics, including of course their specific inductive capacities. He outlined the problem in the introduction to "Dynamical Theory":

> The practical investigation of the inductive capacity of dielectrics is rendered difficult on account of two disturbing phenomena. The first is the conductivity of the dielectric, which, though in many cases exceedingly small, is not altogether insensible. The second is the phenomena called electric absorption...[132]

The empirical prediction Maxwell had made in "Physical Lines" had gone nowhere in the intervening years. But now, as he presented a theory of electric absorption, there was reason for optimism even if he lacked sufficient measurements at the time of submission.

Returning then to the "Theory of Condensers," after Maxwell's brief discussion

[129] In "Dynamical Theory," E was replaced by v and Maxwell provides a helpful section on converting between electromagnetic and electrostatic units. Maxwell (1890a, p. 569).

[130] Maxwell (1890a, p. 572); Maxwell (1890h, p. 501).

[131] Maxwell (1890a, pp. 582–583).

[132] Maxwell (1890a, pp. 531–532).

of specific capacity of electric induction, come three novel results describing peculiar phenomena of electric absorption in capacitors.[133]:

> When the dielectric of which the condenser is formed is not a perfect insulator, the phenomena of conduction are combined with those of electric displacement. The condenser, when left charged, 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. 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."[134]

Maxwell first describes the device to be investigated, a parallel plate capacitor containing a dielectric made up of a number of different layers of different materials that will be charged and discharged and may exhibit electric absorption under particular conditions.

The layers of this capacitor of made of materials of varying values of electric elasticity $k_1, k_2, k_3 \ldots$ and varying thicknesses $a_1, a_2, a_3 \ldots$ In keeping with this nomenclature, the resistance of each layer is $r_1, r_2, r_3 \ldots$, the electric displacement within a layer is $f_1, f_2, f_3 \ldots$, the current is $p_1, p_2, p_3 \ldots$, the potential at each surface (starting with the surface made up of the inside of the first conductor and the outer surface of the first layer of dielectric) is $\psi_1, \psi_2, \psi_3 \ldots$, and finally the electricity per unit area on each surface is (starting again with the conductor/dielectric surface) is $e_1, e_2, e_3 \ldots$ Additionally, Maxwell stipulates that the total sum of resistances adds up to r, the resistance of the whole capacitor and that

$$a_1k_1 + a_2k_2 + a_3k_3 + \cdots = ak \qquad \text{DT P.5 (50)}$$

where k is the value for air and a is "the thickness of an equivalent condenser of air." Given this description of the capacitor and recourse to his general equations of the electromagnetic field provided in Part III, Maxwell goes on to provide a quantitative theory of electrical absorption.

Let us reconstruct and clarify Maxwell's work in this section, after which we will discuss its outsized significance. Maxwell begins by applying the equation of free energy (G) and continuity (H)

$$e + \frac{df}{dx} + \frac{dg}{dy} + \frac{dh}{dz} = 0 \qquad \text{DT P.3 (G)}$$

[133] As it would turn out, Maxwell had been (partly) beaten to the punch. See footnote 148.

[134] Maxwell (1890a, p. 573).

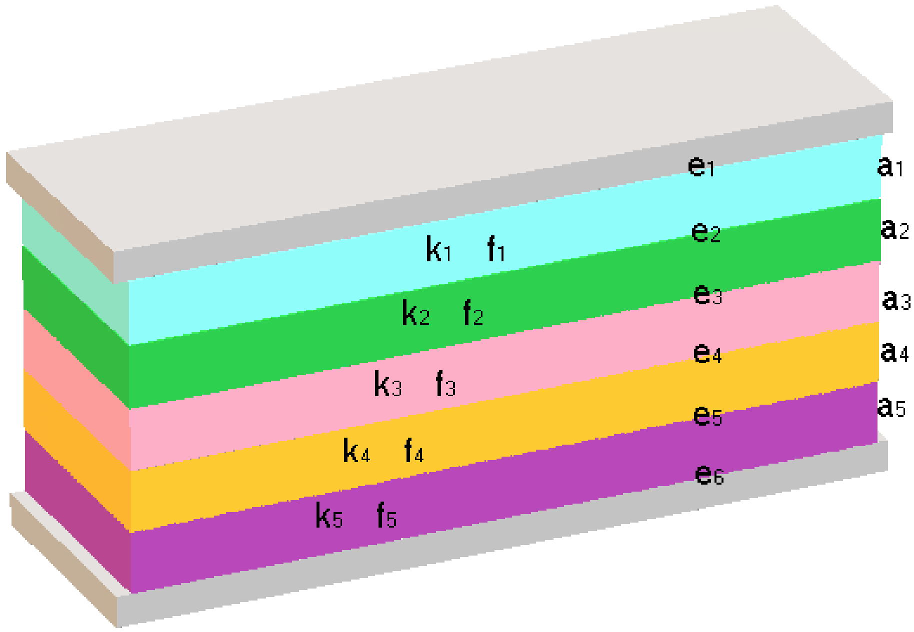

Figure 3.5: The Stratified Capacitor in "Dynamical Theory"

$$\frac{de}{dt} + \frac{dp}{dx} + \frac{dq}{dy} + \frac{dr}{dz} = 0 \qquad \text{DT P.3 (H)}$$

to obtain expressions for the electricity per unit area on each surface and how it changes in time

$$e_1 = -f_1 \qquad \frac{de_1}{dt} = -p_1$$

$$e_2 = f_1 - f_2 \qquad \frac{de_2}{dt} = p_1 - p_2 \qquad \text{DT P.5 (51)}$$

We might take a minute to appreciate that the combination of equations (G) and (H) directly contradict those of (A) and (C), i.e., Maxwell's version of Ampère's Law.

$$p' = p + \frac{df}{dt}$$

$$q' = q + \frac{dg}{dt} \qquad \text{DT P.3 (A)}$$

$$r' = r + \frac{dh}{dt}$$

$$\begin{aligned} \frac{d\gamma}{dy} - \frac{d\beta}{dz} &= 4\pi p' \\ \frac{d\alpha}{dz} - \frac{d\gamma}{dx} &= 4\pi q' \\ \frac{d\beta}{dx} - \frac{d\alpha}{dy} &= 4\pi r' \end{aligned} \qquad \text{DT P.3 (C)}$$

As Daniel Siegel argues this was more than just a simple error, Maxwell was committed to preserving the "field-primacy perspective on electric charge."[135] Regardless, this change of sign does not affect the outcome of any of the results of this section. Now Maxwell uses his Equation of Electric Elasticity (E) and Equation of Electric Resistance (F), better known as Ohm's law

$$\begin{aligned} P &= kf \\ Q &= kg \\ R &= kh \end{aligned} \qquad \text{DT P.3 (E)}$$

$$\begin{aligned} P &= -\rho p \\ Q &= -\rho q \\ R &= -\rho r \end{aligned} \qquad \text{DT P.3 (F)}$$

to obtain

$$\begin{aligned} \psi_1 - \psi_2 &= a_1 k_1 f_1 = -r_1 p_1 \\ \psi_2 - \psi_3 &= a_2 k_2 f_2 = -r_2 p_2 \end{aligned} \qquad \text{DT P.5 (52)}$$

and after the electromotive force has been applied long enough so that the current is the same in every layer

$$p_1 = p_2 = \cdots = p = \frac{\psi}{r} \qquad (3.8)$$

Pausing briefly before we continue down Maxwell's path to electric absorption, we must make note of the flipped sign in Maxwell's version of Ohm's law. Maxwell is somewhat notorious for having "sign dyslexia," however, the nature of the sign

[135] Siegel (1991, p. 149).

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" they appear in final, individually lettered equations, the apogee of his electromagnetic theory. Along similar lines the final equations in "Physical Lines" are consistent among themselves, if different from the modern equations, while as we have noted certain final equations in "Dynamical Theory" are internally inconsistent.[136] Perhaps the most telling evidence for our purposes, however, is from an early draft of "Dynamical Theory," examined in Appendix 2 of Siegel's Innovation in Maxwell's Electromagnetic Theory. There we see Maxwell finalizing Eq. (E), seemingly laboring over the addition of negative signs which are ultimately absent from the published paper.[137] Given the apparent care in deciding the sign of Equation (E) it seems extremely unlikely that Maxwell would flippantly add a negative sign into Ohm's law, the very next equation. This negative sign seems very contrived in Ohm's law, implying opposite directions for the electromotive force and the resulting current.

Indeed, the earliest surviving draft fragment of Maxwell's "Dynamical Theory of the Electromagnetic Field" dated approximately to the summer of 1864 shows that amongst many of the general equations of the electromagnetic field, Maxwell initially wrote Eq. (F) *without* a negative sign.

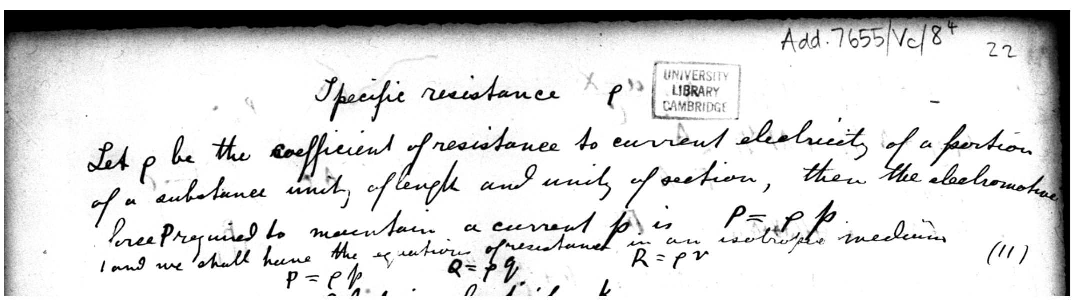

Figure 3.6: A positive variant of Maxwell's Equation of Electric Resistance (F), i.e., Ohm's law, from an early draft of "Dynamical Theory"[138]

In a letter from September 7th of the same year Maxwell wrote to his 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

[136] Siegel (1991, pp. 214–215).
[137] Siegel (1991, pp. 180–181).
[138] Maxwell (1864a).

> of good dielectrics, such as glass, shell-lac, gutta-percha, ebonite, sulphur, etc.[139]

It appears then that before Maxwell had developed his "Theory of the Condenser" and 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 8[140] general equations of the field? As was noted above, it is unlikely this was just another accident. We shall see shortly that Maxwell's approach to developing a theory of capacitors presented him with at least one pressing reason to make such an unphysical modification to Ohm's law.

Returning then to Maxwell derivation, by substituting ψ/r in for p_1 ($p_1 = p$ after time) we can rearrange

$$a_1 k_1 f_1 = -r_1 \frac{\psi}{r} \tag{3.9}$$

so that

$$f_1 = -\frac{\psi}{r}\frac{r_1}{a_1 k_1} \qquad \text{DT P.5 (53)}$$

and as e_1 is the opposite of f_1

$$e_1 = \frac{\psi}{r}\frac{r_1}{a_1 k_1} \qquad \text{DT P.5 (53)}$$

Similarly, for f_2

$$f_2 = -\frac{\psi}{r}\frac{r_2}{a_2 k_2} \qquad \text{DT P.5 (53)}$$

As $e_2 = f_1 - f_2$, we obtain

$$e_2 = \frac{\psi}{r}\left(\frac{r_2}{a_2 k_2} - \frac{r_1}{a_1 k_1}\right) \qquad \text{DT P.5 (53)}$$

In this way, Maxwell has demonstrated how to write expressions for the electric displacement within each layer and the quantities of electricity on any surface bounding or within the capacitor's dielectric. Now we are to imagine that the two conductive plates of the capacitor are joined by a perfectly conducting wire, "so that their potentials are instantly rendered equal."[141] In this instant, only the quantity of electricity on the two "extreme" surfaces, those at the meeting of conductive plate and dielectric, will have the time to be affected, i.e., only e_1 will change. At that moment of

[139] Maxwell (1995, p. 164).

[140] By Maxwell's count he has found 20 such equations, but he counts each individual component equation, meaning all but Eqs. (G) and (H) are counted triply.

[141] Maxwell (1890a, p. 574).

discharge the difference in potentials will equalize and fall to zero and thus

$$\psi' = a_1k_1f_1 + a_2k_2f_2 + a_3k_3f_3 + \cdots = 0 \tag{3.10}$$
$$\psi' = a_1k_1(-e_1) + a_2k_2(f_1 - e_2) + a_3k_3(f_2 - e_3) + \cdots = 0 \tag{3.11}$$
$$\psi' = a_1k_1(e_1) + a_2k_2(e_1 + e_2) + a_3k_3(e_1 + e_2 + e_3) + \cdots = 0 \tag{3.12}$$

We will represent the changed quantity of electricity on the extreme surface, formally e_1, as e'_1, such that after the instant discharge we now have the equation

$$\psi' = a_1k_1e'_1 + a_2k_2(e'_1 + e_2) + a_3k_3(e'_1 + e_2 + e_3) + \cdots = 0 \qquad \text{DT P.5 (54)}$$

We can now take steps to reduce this equation and find e'_1.

$$0 = (a_1k_1 + a_2k_2 + a_3k_3 + \dots)\, e'_1 + a_2k_2e_2 + a_3k_3e_2 + a_3k_3e_3 + \dots \tag{3.13}$$

Following from Eq. (DT P.5 (53)), $e_3 = f_2 - f_3$ and thus

$$e_3 = \frac{\psi}{r}\left(\frac{r_3}{a_3k_3} - \frac{r_2}{a_2k_2}\right) \tag{3.14}$$

Substituting in our various values for e_i, we find

$$0 = ake'_1 + a_2k_2\frac{\psi}{r}\left(\frac{r_2}{a_2k_2} - \frac{r_1}{a_1k_1}\right) + a_3k_3\frac{\psi}{r}\left(\frac{r_2}{a_2k_2} - \frac{r_1}{a_1k_1}\right) + a_3k_3\frac{\psi}{r}\left(\frac{r_3}{a_3k_3} - \frac{r_2}{a_2k_2}\right) + \dots \tag{3.15}$$

$$0 = ake'_1 + \frac{\psi}{r}\left(r_2 - \frac{r_1a_2k_2}{a_1k_1} + \frac{r_2a_3k_3}{a_2k_2} - \frac{r_1a_3k_3}{a_1k_1} + r_3 - \frac{r_2a_3k_3}{a_2k_2} + \dots\right) \tag{3.16}$$

$$0 = ake'_1 + \frac{\psi}{r}\left(r_2 + r_3 + \cdots - \frac{r_1(a_2k_2 + a_3k_3 + \dots)}{a_1k_1}\right) \tag{3.17}$$

We are reminded that $a_2k_2 + a_3k_3 + \cdots = ak - a_1k_1$ and $r_2 + r_3 + \cdots = r - r_1$ so that

$$0 = ake'_1 + \frac{\psi}{r}\left(r - r_1 - \frac{r_1(ak - a_1k_1)}{a_1k_1}\right) \tag{3.18}$$

$$0 = ake'_1 + \frac{\psi}{r}\left(r - \frac{r_1ak}{a_1k_1}\right) \tag{3.19}$$

$$-ake'_1 = \frac{\psi}{r}\left(r - \frac{r_1ak}{a_1k_1}\right) \tag{3.20}$$

$$e'_1 = \frac{\psi}{r}\frac{r_1}{a_1k_1} - \frac{\psi}{ak} \qquad \text{DT P.5 (55)}$$

From this we notice that

$$e'_1 = e_1 - \frac{\psi}{ak} \qquad \text{DT P.5 (55)}$$

meaning that the instantaneous discharge is ψ/ak.

Having obtained this expression for instantaneous discharge, Maxwell is finally properly equipped to pursue the suite of phenomena associated with electric absorption. To begin, we are to imagine that immediately after this discharge the connection between the capacitor plates is broken. Considering the now disconnected capacitor system at some time t after discharge, the potential difference would again be represented:

$$\psi' = a_1k_1f_1 + a_2k_2f_2 + \dots \tag{DT P.5 (56)}$$

Leaning again on Eq. (DT P.5 (52)) and thus critically upon Maxwell's oppositely signed version of Ohm's law

$$a_1k_1f_1 = -r_1\frac{df_1}{dt} \tag{3.21}$$

$$a_2k_2f_2 = -r_2\frac{df_2}{dt} \tag{3.22}$$

where without an externally applied electromotive force, the only current in each layer is a displacement current. After integration, the displacement in any layer is of the form

$$f_1 = A_1e^{\frac{-a_1k_1}{r_1}t} \tag{3.23}$$

$$f_2 = A_2e^{\frac{-a_2k_2}{r_2}t} \tag{3.24}$$

Before going on to solve for the values of $A_1, A_2, \dots$ note that the negative sign from Maxwell's peculiar version of Ohm's law has ended up in the exponent of his expression for displacement. Without switching the sign of Ohm's law, these exponents would necessarily have been positive. The sign of this exponent will prove absolutely critical to the equation that Maxwell constructs. At the moment of discharge, $t = 0$, we find that

$$f_1 = A_1 \qquad f_2 = A_2 \tag{3.25}$$

and since by Eq. (DT P.5 (56)) and Eq. (DT P.5 (54))

$$\psi' = a_1k_1f_1+a_2k_2f_2+\dots = a_1k_1e_1'+a_2k_2(e_1'+e_2)+a_3k_3(e_1'+e_2+e_3)+\dots = 0 \tag{3.26}$$

we can solve for $A_1, A_2, \ldots$

$$A_1 = f_1 = e_1' \tag{3.27}$$

$$A_1 = \frac{\psi}{r}\frac{r_1}{a_1 k_1} - \frac{\psi}{ak} \qquad \text{DT P.5 (57)}$$

$$A_2 = f_2 = e_1' + e_2 \tag{3.28}$$

$$A_2 = \frac{\psi}{r}\frac{r_1}{a_1 k_1} - \frac{\psi}{ak} + \frac{\psi}{r}\left(\frac{r_2}{a_2 k_2} - \frac{r_1}{a_1 k_1}\right) \tag{3.29}$$

$$A_2 = \frac{\psi}{r}\frac{r_2}{a_2 k_2} - \frac{\psi}{ak} \qquad \text{DT P.5 (57)}$$

and rewrite $f_1, f_2, \ldots$

$$f_1 = \left(\frac{\psi}{r}\frac{r_1}{a_1 k_1} - \frac{\psi}{ak}\right) e^{\frac{-a_1 k_1}{r_1} t} \tag{3.30}$$

$$f_2 = \left(\frac{\psi}{r}\left(\frac{r_2}{a_2 k_2} - \frac{\psi}{ak}\right)\right) e^{\frac{-a_2 k_2}{r_2} t} \tag{3.31}$$

Recombined and reorganized the difference of potential at time t is

$$\psi' = a_1 k_1 \left(\frac{\psi}{r}\frac{r_1}{a_1 k_1} - \frac{\psi}{ak}\right) e^{\frac{-a_1 k_1}{r_1} t} + a_2 k_2 \frac{\psi}{r}\left(\frac{r_2}{a_2 k_2} - \frac{\psi}{ak}\right) e^{\frac{-a_2 k_2}{r_2} t} + \ldots \tag{3.32}$$

$$\psi' = \psi\left\{\left(\frac{r_1}{r} - \frac{a_1 k_1}{ak}\right) e^{\frac{-a_1 k_1}{r_1} t} + \frac{\psi}{r}\left(\frac{r_2}{a_2 k_2} - \frac{\psi}{ak}\right) e^{\frac{-a_2 k_2}{r_2} t} + \ldots\right\} \qquad \text{DT P.5 (58)}$$

At a glance we can see that the phenomena of electric absorption only applies to dielectrics of varied materials. In a homogeneous dielectric $r_1, r_2, \cdots = r$ and $a_1 k_1, a_2 k_2, \cdots = ak$ and the equation is 0 at all times t, i.e., the difference of potential remains 0 after the instantaneous discharge.

$$\psi' = \psi\left(\frac{r}{r} - \frac{ak}{ak}\right) e^{\frac{-ak}{r} t} = 0 \tag{3.33}$$

There will be no reestablished potential difference and "gradual dissipation of the internal charges." All charge will have been expended during the initial instantaneous discharge. The great oddity then is that a dielectric made up of layers of different materials may experience electric absorption, although the phenomena would not appear in isolation in any of the individual materials.[142] As Maxwell indicates the value of this equation will never change sign because the coefficients as we have

[142] Maxwell more explicitly describes this peculiarity in Maxwell (1873b, Vol. 1, p. 381).

written them above are in descending order of magnitude. When $t = 0$ the difference in potential is 0, just as we assumed to get the value of discharge in the first place.

$$\psi' = \psi \left\{ \left(\frac{r_1}{r} - \frac{a_1 k_1}{ak} \right) + \frac{\psi}{r} \left(\frac{r_2}{a_2 k_2} - \frac{\psi}{ak} \right) + \ldots \right\} = \psi \left(\frac{r}{r} - \frac{ak}{ak} \right) = 0 \qquad (3.34)$$

When t is positive the difference in potential will be positive. There is a gradual transferral of electric displacement from inner layers to extreme layers reestablishing charge on the extreme surfaces and a potential difference in the same direction as the capacitor was initially set upon charging. There is of course general dissipation of charge in the capacitor as a whole and thanks to the negative sign in the exponent of each quantity we can clearly see that as time passes the potential difference will eventually disappear as the internal charges are eventually lost to electric absorption.

Finally, Maxwell asserts the generality of his result beyond ideally stratified dielectrics: "Any substance, therefore, the parts of which are not mathematically homogeneous, though they may be apparently so, may exhibit phenomena of absorption."[143]

Following Eq. (DT P.5 (58)) is the final, somewhat anticlimactic[144] account of electric absorption. Here Maxwell seeks to find "the total amount of electricity" that would pass between the conductive plates of the capacitor if it was discharged for a second time, now by a much less fantastic wire, one possessing a resistance R.

Taking the sum of the electromotive force within each layer of the dielectric, each a product of the current in that layer and its specific resistance as per Eq. (F), to be equal to that within the wire during discharge, Maxwell arrives at

$$\psi' = p_1 r_1 + p_2 r_2 + \cdots = pR \qquad \text{DT P.5 (59)}$$

A time derivative then yields

$$q_1 r_1 + q_2 r_2 + \cdots = qR \qquad \text{DT P.5 (60)}$$

where q and q_i are "the quantities of electricity which traverse the different conductors."[145] Thinking then about how the surfaces dispense with and collect electricity from one another, Maxwell decides that the quantities of electricity on each surface (beginning with the extreme surface and working inward into the capacitor) must be

$$e'_1 - q - q_1 \qquad (3.35)$$

$$e_2 + q_1 - q_2 \qquad (3.36)$$

[143] Maxwell (1890a, p. 575).

[144] It is hard to surpass the prior derivation as it essentially covered everything Maxwell was concerned with in this part. As we will see it already implies the final result that Maxwell uses much tricky algebra to achieve.

[145] Maxwell (1890a, p. 576).

The extreme surface began with the quantity of electricity e_1' and released some quantity q into the connecting wire R and some amount q_1 inward to the second surface. This second surface receives q_1 and gives up q_2; however, exactly how Maxwell envisions the exchanges of electricity between layers is unclear. Eventually the discharge through the wire will be complete and the quantity of electricity on each surface will "vanish," as such

$$q_1 = e_1' - q \tag{3.37}$$
$$q_2 = e_2 + q_1 = e_1' + e_2 - q \tag{3.38}$$

Plugging these values for q_1 and q_2 back into Eq. (DT P.5 (60)) and also retrieving our original expressions for electrical quantities on the surfaces, e_1', e_2,... we can solve for the total amount of electricity that is discharged through the wire R.

$$qR = r_1(e_1' - q) + r_2(e_1' + e_2 - q) + \ldots \tag{3.39}$$
$$qR = r_1\left(\frac{\psi}{r}\frac{r_1}{a_1k_1} - \frac{\psi}{ak}\right) - r_1q + r_2\left(\frac{\psi}{r}\frac{r_1}{a_1k_1} - \frac{\psi}{ak}\right) + r_2\frac{\psi}{r}\left(\frac{r_2}{a_2k_2} - \frac{r_1}{a_1k_1}\right) - r_2q + \ldots \tag{3.40}$$
$$qR = \frac{\psi}{r}\frac{{r_1}^2}{a_1k_1} - \frac{\psi r_1}{ak} - r_1q + \frac{\psi}{r}\frac{r_1r_2}{a_1k_1} - \frac{\psi r_2}{ak} + \frac{\psi}{r}\frac{{r_2}^2}{a_2k_2} - \frac{\psi}{r}\frac{r_1r_2}{a_1k_1} - r_2q + \ldots \tag{3.41}$$
$$qR = \frac{\psi}{r}\frac{{r_1}^2}{a_1k_1} + \frac{\psi}{r}\frac{{r_2}^2}{a_2k_2} - \frac{\psi r_1}{ak} - \frac{\psi r_2}{ak} - r_1q - r_2q + \ldots \tag{3.42}$$
$$qR = \frac{\psi}{r}\frac{{r_1}^2}{a_1k_1} + \frac{\psi}{r}\frac{{r_2}^2}{a_2k_2} + \cdots - \frac{\psi(r_1 + r_2 + \ldots)}{ak} - (r_1 + r_2 + \ldots)q \tag{3.43}$$
$$qR = \frac{\psi}{r}\frac{{r_1}^2}{a_1k_1} + \frac{\psi}{r}\frac{{r_2}^2}{a_2k_2} + \cdots - \frac{\psi r}{ak} - qr \tag{3.44}$$
$$q(r + R) = \frac{\psi}{r}\left(\frac{{r_1}^2}{a_1k_1} + \frac{{r_2}^2}{a_2k_2} + \ldots\right) - \frac{\psi r}{ak} \tag{3.45}$$

This, however, is not the expression Maxwell derives. Instead he writes down

$$qR = \frac{\psi}{r}\left(\frac{{r_1}^2}{a_1k_1} + \frac{{r_2}^2}{a_2k_2} + \ldots\right) - \frac{\psi r}{ak} \tag{3.46}$$

missing the quantity qr. I cannot conceive of any physical justification to drop this quantity, nor does Maxwell make any attempt at any. As we shall see below, a similar calculation in his *Treatise* does not repeat the omission. It appears safe to conclude this is nothing more than a minor algebra mistake.

Maxwell's final act in Part V is to rewrite the above equation so that it appears as "a quantity essentially positive; so that, when the primary electrification is in the one direction, the secondary discharge is always in the same direction as the primary discharge."[146] In the interest of completeness, let's reorder the above equation to acquire that "essentially positive" quality. In the interest of brevity, let's only consider a capacitor with two dielectric layers.

$$= \frac{\psi}{r}\left(\frac{{r_1}^2}{a_1k_1} + \frac{{r_2}^2}{a_2k_2}\right) - \frac{\psi r}{ak} \tag{3.47}$$

$$= \frac{\psi}{r}\left(\frac{{r_1}^2}{a_1k_1} + \frac{{r_2}^2}{a_2k_2} - \frac{r^2}{ak}\right) \tag{3.48}$$

$$= \frac{\psi}{akr}\left(\frac{akr_1{}^2}{a_1k_1} + \frac{akr_2{}^2}{a_2k_2} - r^2\right) \tag{3.49}$$

Since $r = r_1 + r_2$ if the capacitor contains only two layers

$$= \frac{\psi}{akr}\left(\frac{akr_1{}^2}{a_1k_1} + \frac{akr_2{}^2}{a_2k_2} - (r_1 + r_2)^2\right) \tag{3.50}$$

$$= \frac{\psi}{akr}\left(\frac{akr_1{}^2}{a_1k_1} + \frac{akr_2{}^2}{a_2k_2} - {r_1}^2 - 2r_1r_2 - {r_2}^2\right) \tag{3.51}$$

$$= \frac{\psi}{akr}\left(\frac{akr_1{}^2}{a_1k_1} + \frac{akr_2{}^2}{a_2k_2} - \frac{a_1k_1r_1{}^2}{a_1k_1} - 2r_1r_2 - \frac{a_2k_2r_2{}^2}{a_2k_2}\right) \tag{3.52}$$

$$= \frac{\psi}{akr}\left(\frac{(ak - a_1k_1)r_1{}^2}{a_1k_1} + \frac{(ak - a_2k_2)r_2{}^2}{a_2k_2} - 2r_1r_2\right) \tag{3.53}$$

Similarly, because $ak = a_1k_1 + a_2k_2$, then $ak - a_1k_1$ and $ak - a_2k_2$ are equal to a_2k_2 and a_1k_1 respectively, and thus

$$= \frac{\psi}{akr}\left(\frac{a_2k_2r_1{}^2}{a_1k_1} + \frac{a_1k_1r_2{}^2}{a_2k_2} - 2r_1r_2\right) \tag{3.54}$$

$$= \frac{\psi}{akr}\left(\frac{a_1k_1a_2k_2}{a_1k_1a_2k_2}\left(\frac{a_2k_2r_1{}^2}{a_1k_1} + \frac{a_1k_1r_2{}^2}{a_2k_2} - 2r_1r_2\right)\right) \tag{3.55}$$

$$= \frac{\psi}{akr}\left(\frac{a_1k_1a_2{}^2k_22r_1{}^2}{a_1{}^2k_1{}^2a_2k_2} + \frac{a_1{}^2k_1{}^2a_2k_2r_2{}^2}{a_1k_1a_2{}^2k_2{}^2} - \frac{2a_1k_1a_2k_2r_1r_2}{a_1k_1a_2k_2}\right) \tag{3.56}$$

$$= \frac{\psi}{akr}\left(a_1k_1a_2k_2\left(\frac{{r_1}^2}{a_1{}^2k_1{}^2} + \frac{{r_2}^2}{a_2{}^2k_2{}^2} - \frac{2a_1k_1a_2k_2r_1r_2}{a_1k_1a_2k_2}\right)\right) \tag{3.57}$$

$$= \frac{\psi}{akr}\left(a_1k_1a_2k_2\left(\frac{r_1}{a_1k_1} - \frac{r_2}{a_2k_2}\right)^2\right) \tag{3.58}$$

[146] Maxwell (1890a, p. 576).

If we don't correct Maxwell's algebra mistake we get

$$qR = \frac{\psi}{akr}\left(a_1k_1a_2k_2\left(\frac{r_1}{a_1k_1} - \frac{r_2}{a_2k_2}\right)^2\right) \tag{3.59}$$

$$q = \frac{\psi}{akrR}\left(a_1k_1a_2k_2\left(\frac{r_1}{a_1k_1} - \frac{r_2}{a_2k_2}\right)^2\right) \tag{3.60}$$

or as he writes it

$$q = \frac{\psi}{akrR}\left\{a_1k_1a_2k_2\left(\frac{r_1}{a_1k_1} - \frac{r_2}{a_2k_2}\right)^2 + a_2k_2a_3k_3\left(\frac{r_2}{a_2k_2} - \frac{r_3}{a_3k_3}\right)^2 + \dots\right\} \tag*{DT P.5 (61)}$$

If we wish to correct the error we can again find q, the quantity of electricity discharged through the wire R

$$q(R+r) = \frac{\psi}{akr}\left\{a_1k_1a_2k_2\left(\frac{r_1}{a_1k_1} - \frac{r_2}{a_2k_2}\right)^2 + a_2k_2a_3k_3\left(\frac{r_2}{a_2k_2} - \frac{r_3}{a_3k_3}\right)^2 + \dots\right\} \tag{3.61}$$

$$q = \frac{\psi}{akr(R+r)}\left\{a_1k_1a_2k_2\left(\frac{r_1}{a_1k_1} - \frac{r_2}{a_2k_2}\right)^2 + a_2k_2a_3k_3\left(\frac{r_2}{a_2k_2} - \frac{r_3}{a_3k_3}\right)^2 + \dots\right\} \tag{3.62}$$

Corrected or not the secondary discharge q is shown to be necessarily positive, just like the initial instantaneous discharge. While this latter result is already implied by the unchanging sign of the potential difference in Eq. (DT P.5 (58)), Maxwell obtained an eminently practical result regarding the quantity of electricity discharged by a capacitor through something like a real wire with non-negligible resistance. That the theory be practical was vital. As Maxwell noted in Part I and as he had experience first-hand as part of his work with the Standards Committee, electric absorption wreaked havoc on the accurate measure of electric quantities.

Returning then to the issue of Maxwell's sign-swapped Ohm's law, we see that this sign change is absolutely critical in achieving the appropriate representation of electric absorption, as was first pointed out by Olivier Darrigol.[147] Without the

[147] To my knowledge only Olivier Darrigol has noted this reasoning behind Maxwell's sign swapped Ohm's law. It appears in footnote 60 on p162. In the same footnote Darrigol also claims Maxwell is inconsistent in using this negative version of Ohm's law, stating that he uses the modern positive variant in "his study of wave absorption by conductors." I assume that Darrigol is referring to the section titled "Relation between Electric Resistance and Transparency" in Part VI, wherein Maxwell does indeed apply Eq. (F). Nonetheless, it seems to me that Maxwell remains consistent here, again using his negative variant of Ohm's law. Darrigol (2000, p. 162 n60); Maxwell (1890a, pp. 586–587).

sign change the expression for the difference of potential would explode, implying some sort of infinite wellspring of internal charge flowing out from the dielectric. The situation we are left with is that Maxwell modified a fundamental equation of electromagnetism, one of his select few general equations of the electromagnetic field, to satisfy the needs of this investigation of electrical technology. The abstract theoretical physics of Maxwell's electromagnetic theory (albeit what is perhaps the most practical element of it) ultimately took a back seat in favor of the immediate needs presented by modeling the workings of an (idealized) technology and the very real issues surrounding submarine telegraphy that inspired it. That the theory of the capacitor receives its own section, in the same sense that the general equations of the field receive their own section, is not a meaningless quirk of the organization of this paper. They are obviously not equal in their significance, but neither is the capacitor purely supplementary; Maxwell reaches back into the general equations and rewrites fundamental theoretical physics to accommodate electrical technologies. And if we look to the beginning of the paper we can see why.

The concept of electric displacement itself is buoyed by Maxwell's ability to model electrical absorption. Certainly, this is most true in the sense that Maxwell depended on displacement to produce what he believed at the time of writing was a novel account of a previously confounding set of empirical phenomena, the first successful quantitative account of electric absorption.[148] Maxwell's account of electric absorption is uniquely dependent on the concept of displacement. The relative paucity of electromagnetic relations in his account of electric absorption streamlines its contingencies; the efficacy of his theory of electric absorption is almost exclusively reliant on the efficacy of the concept of displacement. This milestone was not quite as powerful evidence as the prediction of an entirely new discipline-uniting physical relation like $D = i^2/\mu$. Nevertheless, successfully accounting for the complex suite of electrical phenomena classed under the name "electric absorption" illustrated the vast explanatory power of Maxwell's electromagnetic theory and of the concept of displacement in particular.[149]

[148]By the time he had sent the paper into Philosophical Transactions, he had "seen a paper by M. Gaugain in the *Annales de Chimie* for 1864, in which he has deduced the phenomena of electric absorption and secondary discharge from the theory of compound condensers." Maxwell (1890a, p. 576). Jean-Mothée Gaugain, a French engineer, had not produced anything like Maxwell's mathematical theory of absorption and secondary discharge. What Gaugain did claim to show through a careful set of experiments on capacitors with various dielectric materials was that the idea of a literal "absorption" of charge into the dielectric was unlikely. The charge on the capacitor plates remained the same no matter how long he left them, but the residual charge increased as the system was left to sit longer. Additionally, Gaugain demonstrated that the instantaneous charge and discharge of a capacitor were equal. Maxwell worked out this equality in his updated analysis of a stratified dielectric in the *Treatise*. Gaugain (1864, pp. 311–316); Agastra and Selleri (2014, pp. 378–379).

[149]Herschel (1831, pp. 25–34).

Maxwell's conception of an elastic ether provided the impetus for electrical displacement and the displacement current in Part III of "Physical Lines." Insofar as electric displacement remained for Maxwell more than just the mathematics associated with it, it retained conceptual links to this elastic lineage. After all, Eq. (E), $P = kf$, is called the "equation of electric elasticity." This original elastic nature of displacement is supported by its usefulness in dealing effectively with electric absorption, which by analogy, Maxwell insists is 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. . . It appears therefore that certain phenomena in electricity and magnetism lead to the same conclusion as those of optics, namely, that there is an aethereal medium pervading all bodies, and modified only in degree by their presence; that the parts of this medium are capable of being set in motion by electric currents and magnets; that this motion is communicated from one part of the medium to another by forces arising from the connexions of those parts; that under the action of these forces there is a certain yielding depending on the elasticity of these connexions; and that therefore energy in two different forms may exist in the medium, the one form being the actual energy of motion of its parts, and the other being the potential energy stored up in the connexions, in virtue of their elasticity.[150]

Maxwell's triumph in accounting for electric absorption in a capacitor system via electric displacement vindicates both his analogy between electric absorption and elastic phenomena and the more fundamental analogy linking displacement and elasticity. The similar analogical relations between electric displacement and elasticity and between electric absorption and elasticity mutually support and reinforce one another as a consequence of the effectiveness of displacement in accounting for the novel phenomenon of electric absorption. Indeed, Maxwell sees this success as strong evidence for his conception of the ether as an elastic medium,

> a complicated mechanism capable of a vast variety of motion, but at the same time so connected that the motion of one part depends, according to definite relations, on the motion of other parts, these motions being

[150] Maxwell (1890a, pp. 532–533).

> communicated by forces arising from the relative displacement of the connected parts, in virtue of their elasticity.[151]

In a circular sort of a reasoning, albeit a not altogether unscientific sort,[152] the success of Maxwell's theory, built in part of elastic concepts (of which his "Theory of Condensers" is most certainly an example), justifies the dynamical approach guiding the construction of the theory. "Such a [complicated] mechanism must be subject to the general laws of Dynamics, and we ought to be able to work out all the consequences of its motion, provided we know the form of the relation between the motions of the parts."[153]

On a final practical note, we may remind ourselves that Maxwell's work with the capacitor to develop a quantitative account of electric absorption promised to help alleviate the major roadblock to measuring specific inductive capacity, D. As such, it could confirm his electromagnetic theory of light via the relation between the specific inductive capacity and the index of refraction. In fact, as Maxwell was undoubtedly aware in 1864, but would not make explicit until 1868, the ability to correct for the effects of electric absorption could also explain some of the disagreement between his calculated wave velocity and the speed of light. The experiments of Kohlrausch and Weber on capacitors that were Maxwell's sole source of the values that formed the wave velocity in "Physical Lines" and "Dynamical Theory" were flawed.

> The capacity of the condenser was measured by dividing its charge repeatedly with a sphere of known radius. Now, since all condensers made with solid dielectrics exhibit the phenomena of "electric absorption," this method would give too large a value for the capacity, as the condenser would become recharged to a certain extent after each discharge, so that the repeated division of the charge would have too small an effect on the potential. The capacity being overestimated, 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.[154]

The capacitor in Maxwell's "Dynamical Theory" thus takes priority over abstract electromagnetic equations, bolsters even more abstract analogies between physical realms (elasticity and electromagnetism), and even promises to resurrect Maxwell's

[151] Maxwell (1890a, p. 533).

[152] Smith (2014).

[153] Maxwell (1890a, p. 533).

[154] Maxwell (1890d, p. 136). Maxwell's claim that Kohlrausch and Weber's value of v was too high would prove correct. Unfortunately, his own experimental determination of v, which he had only just presented immediately before this quotation, was very nearly as inaccurate, just now too low.

empirical program to validate his electromagnetic theory of light. Nevertheless, it is in a slight modification in Maxwell's *Treatise on Electricity and Magnetism* eight years later that the technological co-conspirators of the capacitor and submarine cable left what is very likely their most significant mark on Maxwellian electromagnetic theory.

3.4.2 Cables and Capacitors in Maxwell's *Treatise*

Although slightly expanded, the sections of Maxwell's discussion of capacitors and electric absorption that we are interested in mostly mirror the account given in Part V of "Dynamical Theory."[155] There is one particularly notable difference of approach, a difference that was instrumental in shaping the work of physicists who learned electricity and magnetism from the *Treatise* and continued to work as "Maxwellians" until the advent of Larmor's electron theory.

In Volume 1, Chapter X, "Conduction in Dielectrics" of Maxwell's *Treatise on Electricity and Magnetism*, we find a slightly expanded treatment of capacitors and dielectrics. Nevertheless, the section which we are interested in, "Theory of a Composite Dielectric," is essentially a copy of Maxwell's discussion of electric absorption in his "Dynamical Theory."[156] What he now explicitly refers to as Ohm's law has lost the negative sign he had saddled it with in 1864.

$$X_1 = r_1 p_1 \qquad \text{Treatise Art. 328 (1)}$$

and as an added bonus the sign of the Equation of Free Electricity (G) changed to be consistent with Ampère's law[157]

However, it is a shift in approach to deriving Eq. (DT P.5 (58)), Maxwell's equation describing the gradual dissipation of internal charge of a capacitor, that both allows for this return to a "properly" signed Ohm's law as well as heralds an enormous reconceptualization of dielectrics. Maxwell is again considering a capacitor containing a multi-layered dielectric, having just had the connection between its plates severed after an instantaneous discharge. He begins by defining his variables,

> Let a_1 , a_2, &c. be the thicknesses of the different strata.
> X_1, X_2, &c. the resultant electrical force within each stratum.
> p_1, p_2, &c. the current due to conduction through each stratum.
> f_1, f_2, &c. the electric displacement.
> u_1, u_2, &c. the total current, due partly to conduction and partly to variation of displacement.
> r_1, r_2, &c. the specific resistance referred to unit of volume.

155 Maxwell (1873b, Vol. 1, pp. 374–385).
156 Maxwell (1873b, Vol. 1, pp. 376–385).
157 Maxwell (1873b, Vol. 1, p. 223); discussed in Siegel (1991, p. 150).

> ... k_1, k_2, &c. the reciprocal of specific inductive capacity.
> E the electromotive force due to a voltaic battery, placed in the part of the circuit leading from the last stratum towards the first, which we shall suppose good conductors.
> Q the total quantity of electricity which has passed through this part of the circuit up to the time t.
> ... [I have omitted variables which we will not encounter or which are later redefined][158]

Maxwell's k_i in the *Treatise*, the "reciprocal of specific inductive capacity," is an electrostatic measurement. In "Dynamical Theory" k_i, the "coefficient of electric elasticity," is an electromagnetic measurement, hence the imposition of 4π in Maxwell's new relation between electrical force and displacement.[159]

$$X_1 = 4\pi k_1 f_1 \qquad \text{Treatise Art. 328 (2)}$$

His derivation of an equivalent of Eq. (DT P.5 (58))/Eq. (Treatise Art. 329 (24)); however, proceeds very differently. First, we must note that Maxwell is solving not for displacement, but for $X_1, X_2, \ldots$, the electrical force within each layer. This change of perspective will slightly alter the look of the intermediate equations, but is not in and of itself of any significance.

In "Dynamical Theory," Maxwell uses his reversed Ohm's law, embedded within the equation:

$$\begin{aligned} \psi_1 - \psi_2 &= a_1 k_1 f_1 = -r_1 p_1 \\ \psi_2 - \psi_3 &= a_2 k_2 f_2 = -r_2 p_2 \end{aligned} \qquad \text{DT P.5 (52)}$$

along with the assumption that after disconnecting the plates the only current, $p_1, p_2, \ldots$, in a given layer is the displacement current

$$a_1 k_1 f_1 = -r_1 \frac{df_1}{dt} \tag{3.63}$$

$$a_2 k_2 f_2 = -r_2 \frac{df_2}{dt} \tag{3.64}$$

to obtain after integration

$$f_1 = A_1 e^{\frac{-a_1 k_1}{r_1} t} \tag{3.65}$$

$$f_2 = A_2 e^{\frac{-a_2 k_2}{r_2} t} \tag{3.66}$$

[158] Maxwell (1873b, Vol. 1, pp. 376–377).
[159] Maxwell (1890a, p. 569).

In the *Treatise*, Maxwell finds a new starting point, the equation of total current

$$u_1 = p_1 + \frac{df_1}{dt} \qquad \text{Treatise Art. 328 (3)}$$

which is the same in both his "Dynamical Theory" and *Treatise*. When expressed in terms of electrical force within layers this becomes

$$u = \frac{1}{r_1}X_1 + \frac{1}{4\pi k_1}\frac{dX_1}{dt} \qquad \text{Treatise Art. 328 (8)}$$

Maxwell makes the assumption that with the connection between plates broken, the total current, u, is 0. Note that the version of Ohm's law used in the above step from the *Treatise* is entirely positive, as is modern convention. From here Maxwell goes on to integrate and obtain nearly the same negative time exponent

$$0 = \frac{1}{r_1}X_1 + \frac{1}{4\pi k_1}\frac{dX_1}{dt} \tag{3.67}$$

$$\frac{1}{X_1}\frac{dX_1}{dt} = -\frac{4\pi k_1}{r_1} \tag{3.68}$$

$$X_1 = X' e^{-\frac{4\pi k_1}{r_1}t} \qquad \text{Treatise Art. 329 (23)}$$

as in "Dynamical Theory," which allows for accurate modeling of dissipation. The coefficient X' is just the electric force in the extreme layer immediately after instantaneous discharge, i.e., $X' = X_1$ at $t = 0$. Here X' acts as the analogue of A_1, which was determined to be equal to the quantity of electricity on the extreme surface, e'_1, in "Dynamical Theory." Having already solved for X' Maxwell is able to write out the complete expression for X_1

$$X_1 = E_o \left\{ \frac{r_1}{R} - 4\pi k_1 C \right\} e^{-\frac{4\pi k_1}{r_1}t} \tag{3.69}$$

where "C [is] the electric capacity of the system as measured in this instantaneous way"

$$C = \frac{Q}{E} = \frac{1}{4\pi(k_1 a_1 + k_2 a_2 + \dots)} \qquad \text{Treatise Art. 329 (16)}$$

which in the case of Maxwell's 1864 derivation was written with respect to an imagined equivalent air capacitor, $1/ak$, and R is the total resistance of the system

$$R = r_1 a_1 + r_2 a_2 + \dots \qquad \text{Treatise Art. 329 (18)}$$

Given that

$$E = a_1 X_1 + a_2 X_2 + \dots \qquad \text{Treatise Art. 328 (10)}$$

Maxwell goes on to find the *Treatise*'s equivalent of Eq. (DT P.5 (58)):

$$E = E_o \left\{ \left(\frac{a_1 r_1}{R} - 4\pi k_1 C \right) e^{-\frac{4\pi k_1}{r_1} t} + \left(\frac{a_2 r_2}{R} - 4\pi k_2 C \right) e^{-\frac{4\pi k_2}{r_2} t} + \ldots \right\} \quad \text{Treatise Art. 329 (24)}$$

To find the instantaneous discharge at any time t, i.e., the residual discharge, we merely multiply the above equation by C as $EC = Q$.

Thus, we have seen that Maxwell's new method avoids the need to reverse Ohm's law to model electric absorption. It is worth noting that although it obviously is extremely close to Eq. (DT P.5 (58)) there are real differences between the two equations. As noted above, where Maxwell once wrote $1/ak$, he now writes C. This more concise nomenclature aside, we note that thanks to his new approach, the layer thickness, a_i, has disappeared from the exponents and reappeared in the first term in each layer's expression, for example $a_1 r_1/R$. These first terms now involve the thickness of the specific layer and that of the entire dielectric due to the definition of R versus Maxwell's use of $r = r_1 + r_2 + \ldots$ in 1864.

Before continuing, let's demonstrate that this total current approach would not work in "Dynamical Theory" with Maxwell's reversed Ohm's law. Thus, instead of Eq. (Treatise Art. 328 (1)) we will substitute

$$P = -\rho p \quad \text{DT P.3 (F)}$$

into Eq. (Treatise Art. 328 (3)) to form a new version of Eq. (Treatise Art. 328 (8)) (in keeping with the variable names in 1864, P replaces X_1 and P' replaces X')

$$u_{1864} = -\frac{1}{\rho} P + \frac{1}{k} \frac{dP}{dt} \tag{3.70}$$

When $u = 0$

$$0 = -\frac{1}{\rho} P + \frac{1}{k} \frac{dP}{dt} \tag{3.71}$$

$$\frac{1}{P} \frac{dP}{dt} = \frac{k}{\rho} \tag{3.72}$$

$$P = P' e^{\frac{k}{\rho} t} \tag{3.73}$$

We note that the total current approach pioneered in the *Treatise* does not yield a negative exponent in combination with the version of Ohm's law used in Maxwell's "Dynamical Theory." This approach could simply not properly model electric absorption (most clearly it absolutely fails to describe the dissipation of charge) in conjunction with Ohm's law as Maxwell wrote it in 1864, i.e., Eq. (F). Simply put Maxwell was not thinking about the dielectric in terms of two opposing currents as he developed his "Dynamical Theory."

Maxwell nonchalance about setting the total current to zero upon disconnection[160] hides a substantial conceptual development that occurs between these two theories, the consequence of which would be highlighted by Maxwell's successors. Whereas in 1864 he had assumed that the only current in the dielectric was a displacement current, in 1873 he committed himself to 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 indicate Maxwell's change in understanding. In 1864, Maxwell notes 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.[161]

This idea of "combination" is reflected in Maxwell's derivation; he inserts the displacement current df/dt into Eq. (F) as the replacement for the standard conduction current. Maxwell's brief discussion of dielectrics in 1868's inelegantly titled "On a Method of Making a Direct Comparison of Electrostatic with Electromagnetic Force; with a Note on the Electromagnetic Theory of Light" suggests a similar conception. The dielectric supports *only* the increase or decrease of electric displacement which is equivalent in effect to an electric current.[162] However, in 1873, Maxwell, concerned with the same situation, explicitly 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* [emphasis is mine].[163]

Returning to his investigation of capacitor phenomena and developing an entirely new approach based around the total current u has fundamentally altered the way Maxwell conceptualized dielectrics and more critically charge and its dissipation. Additionally, this explanation of electric absorption within a capacitor provides a physical and mathematical justification for the asymmetry of magnetic field effects and capacitors. There is no magnetic field produced when the charge dissipates within a capacitor as t goes to infinity, because there is no current to produce it. The yielding of displacement within the dielectric is accompanied by an equal and opposite conduction current in the same dielectric. In Maxwell's hands, the capacitor remade the concept of charge and placed a physical asymmetry at the heart of electromagnetic theory.

[160]Maxwell matter of factly states $u = 0$ without bothering to elaborate. Maxwell (1873b, Vol. 1, p. 379).
[161]Maxwell (1890a, p. 573).
[162]Maxwell (1890d, p. 139).
[163]Maxwell (1873b, Vol. 1, p. 374).

Finally, what of Maxwell's practical result for secondary discharge through a wire of nonzero resistance? This does reappear in slightly altered form in the *Treatise*, although it is no longer a "secondary" discharge as Maxwell imagines the discharge as occurring when the capacitor is fully charged. Again, Maxwell's starting point is somewhat altered

$$E = a_1 r_1 p_1 + a_2 r_2 p_2 + \cdots + R_o u = 0 \qquad \text{Treatise Art. 330 (26)}$$

where R_o is the resistance of the wire. He recasts the above equation by substituting conduction currents via the equation of total current Eq. (Treatise Art. 328 (3)) and his proof that the total current is the same in each layer and the connecting wire and battery,[164] i.e.,

$$u_1 = u_2 = \cdots = u \qquad \text{Treatise Art. 328 (7)}$$

This substitution yields

$$-R_o u = a_1 r_1 (u - \frac{df_1}{dt}) + a_2 r_2 (u - \frac{df_2}{dt}) + \ldots u(R_o + R) \quad = a_1 r_1 \frac{df_1}{dt} + a_2 r_2 \frac{df_2}{dt} + \ldots \tag{3.74}$$

thanks to the identity $a_1 r_1 + a_2 r_2 + \cdots = R$. Maxwell then integrates with respect to time to find Q

$$Q(R_o + R) = a_1 r_1 (f_1' - f_1) + a_2 r_2 (f_2' - f_2) + \ldots \qquad \text{Treatise Art. 330 (29)}$$

where f_1' is the final value of displacement and thus $= 0$ as we are investigating a total discharge through the wire. Therefore, after substituting in the *Treatise* values for f_i, Maxwell gets

$$Q(R_o + R) = \frac{E_o}{4\pi R} \left(\frac{a_1 {r_1}^2}{k_1} + \frac{a_2 {r_2}^2}{k_2} + \ldots \right) - E_o C R \qquad \text{Treatise Art. 330 (30)}$$

which we can compare to Eq. (DT P.5 (61)). As promised Maxwell corrects his algebraic mistake, albeit he does make a sign error (apparently forgetting that he was left with $-f_1,\ -f_2,\ \ldots$).[165] Ultimately, Maxwell has again arrived at a fairly similar result (to a slightly altered problem) and has again changed his approach to incorporate the concept of the total current.

Maxwell concludes this final discussion of stratified dielectrics noting that although this separation of materials is obviously idealized, electric absorption would still occur in "cases in which the materials are arranged otherwise. . . though the calculations

[164] See the beginning of Maxwell (1873b, Vol 1. Article 328) for Maxwell's brief proof.

[165] It would take until the third edition of the *Treatise* for this sign error to finally be corrected. Maxwell (1892, Vol. 1, p. 457).

would be more complicated,...[and] even though these individual parts should be microscopically small."[166] This echoes his remark from "Dynamical Theory," with a touch of added humility regarding the complication of actually accounting for less ideal scenarios.

Chapter X ends with a hydrodynamic model, a so-called "Mechanical Illustration of the Properties of the Dielectric," which it bears mentioning is more than capable of exhibiting electric absorption.[167] Sandwiched between the model and his account of a stratified capacitor, Maxwell lays out what is essentially regurgitated elements of Thomson's mathematical telegraph theory, what Varley had called "inductive absorption."[168] Here Maxwell does mention how this phenomenon "actually occurs in telegraph cables" and even runs through a practical case with a cylindrical wire.[169] Although, Maxwell's references to Jenkin and telegraphy are absent from his treatment of electric absorption within the *Treatise*, the ancestral connection to his analysis in "Dynamical Theory" and thus to Jenkin's Joint Committee testimony remains unbroken.

As a final note, Maxwell's discussion of the relationship between the inductive capacity of a dielectric and that material's index of refraction resides within "Chapter XX Electromagnetic Theory of Light," once again removed from his discussion of capacitors as it had been in "Dynamical Theory." Here Maxwell finally offers a tentative confirmation of his prediction. Passable data available on the dielectric capacity of solid paraffin compared to the index of refraction of melted paraffin (at three different frequencies) yielded a fairly close agreement, respectively 1.405 to 1.422. Nevertheless,

> [t]he difference between these numbers is greater than can be accounted for by errors of observation, and shews that our theories of the structure of bodies must be much improved before we can deduce their optical from their electrical properties.[170]

[166] Maxwell (1873b, Vol. 1, p. 381).

[167] Maxwell (1873b, Vol. 1, pp. 385–386).

[168] Maxwell does not credit Thomson; however, around the time of Maxwell's composition of the *Treatise*, he wrote a condensed abstract of Thomson's 1855 paper "On the theory of the Electric Telegraph" (and clearly labeled it as such) that resembles elements of the section that appears in the *Treatise*. Maxwell (1873a).

[169] At the beginning of this section, Maxwell analyzes a system of capacitors and resistors that can replicate the functioning of a submarine telegraph cable: "By an apparatus arranged in this way, Mr. Varley succeeded in imitating the electrical action of a cable 12,000 miles long." These sorts of artificial lines were first dreamed up by Thomson and practically proposed by Varley. Starting in 1879, artificial lines would make possible the delicate balancing act necessary for successful simultaneous signal reception and transmission, i.e., duplex telegraphy. Maxwell (1873b, Vol. 1, pp. 381–385); Coates and Finn (1979, [. 29).

[170] Maxwell (1873b, Vol. 2, pp. 388–389).

Maxwell continued, noting that the numbers were close enough that, if similar levels of agreement could be found across a variety of dielectric materials then "we should be warranted in concluding that the square root of K [dielectric inductive capacity], though it may not be the complete expression for the index of refraction, is at least the most important term in it."[171] Unfortunately, by the time J.J. Thomson was editing the 1891 third edition of the *Treatise*, multiple experiments on glass had done nothing but further confuse the situation.[172] Joseph Larmor reported that Ludwig Boltzmann had obtained a sufficient confirmation of Maxwell's electro-optical relation while working on gases in Helmholtz's laboratory in 1872. Finishing so close to the publication of the first edition of Maxwell's *Treatise*, these results did not make it in.[173] Boltzmann did eventually publish an account of his experiments on the relationship between D and the index of refraction in 1874 under the title "Über die Verschiedenheit der Dielektricitätsconstante des krystallisirten Schwefels nach Verschiedenen Richtungen."[174] The agreement between values Boltzmann finds appears slightly worse than that listed for paraffin in the *Treatise*, albeit across a wider range of materials (primarily sulfur crystals). Whether it was due to this slightly worse agreement or simply because Niven and J.J. Thomson were unaware of the paper, Boltzmann's results do not appear in either of the later two editions of the *Treatise* For his part, Boltzmann seemed confident that he had supplied all the evidence necessary to confirm 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.[175]

Regardless of its questionable success, there was at least one other long-running experimental program attempting to verify Maxwell's electromagnetic theory of light, both in Britain and on the continent. Before Hertz's experiments, the electromagnetic theory of light was not seen to rest exclusively on ever more exact measures of the ratio of electrostatic and electromagnetic forces and their agreement with measures of the speed of light.[176]

The evolving theory of electric absorption obviously owed much to concepts and relations borrowed from Maxwell's broader electromagnetic theory, similarly the broader

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[171] Maxwell (1873b, Vol. 2, p. 389).

[172] Maxwell (1892, Vol. 2, p. 438). The first of the two notes describing unsuccessful experiments on glass was actually added by W.D. Niven in the 2nd edition. Maxwell (1881, Vol. 2, p. 399).

[173] Larmor (1936, pp. 729); Siegel (1991, pp. 141–142).

[174] Boltzmann (1874).

[175] Original German: "Durch Bestätigung dieser Folgerung an Schwefelkrystallen... wurde die Richtigkeit der *Maxwell*'schen Theorie schon lange vor den klassischen Versuchen *Hertz*' wahrscheinlich gemacht." Maxwell (1898, p. 140); discussed in Maxwell (1990, p. 687 n17).

[176] This runs counter to the claim that *all* scientific confidence rested on measures of the ratio of units. See Schaffer (1995, p. 161).

theory benefited from the explanatory power and much needed, albeit incomplete, sources of error correction provided by the account of electric absorption. If we are to reconnect to where this discussion began, we might also ask what did Maxwell's theory of electric absorption owe to the work of Fleeming Jenkin and Michael Faraday. Certainly for the general description of the phenomenon and for detailed quantitative accounts of it, Maxwell was greatly indebted to Faraday's *Experimental Researches* and Jenkin's Joint Committee testimony and submissions. The empirical data with which Maxwell's theory of electric absorption was built had been collected primarily by Jenkin and to a lesser extent Faraday. Maxwell's understanding of how electric absorption could sully accurate electrical measurements was hard won through his time working with Jenkin on the Standards Committee. Both Faraday and Jenkin identified electric absorption as intimately involved with dielectric polarization, as did Maxwell consistently, even as the mathematical particulars of his account changed. As we saw in Section 3.3, Maxwell was already in the habit of using capacitors as idealized models for complex electromagnetic phenomena. Most critically, however, it appears that the causal link that drew Maxwell to analyze capacitors with inhomogeneous dielectrics (idealized as perfectly stratified) in relation to electric absorption was inspired by the Jenkin's observation that cables insulated with pure and impure gutta-percha experienced different "extra resistance" effects. The stratified capacitor was born from a combination of Maxwell's earlier work with idealized capacitors and Jenkin's experimental work on electric absorption in different purities of layered gutta-percha cable insulation.

While he was always quick to credit Faraday, Maxwell was also not *entirely* oblivious to the role played by telegraphy in shaping electrical science. In the *Treatise*, he described something like a relation of mutual shaping between science and technology, even appreciating the latter's role in bridging the gap between market forces and electrical science.[177] Nevertheless, he did wildly undersell the extent to which submarine telegraphy materially influenced electromagnetic theory:

> The important applications of electromagnetism to telegraphy have also reacted on pure science by giving a commercial value to accurate electrical measurements, and by affording to electricians the use of apparatus on a scale which greatly transcends that of any ordinary laboratory. The consequences of this demand for electrical knowledge, and of these experimental opportunities for acquiring it, have been already very great, both in stimulating the energies of advanced electricians, and in diffusing among practical men a degree of accurate knowledge which is likely to conduce

[177] In a review of Jenkin's *Electricity and Magnetism* (which also appeared in 1873), Maxwell similarly notes that "electrical knowledge has acquired a commercial value, and must be supplied to the telegraphic world in whatever form it can be obtained." Maxwell (1995, p. 843).

> to the general scientific progress of the whole engineering profession.[178]

Two years earlier, in his presidential address to the British Association for the Advancement of Science, William Thomson came much closer to appropriately crediting submarine telegraphy, especially its early failures, for its role in shaping British electromagnetic theory.

> This leads me to remark how much science, even in its most lofty speculations, gains in return for benefits conferred by its application to promote the social and material welfare of man. 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 world-wide 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 economic 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. Long may the British Association continue a bond of union, and a medium for the interchange of good offices between science and the world![179]

The discussion which led Thomson to remark on the significant influence of technology on even those "loftiest regions" of science was a consideration of Maxwell's electromagnetic theory of light and its reliance on measurements made by the British Association's Committee on Electrical Standards.[180] Failed submarine cables helped to rescue Faraday's work from obscurity and later contributed similar (but more di-

[178] Maxwell (1873b, Vol. 1, p. viii).

[179] Thomson (Baron Kelvin, pp. 161–162); discussed in Hunt (2005, p. 64–65); Hunt (2010, p. 109).

[180] It may perhaps be appropriate to read some disdain in Thomson's use of "speculations" here, when we consider that he frequently chastised Maxwellians for (in his view) letting their theoretical pursuits carry them away from the lessons of electrical practice. Given the above discussion, how critical submarine telegraphy was to Maxwell's electromagnetic theory, it is ironic that in the words of Norton Wise, "Thomson employed the practical reality of the telegraph as at once a moral and an epistemological weapon against what he regarded as the metaphysical ideality of Maxwellian theory." Wise (1988, p. 92).

rect) support to Maxwell who had made "the first advance along a road of which Faraday was the pioneer."[181]

Through Jenkin and the Joint Committee, submarine telegraphy and its failures in conjunction with the capacitor formed the foundation of Maxwell's theory of electric absorption. As we have seen, in Maxwell's theory electric absorption was not some isolated cul-de-sac, its evidentiary significance as a means of bolstering novel electromagnetic concepts and analogies and as a tool for data correction meant that the effects of electric absorption were felt from Maxwell's fundamental understanding of electrical actions within the dielectric to his electromagnetic theory of light to even his basic conception of the ether as elastic. Of course, the most dramatic example of this influence was in "Dynamical Theory" where modeling electric absorption found its way into Maxwell's general field equations and modified the standard expression of Ohm's law. The most significant would prove to be the conception of dueling conduction and displacement currents within the dielectric. So too then was the influence of the submarine telegraph industry felt in each of these same instances. The repeated failures and lost money, the various committees set up to rescue the industry, the driving forces of British imperialism and private capital are all embedded within Maxwell's electromagnetic theory.

3.5 Maxwellians and the Leaky Condenser

Following Maxwell's untimely death from abdominal cancer in 1879, just as he was beginning revisions for the second edition of his *Treatise on Electricity and Magnetism*, his electromagnetic theory was clarified and extended by a loose cohort of mostly British physicists, the so-called "Maxwellians."[182] Among these Maxwellians, charge dissipation, a constituent phenomenon of electric absorption, ultimately came to occupy a central position within their theoretical work. The phenomenon of charge dissipation that Maxwell had illustrated with his stratified capacitor became commonly referred to by the device it was most associated with, the phenomena was embodied by the "leaky condenser." What proved important about Maxwell's leaky condenser was the final stage of conceptual evolution reached in the *Treatise* discussed above, the opposing equal currents exemplified by the equation $u = 0$ as it appeared in Article 329.[183] As Jed Buchwald argues, "most of the major conceptual changes in Maxwellian theory that took place between 1885 and 1895 were in some way con-

[181] Thomson (Baron Kelvin, p. 160).

[182] Maxwellians here is merely intended to refer to the broader disorganized community of mostly British physicists who took up Maxwell's electromagnetic theory and attempted to apply and/or expand upon it.

[183] Maxwell (1873b, Vol. 1, p. 379).

nected with this type of situation [the leaky condenser]."[184] Borrowing heavily from Buchwald's account in *From Maxwell to Microphysics*,[185] let us briefly explore the influence of the leaky condenser on electromagnetic theory.

Conduction for Maxwell and the Maxwellians was a convoluted process and the shifting meaning of "displacement" in the *Treatise* did not help matters. Stretching back to "Physical Lines," charge was described as an epiphenomenon resulting from a discontinuity of displacement. Polarization in a dielectric cancels out within the dielectric but upon reaching the plate of a capacitor for example, the conductivity of the capacitor does not support polarization and thus an unequalized charge is left on the shared surface. "According to this theory, all electrification is the residual effect of the polarization of the dielectric."[186] Displacement and electric polarization are effectively one and the same, except that displacement is not definitionally limited to dielectrics. Conduction was taken to be a process by which the displacement was constantly decaying and being converted into heat.

> In the phenomenon called the electric current the constant passage of electricity through the medium tends to restore the state of polarization as fast as the conductivity of the medium allows it to decay. Thus the external agency which maintains the current is always doing work in restoring the polarization of the medium, which is continually becoming relaxed, and the potential energy of this polarization is continually becoming transformed into heat, so that the final result of the energy expended in maintaining the current is to raise the temperature of the conductor.[187]

If we return briefly to the stratified capacitor we discussed above, we can recall that after the charged capacitor is insulated, charge dissipation in the system occurs thanks to equal and opposing displacement and conduction currents within the dielectric. The leak in the leaky condenser is a result of the breakdown of polarization by the conduction current, gradually over long timescales due to the generally low conductivity of the dielectric. As a consequence of its high conductivity, a conductor performs this exchange insensibly quickly. The applied force powering the current then reinstates the polarization; "for Maxwell, conductors are equivalent to leaky condensers with extremely short relaxation periods."[188] Collecting all of these discussions of displacement and conduction from disparate parts of the *Treatise* and displaying them together does give off the image of a more cohesive physical conception than is probably fair to ascribe to the jumbled ideas contained therein. At the very least it undersells the impact of John Henry Poynting's clarifications which I will now discuss.

[184] Buchwald (1985, p. 32).
[185] Buchwald (1985, pp. 45–48).
[186] Maxwell (1873b, Vol. 1, p. 133).
[187] Maxwell (1873b, Vol. 1, p. 134); discussed in Buchwald (1985, pp. 28–29).
[188] Buchwald (1985, p. 38).

Poynting's theory of energy flow in the electromagnetic field (1884) not only illustrated this fundamental Maxwellian contrast between the conduction current and displacement current, it put it into sharp relief. "A conduction current then may be said to consist of the inward flow of energy with its accompanying magnetic and electromotive forces, and the transformation of the energy into heat within the conductor."[189] Displacement currents did not transform electromagnetic energy into heat, only conduction currents were inherently irreversible.[190] Building on his theory of energy flow, the following year Poynting published a theory of the motion of tubes of displacement.[191] Poynting's tubes moved laterally (sideways), along the path of energy flow. A capacitor discharged by a wire loop would find that the tubes of electric induction that once stretched from plate to plate, would in the process of discharge move laterally along the plates and then into the wire, shrinking in length as they decayed until both ends of the tube came together at a point and disappeared. His energy flow now followed a "real" motion of elements of the electromagnetic field. Any questions regarding the confusing involvement of displacement in conduction are clarified under Poynting's theory. The lateral motion and decay of displacement tubes into a wire is the source of a conduction current's associated magnetic field, the decay being necessary to avoid "a static balance."[192] Conduction currents involve the motion *and* decay of displacement tubes, displacement currents do not involve any such decay. As Poynting wrote to Oliver Lodge in 1886 answering Lodge's question about a paper of John Hopkinson's,

> I think Hopkinson goes in for the yielding of displacement towards the + plate <u>accompanied by an equal conduction current in the opp dir</u> like Maxwell where as I only think of the yielding of displacement and omit the conduction current as unnecessary and doing nothing.[193]

As a referee for Poynting's 1885 paper on the motion of displacement tubes, Hopkinson appreciated "the present paper is a natural sequel [to Poynting's energy flow paper of 1884] and is in my judgement not less important."[194]

Poynting's next contribution was not a new theory, but essentially a reimagining of the stratified capacitor section in Chapter X of the *Treatise*.[195] The math is essentially identical except that where p_i was once the "current due to conduction through each stratum," it was now "the amount of decay of induction per second in each

[189] Poynting (1884, p. 351).
[190] Buchwald (1985, p. 44).
[191] Poynting referred to them as tubes of induction.
[192] Buchwald (1985, p. 47).
[193] Poynting (1886).
[194] Hopkinson (1885).
[195] Poynting (1920a).

stratum."[196] Poynting began the paper with the fair complaint that in Maxwell's theory "[t]he idea of a yielding of displacement in the dielectric, accompanied by a conduction-current in the opposite direction, gives us no help in forming a mental picture of the process actually going on in the dielectric."[197] Finding Maxwell's reasoning for $u = 0$ physically unsatisfying, Poynting, with reference to his theory of laterally moving displacement tubes, could justify this relation by noting that "[n]o fresh tubes enter any layer, so... $u = 0$."[198]

Even in 1895, as the electron was emerging and traditional Maxwellian theory was breathing its last gasps, Poynting wrote in response to Joseph Larmor:

> About the decay of charge in a condenser. Perhaps I ought to have said that it does not produce any external magnetic effect. I suppose there will be fields of molecular dimensions as the tubes of force rearrange themselves and shift about among the atoms. But I think you do not mean this do you? I take it that you would ascribe to the discharge an external magnetic field round the condenser. If so I may take shelter behind Maxwell. In his chapter on the subject Vol 1 3rd Ed p456 he puts $u = 0$ while the condenser is not connected externally and his u is the total current p453 ie he makes a conduction current from + to – equal and opposite to and coinciding with the "displacement" current which is here a lessening of already existing displacement. But this is to my mind a mere mathematical fiction. The one phenomenon is the decay of electric induction. I dont see why we should want to give it any magnetic effect. In its youth when it was moving into the condenser it had a good magnetic time of it. That was the time of true current when the circuit had integral $4\pi C$ round every part, the condenser forming part of the circuit. But to give the decaying charge in the condenser any more field is to give it a quite unfair preference.[199]

For his part J.J. Thomson, building off of Poynting's theories, investigated the "microscopic rearrangements accompanying dissolution" of the moving tubes of displacement.[200] Thomson's theory illustrated how displacement tubes broke down and contracted to molecular dimensions with a conductor.[201] As in Poynting's theory, magnetic intensity is generated by the motion of the tubes, but not their subsequent

[196] Maxwell (1873b, Vol. 1, p. 376); Poynting (1920a, p. 232).

[197] Poynting (1920a, p. 224).

[198] Poynting (1920a, p. 234).

[199] Poynting (1895); discussed in Buchwald (1985, p. 32).

[200] Buchwald (1985, pp. 49–53).

[201] An account of the workings and historical context of Thomson's displacement tubes can be found in Navarro (2012, pp. 60–70) as well as in the first chapter of Thomson's own *Recent Researches in Electricity and Magnetism*, written as something like a third volume of Maxwell's *Treatise*. Thomson (1893, pp. 1–52). Poynting created a similar theory 1895. Poynting (1920b).

breakdown. Oddly, Thomson's gradual process of tube destruction necessitated the motion of progressively smaller and smaller tube fragments while insisting that no magnetic effect was generated. According to this theory, charge motion could not be responsible for the magnetic effect of the conduction current.[202] Ultimately, both Thomson and Poynting solidified the interpretation of Maxwell's conduction current as a process of displacement accumulation and decay and by constructing theories that relied upon it effectively "entrench[ed] that explanation."[203] Another Maxwellian, George Francis FitzGerald, escaped the excessive "literalism" of interpreting electric displacement as a real motion in the ether thanks to an idealized machine of his own, his wheel-and-band model. For FitzGerald, the nature of electric displacement should, barring new evidence, remain undecided, but it was "much more likely. . . [to be] changes in the structure of the elements of the ether, and not actual displacements of the elements."[204] Eventually, Thomson and Poynting's image of the conduction current would collapse under the weight of the Hall effect and Larmor's electron. By 1895, Larmor could confidently write "[t]he conduction current does not involve elastic displacement."[205]

When Oliver Heaviside wrote that "[i]t 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," he clearly laid out not only how central the leaky condenser was within Maxwell's theory, but also how central it remained within Maxwellian theory.[206] Nevertheless, the historical evidence does not bear out Heaviside's origin story. Maxwell's account of the leaky condenser changed dramatically between "Dynamical Theory" and the *Treatise*. In keeping with that shift, the conception of electrical processes in the dielectric formed from Maxwell's accounts of electric absorption also changed radically between Maxwell's two theories. Indeed, as far as the formation of Maxwell's theory of stratified capacitors is concerned it appears consideration of the functions of submarine telegraphs was at least as influential as a leaky condenser. The dual current theory presented in the *Treatise* was not a part of the foundation of Maxwell's theory, but rather its capstone. The concept emerged as an evolutionary development of the analysis presented in "Dynamical Theory" and is thus wedded to the earlier theory's roots in submarine telegraphy and the Joint Committee report. The influence of submarine telegraphy wound its way through not only Maxwell's theory, but also (through the leaky condenser model) helped to frame the concept of conduction among Maxwellians. As Buchwald has shown, a great deal of the Maxwellian's work centered around the concept of conduction and yet it was also conduction, tied as it

[202] Buchwald (1985, pp. 49–53).
[203] Buchwald (1985, p. 53).
[204] FitzGerald (1902, p. 173); discussed in Hunt (2005, pp. 84–87).
[205] Larmor (1895, p. 723); discussed in Buchwald (1985, p. 127).
[206] Heaviside (1894, p. 29).

was to electric absorption, the stratified capacitor, and submarine telegraphy, that through Larmor ended the heyday of Maxwellian physics.

3.6 Cables and Theories of Empire

Plans to lay a new Atlantic cable began to take shape almost immediately after the Joint Committee delivered their report. Cyrus Field's Atlantic Telegraph Company had improved designs for an Atlantic cable, but also had poor timing. The start of the American Civil War represented a major obstacle to obtaining funding from Washington D.C., but even before Field could petition the federal government, enough of the company's other sources of funding had dried up forcing them to temporarily abandon their plans. Finally, in 1864 the newly formed Telegraph Construction and Maintenance Company (formed through the merger of Glass, Elliot and Company and the Gutta Percha Company) bought up the majority of the Atlantic Telegraph Company's stock, which had until then been outstanding. The new cable that was produced to span the Atlantic was, as had been recommended in the Joint Committee's report, covered in far thicker insulation (although less pure), had a far wider diameter copper core, a more robust steel and hemp sheath, and of course was subjected to far more rigorous testing. The 2,700 miles of cable were produced in one single piece, a point which, together with the cable's increased weight raised the issue of what single ship could possibly be up to the task of laying it.[207] Luckily for the Atlantic Telegraph Company, there was another catastrophic failure of the 1850s waiting for just such an opportunity.

The behemoth steamship *Great Eastern* was the largest ship in the world from its launch in 1858 until it was unceremoniously scrapped in 1889.[208] After failing completely as a passenger liner, in 1864 it was sold at auction for £25,000 to associates of the Atlantic Telegraph Company, a miniscule fraction of its £1 million initial cost.[209] The ship was retrofitted with three tanks to safely carry 7000 tons of cables and water (to keep the cables from drying out) after which the finished cable was slowly loaded into its hold. William Thomson and C. F. Varley came aboard to ensure the cable remained electrically sound as it was laid. On July 23, 1865 the *Great Eastern*, having landed its cable at Foilhummerum Bay, Ireland turned to make the westward journey towards Newfoundland. While cable repairs were occasionally necessary, laying proceeded smoothly until in the process of another clumsy repair two thirds of the way into the expedition, the cable broke and sunk in over two and half miles of water. Multiple attempts were made to grapple the cable and haul it to the surface and while the cable was improbably located, the hoisting machinery

[207] Dibner (1964, pp. 87–90).

[208] The ship weighed 25,000 tons and was 692 feet long. Coates and Finn (1979, p. 7).

[209] Dibner (1964, p. 93); Coates and Finn (1979, p. 23).

Figure 3.7: SS *Great Eastern* in Trinity Bay, Newfoundland 1866

and ropes proved too weak to recover the cable. The *Great Eastern* returned to port "shattered in hopes as well as in ropes."[210] Yet again an attempt to lay a submarine telegraph line across the Atlantic had failed.

This failure proved to be only a small hindrance. The very next year, 1866, the *Great Eastern* set out again with improved recovery equipment and an entirely new full length of cable with the intent of not only laying a trans-Atlantic submarine cable, but also of raising the failed 1865 cable and completing it as well. To offset some financial difficulties, the Atlantic Telegraph Company was absorbed within the newly created Anglo-American Telegraph Company. With most of the crew returning, on Friday, July 13 1866 the *Great Eastern* again headed westward from Ireland. On July 28 the cable was successfully landed in Trinity Bay, Newfoundland. The *Great Eastern* then returned to the approximate location of the 1865 cable break and after numerous attempts succeeded in raising the failed line and splicing it into the remainder of cable that it still had in its hold. By September 7, the second cable was landed in Trinity Bay and there were then two working Atlantic cables.[211] Celebration was mostly contained to Britain, unlike the attempts of the late 1850s the 1866 expedition was almost exclusively a British undertaking.[212]

In the aftermath of the double success of the Atlantic cable enterprise, a new era of submarine telegraphy dawned. Before 1870, the Telegraphic Construction Company laid the Malta-Alexandria cable, another Atlantic line connecting France and Canada, a new Red Sea cable between Egypt and India eventually acquiring an extension to

[210] Bright (2014, p. 90).
[211] Dibner (1964, pp. 84–149); Bright (2014, pp. 78–105).
[212] Coates and Finn (1979, p. 25).

Australia, and even more across the Mediterranean.[213] During the 1870s, British telegraph companies laid cables to Singapore, Hong Kong, China, and New Zealand. By the close of the decade, extensive submarine cable connections and overland routes connected every continent with the sole exception of Antarctica. Just before 1900, there were sixteen cables spanning the Atlantic, twelve of which were in working order.[214] Some cables were commercially viable, others were simply projections of colonial power.[215]

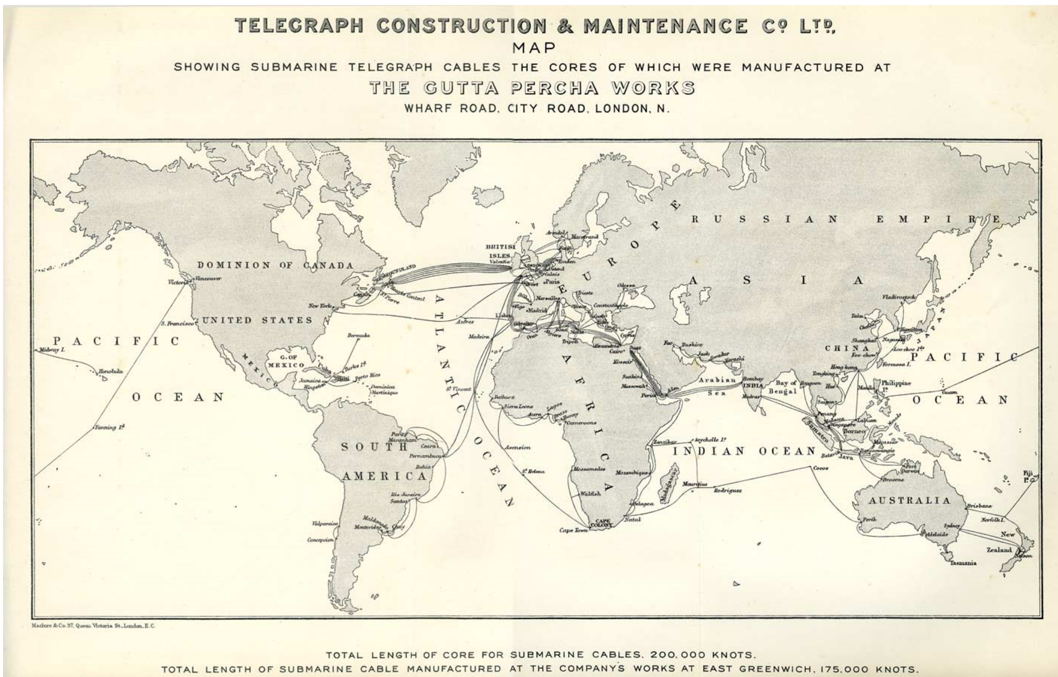


Figure 3.8: 1903 Telegraph Construction and Maintenance Company Map of Cables Manufactured at Gutta Percha Works

With few exceptions this new connected world was shaped by and for British interests. As submarine telegraphy gradually transformed into a more reliable investment in the wake of the Joint Committee report, "[o]nly Britain had a capital market large and resilient enough to invest hundreds of thousands of pounds sterling in risky high-technology enterprises, lose them, and try again."[216] The technical knowledge of how to build and lay submarine telegraphs remained greedily guarded, the world may have been connected, but it was British companies that connected it (specifically the

[213] Bright (2014, pp. 108–109).
[214] Headrick 35
[215] Headrick (1988, p. 98).
[216] Headrick (1991, p. 24).

Eastern group and the Telegraph Construction and Maintenance Company).[217] With the accompanying transition to steamships, the submarine telegraph remade global shipping and commodities markets; ships could be rerouted mid-route to optimize the sale price of their cargo. Instantly available price information from far away markets mollified the risk of speculation enough to fuel the expansion of "futures" markets to a wider range of commodities. Telegraphy's supercharging of the futures market generally seems to have contributed to a "braking action on price fluctuations," but may also have set the stage for the Panic of 1873.[218] News traveled almost instantly across oceans and news agencies paid handsomely for access. Wars could be covered in almost real time, much to the chagrin of commanders worried about press reports on troop movements.[219] Traveling across British lines, British wire services controlled much of the international flow of news, delivering a British perspective to its colonies and its competitors.[220]

In anticipation of the coming global submarine telegraph network, expectations for peace between nations through continuous communication ran high. In actuality, diplomatic cables were rare and opinions differed on whether instant communication quelled international conflicts or had the potential to inflame them.[221] Few seemed to remember that during the Crimean War, Britain had laid one of the earliest practical submarine telegraph cables across the Black Sea with the singular purpose of delivering battle orders to the front lines.[222] These expectations for peace, no matter how unrealistic, were nevertheless not meant to be universal. This much the *London Daily News* made abundantly clear upon the brief success of the 1858 Atlantic cable,

> We have messages of peace and love for our brethren of the extreme West, but our hearts pant with burning words for the encouragement of our heroes in the East. If it be our mission to civilize the dark abodes of

[217]Headrick (1991, p. 46).

[218]Coates and Finn (1979, pp. 70–72); Nelson (2008).

[219]Coates and Finn (1979, 77–82).

[220]Hunt (1997, p. 320).

[221]Coates and Finn (1979, p. 83). The *Trent* affair (the seizure by a Union vessel of two Confederate officials from the British steamship *Trent*) provides a clear source of disagreement over the merits of the telegraph as a diplomatic tool. While Cyrus Field was confident that a trans-Atlantic cable would have quickly smoothed everything over, Lord Lyons, the British minister to the United States during the *Trent* affair, insisted that the cooling down period made possible by the lack of an Atlantic cable helped avoid a war. Coates and Finn (1979, p. 20, 90).

[222]Coates and Finn (1979, p. 80–81). This sort of historically oblivious techno-optimism remains a common fixture in discussions of technology even in contemporary times. We may recall the general excitement and hopeful praise that accompanied the early rise of Facebook, which now looks naive in light of its flagrant abuses of user privacy and exploitation as a tool of deceptive electioneering. However, given the social network's origin as Facemash, stealing images of Harvard's undergraduate women from University servers so that site visitors could rank their attractiveness, we needn't have been surprised.

> 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.[223]

This drive to colonize was remarkable in Britain only due to its fervor, governments of the late-19th century, the major European powers, the United States, and Japan all engaged in a rapid colonial expansion referred to as the New Imperialism. The British Empire in particular swelled as the near instant communication of the telegraph optimized the business of subjugation and economic exploitation. Essentially all telegraph lines introduced into non-Western societies served as, "to one degree or another, part of the imperialist movement."[224] Land lines were also critical tools of empire (particularly in India), but for our purposes here we will be limited to the colonial applications of submarine cables. During the period of explosive growth of the British telegraph network after the Joint Committee report, Britain's imperial expansion into Africa inspired new lines across the continent. White South Africans pestered London for a telegraphic connection to the center of the Empire. The British government remained uninterested until the 1879 Zulu victory at the battle of Isandhlwana during the British invasion of Zululand. With a second invasion of Zululand and the coming annexation of the territory, the British government agreed to subsidize a cable from Aden to Durban.[225] In West Africa, despite a recent war with the Kingdom of Ashanti during which communications were extremely slow, Britain was only inspired to invest in telegraphic connections to their colonial possessions after the French committed to telegraphic links to their African colonies. By the end of 1886, Cape Verdes was linked to the British colonies of the Gambia, Sierra Leone, the Gold Coast, and Nigeria. Africa was a continent of submarine cables, lacking much of an overland telegraph network in its interior. This was due both to the difficulty of constructing lines through harsh terrain but also to the poverty of the peoples in these colonies, "telegraph companies could not expect to get enough local business to defray their expenses."[226] African submarine cables were uniquely imperialistic tools in the vast British overseas telegraph network, "a part of the colonial but not of the indigenous economy."[227] In China officials rightly saw attempts to lay telegraphic connections as "less a means of communicating than a wedge to pry China open to foreign influences, a threat to their sovereignty, and a source of potential conflict with the Europeans."[228] Consistent Chinese resistance was met with blatant violations of

[223] London Daily News (1858, p. 4); discussed in Coates and Finn (1979, p. 133).
[224] Headrick (1991, pp. 50–51).
[225] Headrick (1991, pp. 62–63).
[226] Headrick (1991, p. 66).
[227] Headrick (1991, pp. 64–66).
[228] Headrick (1991, p. 57).

sovereignty. Despite explicit orders not to land cables (as a compromise, cables would terminate nearby, but offshore), Western telegraph companies connected Shanghai to the global telegraph network in the dead of night.

Once the cables were laid, the "nerves of the British Empire" afforded it unparallel military flexibility, rapid deployment, and direct command and control.[229] Already possessing the world's most powerful navy, Britain's submarine cables, acting as giant capacitors with the surrounding seawater rendered a conductive plate, transformed the oceans into agents of the British Empire. Whereas troops that were already in transit had been previously deemed unavailable, the telegraph network allowed for more efficient redeployment of soldiers and ships. Soldiers needn't be spread so thinly across the Empire as troops could be ordered to move and quash a rebellion at a moment's notice. In addition to increased mobility, military planning in London could be quickly passed along to the front lines.[230] Nevertheless, telegraphic contact was no guarantee of colonial stability. Relief efforts in 1884 during the Mahdi uprising in the Sudan were obsessively micromanaged by submarine cable from the War Office and still resulted in disaster for British and Egyptian troops. The fluid nature of warfare and colonial relations during the period of rapid expansion limited the effectiveness of central administration to direct imperial efforts via telegraph. The telegraph was most useful after conquest and subjugation, allowing the bureaucracy of Britain to replicate across the world, seamlessly integrating new colonies into its imperial economy.[231] For the case of India, Karl Marx summarized this process:

> The political unity of India, more consolidated, and extending farther than it ever did under the Great Moguls, was the first condition of its regeneration. That unity, imposed by the British sword, will now be strengthened and perpetuated by the electric telegraph.[232]

British control over markets expanded in step with its colonial properties and its abilities to defend them. The global cable network provided a means by which to centralize control over its sprawling empire. The key to the construction of Britain's and indeed any submarine cable network was access to a sufficient supply of gutta-percha to act as cable insulation.

This natural latex, whose name originates from the Malay word *getah* for "gum," comes from the sap of a set of rainforest trees indigenous to Southeast Asia. Across British Malaya, Sumatra, Borneo, Siam, Cambodia, the southern Philippines, and the southernmost region of Vietnam these trees grew together by the hundreds. Mature

[229] Headrick (1991, p. 36); Morus (2000).

[230] Coates and Finn (1979, pp. 102–106).

[231] For the purposes of conquest and subjugation, Britain had recently deployed yet another revolutionary technology, the Martini-Henry breech-loading lever-action rifle.

[232] Marx and Engels (1979, p. 218); discussed in Tully (2009, p. 559).

trees reached heights of sixty to eighty feet. As Tully demonstrates, the worldwide submarine telegraph industry, with its massive mechanized cable production facilities, was utterly dependent upon the skill and speed of local laborers who would venture through dangerous jungle to fell these trees en masse. Once downed the extraction process could begin. The valuable sap ran in veins through the heartwood. Accessing and draining it took time as the extremely viscous gutta-percha flowed slowly and rapidly hardened. To supply the needs of the telegraph industry this effort was replicated millions of times over across Southeast Asia. The harvest of an average mature tree yielded about eleven ounces of gutta-percha.[233] The insulation of the 1865 Atlantic cable weighed 400 lbs. per mile.[234] Across the delivered length of cable, approximately 2700 miles, that adds up to well over 500 tons of gutta-percha insulation.[235] Even by a generous estimate admitting to the adulteration of the cable's insulation with tar and other additives, likely over 1 million trees were harvested to construct this cable. Unsurprisingly then, as global submarine telegraphs rapidly expanded their reach in the last third of the 19th century exploitation of gutta-percha facilitated an environmental disaster.[236]

What had been a sustainable local practice before the onslaught of Western demand transformed in a few short decades to wreak havoc on the rainforest. The most coveted species of gutta-percha producing trees became extinct in certain regions starting early in the history of submarine telegraphy. The *Isonandra gutta* was extinct in Singapore by 1857 and by the mid-1870s from Malacca and Selangor as well. Singaporean export of gutta-percha alone averaged millions of pounds. For a tree that took between twenty and thirty years to reach maturity, the yearly felling of tens of millions would never be sustainable.[238] Partially insulated from the gutta-percha trade by Chinese middlemen, Europeans were more than happy to condemn the environmental "vandalism" of their colonial subjects while simultaneously

[233] Tully (2009, pp. 565–571).

[234] Dibner (1964, p. 88). The insulation of the earlier failed Atlantic cables weighed only 261 lbs. per mile.

[235] Dibner (1964, p. 90).

[236] Tully performs a similar calculation for the total number of trees felled to construct the nearly 200,000 nautical miles of submarine cable in place at the beginning of the 20th century. After using the 1857 cable's dimensions to roughly estimate the total weight of submarine cable insulation at 27,000 tons of gutta-percha, Tully concludes that nearly 88 million trees must have been cut down (using the same 11 ounce per tree estimate as I do above). 88 million trees appears to be the result of an accidental unit switch, from standard tons (2000 pounds per ton) to imperial/long tons (2240 pounds per ton). Elsewhere Tully consistently uses standard tons. Using standard tons, the estimate comes to 79 million trees. If we estimate based on the weight of insulation per mile of the heavier 1865 Atlantic cable, the total number of trees cut down surpasses 100 million. Tully (2009, p. 575).

[237] Obach (1898, Fig. 11)

[238] Tully (2009, pp. 571–579).

Figure 3.9: Harvesting Gutta-Percha in Sumatra[237]

incentivizing and profiting from it.[239] The colonial extraction of gutta-percha from Southeast Asia became a "self-reinforcing loop: Britain's imperial and commercial power gave it favoured access to Malayan gutta-percha supplies, and so facilitated the construction of a cable network that, in turn, greatly strengthened the Empire and British commerce—including British control of the gutta-percha trade."[240] With limited thought devoted to the sustainability of the gutta-percha harvest, this feedback loop devastated the ecology of British colonies in Southeast Asia.

Of course while electrical engineering and physics provided the demand that devastated forests, they were not alone in becoming wrapped up in the colonialism surrounding cable insulation. Botanists fanned out in search of new sources of gutta-percha or for new natural latexes. Even Joseph Dalton Hooker, the famous botanist and friend of Charles Darwin, wrote to William Siemens in 1874, curious about the quality of an enclosed sample of Trinidadian Balata gum. As Hooker's letter makes

[239]Headrick (1987, p. 13).
[240]Hunt (1998, p. 86).
[241]Photograph by G.R. Lambert & Co., in the collection of the *Tropenmuseum* (TM-60001789)

Figure 3.10: A Lone Remaining Gutta-Percha Tree, Surrounded by a Field of Tobacco in Langkat (c. 1885–1895)[241]

clear, he was acutely aware of the value in discovering a new untouched supply of natural latex. As he says, "if good it may prove a valuable article of import."[242]

Much of the success of submarine telegraphy is owed to the recommendations put forth in the Joint Committee report. The explosion of cable laying that followed its publication made possible submarine telegraphy's use as a tool of empire, remaking markets, pacifying colonies, and reshaping military command. The greater efficiencies it offered were frequently accompanied by the exclusion and brutal repression of Indigenous peoples. The British Empire's insatiable thirst for the stability and efficiency engendered by telegraphic communication wrought environmental devastation upon its Southeast Asian colonies. 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.

Through their ties to the Joint Committee report and the same experiments on cable insulation that made submarine telegraphy so successful, Maxwell and the

[242] Kennett (1953, p. 52).

Maxwellian's evolving dielectric theories share in this imperial legacy, a conjoined twin of Britain's expanding telegraph network. Fleeming Jenkin's testimony comprised, at least in part, the foundation of both the abstract physics of the dielectric taken up by Maxwell and his followers and the best practices utilized by telegraph companies to lay undersea cables across the world. The ecological disaster caused by the rush to build connections across oceans shares a particularly intimate connection to Maxwell's theory. Both are tied to concerns over the same substance, gutta-percha. It was Jenkin's experiments on varying grades of gutta-percha that led eventually to Maxwell's theory of electric absorption in a stratified capacitor in "Dynamical Theory," a theory of confounding electrical processes occurring within inhomogeneous dielectric substances like (most) gutta-percha. This theory had a wide-ranging influence on seemingly disparate abstract elements of his theory of electromagnetism as well as practical issues of electrical measurement. But Maxwell's theory embodies more than his own labor. The manual labor of Indigenous peoples in the forests of Southeast Asia provided the literal raw materials that inspired Maxwell's theorizing. Meanwhile, the knowledge communicated in the report's recommendations assured industry of the economic viability of submarine telegraphy and spiked demand for gutta-percha. Maxwellian theory is a close, but separate branch of the same technological lineage that secured Britain's global empire and reshaped the world to its advantage. Maxwell's theory was not a cause of or caused by these various consequences of the British telegraph network, but his theory and the political and environmental fallout were close kin. Maxwell was well aware of "this demand for electrical knowledge" driven by telegraphy and made full use of the "experimental opportunities" that it had afforded.[243] His physical theory was developed in part due to commercial and political valuations, and arrived with a share of the environmental costs.

3.7 Conclusion

Although the abstract nature of Maxwell's theoretical contributions to electromagnetic physics have seemed to preclude deep connections to technology, we now see that electrical technology, capacitors and submarine telegraphy in particular, played a formative role in the electromagnetic theories that Maxwell presented in "A Dynamical Theory of the Electromagnetic Field" and his *Treatise on Electricity and Magnetism.* In the hands of the Maxwellians, concepts resulting from this technology-to-science knowledge exchange were emphasized, carrying the influence of submarine telegraphy into the Maxwellians' even further abstracted domains of theoretical physics. This connection to submarine telegraphy has also helped us bridge the divide between Maxwell's and the Maxwellians' theoretical physics and the broader historical con-

[243]Maxwell (1873b, Vol. 1, p. viii).

text of this moment in the late-19th century. Economic, environmental, and imperial concerns are linked to these theories through the repeated failures and eventual wild successes of the submarine telegraph industry. Simultaneously, I have also elucidated Maxwell's treatment of the stratified capacitor, an often ignored aspect of his theory of electromagnetism, exploring its development across theories, and its profound connections to an array of other (perhaps more notable) elements of Maxwell's electromagnetic theory. This chapter is a history of technology's direct influence on theoretical physics contained within a broader history of technology; a nesting doll of historical studies illustrating the role of technology and ultimately society in shaping abstract physical theory. Let us conclude by working our way out from the central study of Maxwell's electromagnetic theory.

The capacitor, at least as an idealized technological object, directs Maxwell's physical theories from "On Physical Lines of Force" to the *Treatise*. In "Physical Lines," the displacement current is constructed by means of the implicit consideration of a charging capacitor. The explicit analysis of a capacitor (Leyden jar) births a new experimental program with the potential to generate empirical evidence for Maxwell's electromagnetic theory of light. The analyses of idealized stratified capacitors that appear within "Dynamical Theory" and the *Treatise* both are ostensibly presented as explanations of the phenomenon of electric absorption, which for Maxwell encompasses charge dissipation, residual charge, and secondary discharge. Maxwell's unphysical modification of Ohm's law in "Dynamical Theory" to preserve his theory of electric absorption illustrates that more is at stake besides a working account of an obscure electrical phenomenon. Of course in both cases, deriving equations for electric absorption illustrates the explanatory power of Maxwell's broader electromagnetic theory. However, the success of his model of electric absorption also bore directly on the efficacy of his concept of displacement, the analogies connecting electric absorption and elasticity as well as displacement and elasticity, and suggested data correction that might save his floundering experimental program to confirm the electromagnetic theory of light. The capacitor analysis in the *Treatise* utilizes an entirely different approach to achieve very nearly the same equations. In the *Treatise*, Maxwell is able to recover a standard formulation of Ohm's law, but fundamentally reshapes his understanding of electrical action within dielectrics. Instead of a single combined displacement/conduction current as was the case in "Dynamical Theory," his treatment in the *Treatise* highlights simultaneous and competing conduction and displacement currents. In the case of charge dissipation, these dual currents cancel one another out and produce no magnetic field. It would be this dual current during charge dissipation, the paradigmatic "leaky condenser," that the Maxwellians would emphasize and attempt to clarify. Ultimately, the dual current would be compacted back into one, which described both the movement and decay of displacement tubes. Physical explanations, particularly for conduction, were mined from the imagined motions and decay processes of these displacement tubes. As Maxwellian physics began to collapse owing to the arrival of electron theory, so too did this continuous tradition of deriving electrical phenomena within the dielectric by analyzing varying forms of capacitors.

Ultimately, while the capacitor functions as a convenient way to model electric absorption, the principal source for Maxwell's understanding of electric absorption is Jenkin's testimony before the Joint Committee on the Construction of Submarine Telegraphs. Of primary importance to Maxwell was Jenkin's observation of the differing effects of electric absorption in pure and impure gutta-percha samples. In addition to the Joint Committee report cited by Maxwell in "Dynamical Theory," Maxwell and Jenkin developed a friendship as they worked together on the Committee on Electrical Standards. As a co-authored report demonstrates, Maxwell and Jenkin's measurements were complicated by electric absorption and it is safe to assume that they discussed the phenomena (including the knowledge Jenkin had gained between his time on these committees). Maxwell's theoretical work to describe electric absorption is dependent on, even deduced from Jenkin's experimentation and the Joint Committee report, inextricably linking Maxwell's abstract physics to submarine telegraphy. Maxwell's analyses are built from a combination of idealized capacitors and submarine cable experiments. Specifically, the link to submarine telegraphy is to its costly early failures, the most spectacular of which were the two failed Atlantic cable attempts and the failed Red Sea cable, that prompted the British government to set up the Joint Committee. The historical context surrounding these telegraphic failures, the economic, political, and explicitly imperialistic concerns, is thus transitively responsible for the genesis of Maxwell's theories. The great success of the Joint Committee report in reforming the submarine telegraph industry also ties Maxwell's theory to the consequences of the rapidly expanding global submarine telegraph network. This is naturally in no way a causal connection, that is reserved for the prior examples of telegraphic failures. Rather, Maxwell's theory shares an origin (the Joint Committee report) with the imperialist successes of submarine cables at the end of the 19th century. The market shaping, military moving, colonial legacy of Britain's submarine cable network is the sibling of Maxwell and his followers' electromagnetic theories.

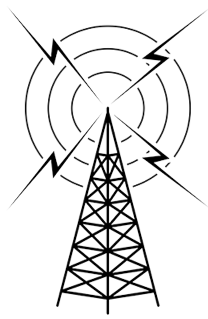
The history of physics, even its more abstract and seemingly parochial corners, is never far removed from the context of human society. Scientists are of their time and place and so too are the theories, experiments, methodologies, and measurements that those scientists produce. When these connections between physical theory and society seem out of reach, the history of technology can act as an effective bridge between them. Such bridges are perhaps more easily imagined linking to histories of experimental physics.[244] While this study is by no means the first to draw connections

[244] Schaffer (1992); Schaffer (1995); Gooday (2004); Hunt (1994).

to theoretical physics, historians of theoretical physics frequently ignore the opportunity to make inroads into broader relevant histories or connect only to the general aesthetics of a given theory. In some ways this project seems fairly obvious, tying together the most conspicuous electrical technology of the 19th century, Britain's global telegraph network, and one of the crowning theoretical achievements of the century, Maxwell's electromagnetic theory (even if this was not the project's starting point). Indeed, this relationship between a practical technology and abstract theory does not retrospectively seem so dramatic a leap in light of the interdisciplinary nature of Fleeming Jenkin's work, standing between engineering and electrical science.[245] Nevertheless, this science-technology relationship breaks down the false walls of disinterest built up around Maxwellian electromagnetic theory. On display is a path of exposure and a bond of kinship between the prevailing political and economic forces within the British Empire of the late-19th century and the minutiae of Maxwellian electromagnetic theory.

[245] Hunt (2014); Layton (1971, p. 578).

Chapter 4



Conclusion: Failure, Waste, and Modernity

4.1 Summary: The Machines that Made Maxwell

Considering the role of technology in James Clerk Maxwell's thinking leaves us with a history of classical electrodynamics that looks very different from the existing historiography. What could once be construed as a clear break towards modern theoretical physics now appears decidedly Victorian. Technologies place Maxwell's electromagnetic theories in their historical context. The particular successes and failures of these technologies, their motivating philosophies, their political, economic, ecological, and even religious connections bind them more closely to Maxwell's theories and locate his physics more immediately in the turmoil of late-19th-century Britain. Both of the technologies described in Chapters 2 and 3 are products of the First and Second Industrial Revolutions, a clever mechanical curiosity in the case of the First and perhaps the grandest realization of the Second. The smooth running steam power promised by the Siemens governor and the command and control offered by Britain's fledgling submarine cable network bear the imprint of the political, cultural, and economic demands which brought them into being.

The Siemens governor discussed in Chapter 2 exemplifies the growing importance of the still nascent concept of efficiency. A wide ranging intellectual shift across sciences, social sciences, and religious thought from the presumption of eternal balance to unbounded growth swept through early-19th-century Britain. Engine models came to dominate, time became a key ingredient where it was once comfortably ignored, and new methods and economies of scale suggested real progress instead of the marginal gains of reorganization. That said, without the promise of static equilibrium, waste became a central concern across these newly altered disciplines and thus in its wake the concept of efficiency began to crystalize. The governor designed by the Siemens brothers arrived before engineers regularly integrated economics into their calculations of efficiency. The Siemens governor embodied this still forming, purely mechanical sense of efficiency common in the mid-19th century. It responded to changes in input near instantaneously and without overshooting. The governor kept steam (and water) engines running smoothly no matter the situation. The Siemens governor was notably more efficient than its competition (albeit also more complicated and less reliable). In part due to happenstance surrounding a change in his employment, Maxwell read an account of the governor likely around the same time he was beginning work on his second electromagnetic theory, published as “On Physical Lines of Force” between 1861 and 1862. Maxwell’s longstanding appreciation for mechanized industry as well as his Christian faith made the governor an appealing model for the electromagnetic ether. Certainly the differential motion of the Siemens governor made it well-suited to model particular electromagnetic phenomena in the ether, but his religious conviction that the ether reflected God’s universal order and perfection also demanded a uniquely efficient mechanical analogue. The governor played a notable role in shaping Maxwell’s electromagnetic theory in “Physical Lines” as a part of the honeycomb model of the ether, but it played an even larger role in 1864 in his “Dynamical Theory of the Electromagnetic Field.”

While the historiography has traditionally insisted that Maxwell’s “Dynamical Theory” marks his departure from reasoning with mechanical models or analogies, I demonstrate that mechanical analogies remained foundational to Maxwell’s approach in his “Dynamical Theory.” In “Dynamical Theory,” the governor is integral to Maxwell’s understanding of electromagnetic concepts and circuitously guides his mathematics to a generalized equation for the electromotive force on a moving conductor. Maxwell’s theory meanders to equations of the electromagnetic field at a rate determined by the Siemens governor. As a consequence, these equations are molded by Maxwell’s personal history, his faith and fascination with industry, and the governor itself, including elements of the device’s history, all of which drive its connection to Maxwell’s physics. Even after new theories had dispensed with the governor, it remained a powerful teaching tool for students of electromagnetism, leaving a legacy not only in Maxwellian theory but in physics pedagogy as well. Maxwell’s electromagnetic theory, through its association with the Siemens governor, is not only a part of the history of technology, it is a part of the history of efficiency.

As we saw in Chapter 3, submarine telegraphy similarly wound its way to the heart of Maxwellian electromagnetic theory. After the failures of the Atlantic and Red Sea cables, the British government and the Atlantic Telegraph Company formed the Joint Committee on the Construction of Submarine Telegraphs to understand the reasons behind their costly failures and outline best practices to ensure the success of future undersea cables. Both the company and the British government had lost their considerable investments, chance for future profits, and from the government's perspective the ability to instantly manage their far-flung colonial holdings. Amongst the experts that appeared before the Joint Committee to help identify past mistakes and chart a better future for the cable industry was the engineer Fleeming Jenkin. His testimony described in detail electrical phenomena in submerged cables including charge dissipation, residual charge, and secondary discharge that together would come to be called electric absorption. A short few years later, Maxwell found himself working together with Jenkin as members of the BAAS Standards Committee where once again electric absorption complicated their measurements.

In "Dynamical Theory," Maxwell cited Jenkin's report to the Joint Committee in his first attempt to construct a theory of electric absorption. There knowledge derived from failed submarine cables combined with Maxwell's understanding of capacitors (a combination made easier by Faraday's realization that undersea cables act as enormous capacitors). In his earlier electromagnetic theory, "Physical Lines," the charging of idealized capacitors helped to organize the first appearance of Maxwell's displacement current. There Maxwell also found a new empirical research program with the potential to verify his electromagnetic theory of light by analyzing capacitors. The merger of Maxwell's appreciation for idealized capacitors with the knowledge bestowed by Jenkin's study of electric absorption in submerged telegraph cables is present in the electromagnetic theories in both "Dynamical Theory" and his 1873 *Treatise*. Maxwell devoted an entire section of "Dynamical Theory" and the majority of a chapter in his *Treatise* to studying the resulting stratified capacitor, which itself was supposed to shed light on electric absorption. Nevertheless, to produce his initial theory of electric absorption in "Dynamical Theory," Maxwell found himself forced to disfigure a central tenet of electrical science, Ohm's law. Electric absorption conferred a sense of legitimacy to Maxwell's theory as it was the first to account for the phenomenon quantitatively. In doing so, electric absorption would also provide evidence for the concept of electric displacement and his analogies between elasticity and electric phenomena. Additionally, a working theory of electric absorption gave hope of some escape from the questionable data plaguing Maxwell's capacitor-led experimental program. Evidently Maxwell felt that the violation of Ohm's law was an acceptable price to pay for a working theory of electric absorption. Although Maxwell was able to recapture the majority of his theory of electric absorption without violating Ohm's law in the *Treatise*, this new approach necessitated the introduction of competing displacement and conduction currents within the dielectric. It was this dual current and the issues surrounding electric absorption that would become centrally important to those "Maxwellians" in the 1880s and 1890s who wished to continue on in Maxwell's tradition of electromagnetic theory. These issues surrounding electric absorption (particularly the "leaky condenser") and conduction remained a serious annoyance for Maxwellian theory until it was ultimately replaced by electron theory.

Capacitors served as critical models for electrical phenomena in Maxwell's theory, most prominently in the case of electric absorption. It was Jenkin's account of submarine telegraph cables that supplied and organized Maxwell's understanding of electric absorption. The cable failures that delivered the Joint Committee delivered Maxwell's theories. Britain's desire to command its colonies and commercial desires to profit from operating submarine cables and doing business across them made the Joint Committee and thus shaped Maxwell's electromagnetic theories. The success of the Joint Committee in solving the ills of the submarine telegraph industry saw an explosion of new undersea lines in the late-19th century. This success further links Maxwell's theories to consequences of Britain's expanding submarine cable network. This is not a causal connection, but Maxwellian theory was birthed from the same source that made possible violent colonial excesses, market speculation, and the exploitation of the environment.

Together these case studies illustrate that Maxwell's science was embedded in his culture and society. He and his theories of electromagnetism were forged out of the industrial technologies that characterized 19th-century Britain. The history of classical electrodynamics is no longer a "mirror-image twin" of thermodynamics—flipped because their science-technology relationships no longer lead in opposite directions.[1] The formation of Maxwell's electromagnetic theories more closely resembles the technology-led development of thermodynamics outlined by Cardwell.[2] The historical narratives describing the maturation of classical electrodynamics are of a piece with those for thermodynamics as both pillars of 19th-century physical theory now exemplify the role technology and engineering can play in shaping theory.

These technologies guided and left their mark on Maxwell's electromagnetic theories. With them came the worldly concerns so common to technologies engineered to mediate human life, but assumed absent from physical theory. Maxwell's electromagnetic theories are branded as Victorian products. Written onto his theories are concepts of efficiency and his personal Christian faith, the economics and politics of the British Empire (and failures thereof), and the genocidal and ecological violence of

[1] Layton (1971).
[2] Cardwell (1971).

British colonialism. And yet, Maxwell's reliance on technology in his electromagnetic theorizing merely puts into relief a historical claim most already take for granted. Without denying a unique sort of explanatory and predictive power to modern science, we can still recognize that Maxwell and his work are products of their time, the mid-to-late-19th century, and place, England and Scotland. Of course the historical context informed the way Maxwell did physics and thus informed the physical theories he produced. Even so, there is value in showing how global forces and ideas end up in the minutiae of electromagnetic theory; how the original derivation of some of Maxwell's most famous equations is connected to his faith and his employment, to still forming ideas of efficiency, and to a steam engine governor that was a total commercial failure; or how the repeated failure of the Atlantic telegraph cable informed Maxwell's ideas of charge and dielectrics. The macro forces of the world permeate the sciences, seeping into even the most abstruse layers of theoretical physics.

Continuing this project would naturally entail a closer look at the role of technology in Maxwell's theoretical work in other scientific disciplines, beginning with the kinetic theory of gases, the composition of Saturn's rings, and color theory. The extent to which mechanical models influenced his thinking in the former two areas offers just one possible beginning, while his work with his color wheel, color photography, and a homemade ophthalmoscope offer a path for the latter. These are by no means the only possible directions, there are other technological asides that intersect with Maxwell's science (the manner in which evolution gets tangled up with a discussion of telephones for example).[3] Despite an abundance of Maxwell scholarship, his interactions with technology have not received adequate attention. As evidenced by this dissertation, there is still room for Maxwell scholarship that takes seriously the ability of engineering and technology to shape science.

4.2 Failure and Waste

After this summary of both chapters, I'd like to briefly discuss two themes, failure and waste, each of which has been used to frame one of these chapters, but which may now be applied to both. This dissertation was structured such that Chapter 2 is framed by the concept of efficiency, which had emerged from a society-wide concern with waste, while Chapter 3 is framed by failure. Applying the lens of failure to the case of Maxwell and the governor illustrates how complicated the seemingly straightforward concept of failure can be when applied to histories of technology.[4] Reimagining my discussion of submarine telegraphy and Maxwell's theories in the context of waste reveals a connection that binds together this entire project.

[3]Maxwell (1890i).

[4]See Gooday (1998) for a historiographical discussion of technological failure that guides the discussion in this section.

Failure guides Chapter 3 as a central component in the story of how submarine telegraphy ends up shaping Maxwell's electromagnetic theory. It is the unmitigated failure of the Atlantic and Red Sea cables that suggest the need for the Joint Committee and it is testimony at this committee which ultimately shapes Maxwell's electromagnetic theories. In the case of the Siemens governor, I do make some brief mention of failure, the failure of the governor as a commercial product. Despite a dogged effort on the part of Charles Siemens, the governor that he and his brother had designed was never much sought after to tame the steam engines of Britain, a rare failure of two eminently successful businessmen. This sort of failure is of an entirely different sort than the total failure of the initial Atlantic cables. Naturally, these cables were also economic failures. They cost quite a lot in money, time, and effort and either didn't work or worked for such a short time that they never had a chance to make any return on the investment. There is little flexibility to interpret the early Atlantic cables as successes in and of themselves. In their time, they were unanimously regarded as failures and came close to dooming the entire submarine cable industry. It was only after their failure was recognized that any "successes" could be had. By contrast, the Siemens governor worked well, as some factory owners had attested. It may not have been as affordable or spectacularly cost saving as a factory owner might have wished, or as simple or reliable as a company engineer would prefer, but it performed the task it was designed to do and in fact it did so more efficiently than its competition.

How then to categorize the sort of failure performed by the Siemens governor? Or was it even a failure in any sense, considering it found a home in observatories and in an idealized form in Maxwell's electromagnetic theories? The Siemens governor might be said to have failed insofar as it did not provide an adequate return on what its inventors had invested in its creation, patenting, and marketing. The failure of the governor appears primarily as a case of poor business sense and badly targeted marketing by Charles Siemens. At least initially, his asking price for the patent was ludicrously high. Perhaps a more reasonable price would have attracted a buyer that would have been able to manufacture the governors at better prices and market them more widely.

Even if it was the spotty reliability that scared away buyers, fault would lie with the Siemens brothers' inability to design to the desires of their potential customers, for whom reliability proved a greater need than yet more efficiency. To add further difficulty in labeling the governor a failure, sacrificing efficiency for reliability may have made it more successful commercially, but potentially less appealing to Maxwell as a model of the near-perfect ether. Reliability, cost, complexity, are all elements that could factor into an explanation of commercial failure and which ultimately have no (or limited) bearing on its success as a scientific object. For Maxwell and even for the Astronomer Royal George Airy, success was measured only in exceptionally smooth running and efficiency. The Siemens governor thus remains a problematic object to assign success or failure to. That it may not have been reliable enough for the purposes it was intended for, or too complicated to be easily repaired, or more efficient than was ever really needed, are all potential explanations of the failure to find a market for the device, none of these explanations saddles the device itself with the failure. The difficulty of assigning failure in the case of the governor illustrates the complexity of using the concepts of failure and success in the history of technology. Beyond that, however, the concept of failure is admittedly not all that helpful in framing the case study of the governor.

Framing Chapter 3 around the idea of waste by contrast is much more rewarding. Waste features prominently in Chapter 2 as a fundamental component of the broad intellectual shift from assumptions of static equilibrium to unbounded growth in the early 19th century, a shift discussed at length in Smith and Wise's three-part "Work and Waste."[5] The burgeoning focus on temporality and rebellion against balance models in favor of engines made waste a motivating concern amongst a wide swath of disciplines. Christian movements with increased emphasis on the descent of humans into sin, orbits degrading in a celestial medium in astronomy, and of course thermodynamics after the assimilation around 1850 of the earlier works of Carnot and Joule by Thomson and Clausius were all deeply concerned with the pernicious effects of waste. Chapter 2 deals less with waste itself, instead following a response to this widespread concern over waste, namely a growing obsession with the concept of efficiency. Unlike Chapter 2, in applying the idea of waste to Chapter 3 there is no need to involve efficiency. Here waste is at the heart of the physical theories (or at least the parts of them I discuss), both Maxwell's and the Maxwellians'. The guiding example behind Smith and Wise's "Work and Waste," the recently graduated William Thomson's miraculous solution to the question of force between oppositely charged spheres, typifies an early success of the reintroduction of temporality to the sciences. The larger intellectual shift had equipped Thomson with the "cultural resources" to solve the problem that had stumped a number of famous names before him.[6] The elements of Maxwell's and the Maxwellians' electromagnetic theories discussed in Chapter 3 may come much later, but the coherence of Maxwell's entire approach rests immediately on waste.

In a sense, this could all be wrapped up very easily with a reminder that the critical phenomena at issue Chapter 3 is electric absorption, an evocative name that encompasses residual charge, secondary discharge, and what is most relevant here—charge dissipation. Dissipation is of course the link to waste. As charge dissipates it is rendered unrecoverable, i.e., it becomes waste. More than any other element of electric absorption, it is waste, via charge dissipation, that drives Maxwell and his successors' conceptual development. Waste is at the center of the oddities in

[5] Wise and Smith (1989a); Wise and Smith (1989b); Wise and Smith (1990).

[6] Wise and Smith (1989a, pp. 265–266).

Maxwell's "Theory of the Condenser" in "A Dynamical Theory of the Electromagnetic Field." Waste (dissipation) is why there needs to be a negative sign in the exponent of the equation for the extreme potentials of the stratified capacitor at some time t. Without the negative sign there is no waste, charge does not eventually dissipate over time. And thus without Maxwell's overwhelming need to model this phenomenon of waste, there would be no need for him to butcher Ohm's law in a desperate attempt to secure a negative exponent. Waste is where Maxwell's conception of what is happening inside of the dielectric comes from. In "Dynamical Theory" and in his 1868 paper "On a Method of Making a Direct Comparison of Electrostatic with Electromagnetic Force," charge dissipation results from a vague process of a "combined" displacement/conduction current. Only displacement currents are possible within the dielectric, but in taking on some of the qualities of a conduction current under certain (in fact, most) circumstances, these displacement currents effect the eventual dissipation of charge as it moves within the dielectric. In Maxwell's *Treatise*, the process of dissipation is reconceived and consequently so is electrical action in the dielectric. Now there are two currents, a displacement current and a conduction current, charge is dissipated as these two currents cancel one another out. In turn, this provides a physical explanation to a mystery of asymmetry: why would there be no magnetic field produced when charges dissipate? Because there is no total current in the dielectric during dissipation. Waste attracted even greater focus amongst Maxwellian theorists looking to expand on Maxwell's *Treatise*. The "leaky condenser" that commanded the attention of many Maxwellians was itself just a new technological packaging for the same concern over charge dissipation. As the Maxwellians grappled with the leaky condenser, they reconceived currents in the dielectric, returning to a single current that they imagined was formed of moving and *decaying* tubes of displacement.

Modeling electric absorption also promised to rescue Maxwell and his theories from one of its pernicious effects. Just as waste was seen as a degrading influence on human potential, the solar system, and everything in between, waste in the form of electric absorption ruined data from a number of potentially theory-validating experiments. Beyond complicating Maxwell's Standards Committee work where he first encountered it, electric absorption had disrupted *both* empirical programs that Maxwell looked to in support of his electromagnetic theory of light. Not only were the numerous capacitor-based experiments to determine the ratio of units (to compare it with the speed of light) thrown off by electric absorption, so too were experiments to obtain the specific inductive capacity of dielectrics so that they could be compared with their indices of refraction. Waste had a deleterious effect on Maxwell's efforts to experimentally verify his electromagnetic theory of light. Attempting to mitigate these effects simultaneously added to his theories' explanatory power and forced a deep examination of fundamental electromagnetic concepts.

Waste is inextricably linked to Maxwell's concept of displacement, the displacement current, and conduction. Coming to terms with charge dissipation forced ugly adaptations of long standing electrical laws and numerous reimaginings of electrical action in the dielectric *and* in conductors. In the dielectric, waste made for one strange combined current, then two currents, then a physically reimagined single current once again. These issues were not settled by Maxwell, instead waste, in the form of charge dissipation, continued to plague the Maxwellians long after his death. Their solutions to the issue of waste created instabilities in Maxwellian theory that were ultimately never solved. Maxwellian theory itself was simply absorbed and replaced by electron theory.

In much the same sense that the Scottish Presbyterian Thomas Chalmers encouraged followers to find personal salvation and reverse their decay into sin and desperation, for Maxwell dissipation represented a natural state that once understood could be properly dealt with.[7] As discussed in Chapter 2, Maxwell acknowledges the potential for waste in his conception of the ether as spectacularly efficient, but not perfectly instantaneous. Waste as dissipation, filtering into Maxwell's electromagnetic theories from submarine telegraphy[8] seemed poised to destroy any hope of empirically verifying the electromagnetic theory of light. Instead, a hard-fought understanding of dissipation became an example of the great success of Maxwellian theory, even if it required constant attention and refinement. Whether it's his understanding of the ether as a substance that minimized waste, and thus deserved the hyper-efficient Siemens governor as a model, or electric absorption forcing him to wrestle with waste through charge dissipation, the resources Maxwell drew from to inspire his electromagnetic theories were products of a Victorian age that had given up static equilibrium in favor of unbounded engines of growth.

4.3 The Past in the Present

Maxwell's electromagnetic theories were shaped by the political, economic, and cultural forces of Victorian Britain. The form physical theories take isn't simply preordained by the physical phenomena being modeled. Elements of our social world, religion, politics, race, economy, are just as much ingredients in the scientific process as nature. The above case studies of Maxwellian theory are an instructive reminder

[7] Wise and Smith (1989b, pp. 400–403).

[8] Perhaps it should not come as a surprise that the parts of Maxwell's theory touched by submarine telegraphy were also so deeply affected by the aforementioned intellectual shift to engine models and rediscovery of temporality. It was after all the Victorian technology that most profoundly broke down usual senses of time and space (with all due respect to the locomotive), connecting people across oceans and completely shattering the timescale on which they expected communication to happen.

that science is not a perfectly objective discipline outside regular life and that there is no one scientific method. Science is at least in part an ineffable creative process that draws on and reflects everything around it, just as much as any art or literature. Maxwell's equations of electromagnetism remain in common use in physics and engineering and the world has only become progressively more electrified over the course of the 20th and 21st centuries. Do embedded Victorian politics seep out and distort the modern products of classical electrodynamics? Rediscovering Maxwellian theory's "Victorian-ness" seems as though it should tell us something more about the foundations of our own modern world.

All of these imprints on Maxwell's theory, are they quickly smoothed over or do they go on to affect the future products of Maxwellian theory? It's an important question given the electrical world that was emerging in the late-19th and early-20th centuries. Electrification of factories and then homes, telephones and wireless radio, all arrived within a few short decades after Maxwell's *Treatise*. Are these technologies also legacies of the frequently unsavory forces that shaped Maxwellian theory? Can it be shown that the Maxwellian mathematical relations and physical concepts infected these century-defining technologies with their condition of Victorian politics and culture. This is a possible future of this project, widening the lens to capture the social and political effects of a uniquely Victorian science as the electrical foundations of the 20th century are built. However, there are a number of stubborn obstacles that severely limit the potential of this approach. The first hurdle is relevant exclusively to Chapter 2. Trying to pick out how Maxwellian theory might have driven efficiency into the heart of electrical technologies in the 20th century is largely a fruitless endeavor. Even by the end of the 19th century, a culture-wide obsession with efficiency had begun to emerge. By the early 20th, industry's obsession with efficiency was so ubiquitous that there is little hope of finding uniquely Maxwellian inroads. Tracing reasonably solid connections to concepts of efficiency smuggled in by Maxwellian theory seems absurdly unlikely during the rise of scientific management.

The second and much larger hurdle concerns simple chronology in the history of electromagnetic theories. Maxwell died in 1879, just six years after the release of the first edition of his *Treatise*, while he was still in the process of editing a second edition. Indeed even before his death, the last five years of Maxwell's life were spent editing the papers of Henry Cavendish, a noble undertaking, but also a regrettable waste of the talents of Britain's most formidable mathematical physicist. Maxwell's electromagnetic theory eventually developed into a research school at Cambridge, but only years after his death in the mid-1880s. His lectures were sparsely attended and at least initially, the novel aspects of his electromagnetic theory were ignored.[9] Maxwell's electromagnetic theory had a slow start. Equally as disappointing, Maxwellian theory, beyond just the equations themselves, simply did not survive for all that long

[9] Warwick (2003).

either. On the continent few ever came to accept the physical understanding of electrical relations and concepts contained within Maxwell's theory of electromagnetism. As Hertz famously quipped: 'What is Maxwell's theory?. . . Maxwell's theory is Maxwell's system of equations."[10] The attendant concepts were abandoned as the theory was reimagined without commitments to mechanical ethers or tubes of induction or displacement. The quick acceptance of Lorentz's electron theory outside of Britain then made quick work of the last vestiges of Maxwell's electromagnetic concepts and the Electromagnetic Worldview wiped clean the mechanical underpinnings of electromagnetic theory.

In Britain, across a series of experiments on cathode ray tubes in the late 1890s J.J. Thomson's discovered the charged corpuscles now referred to as electrons and gradually they came to be accepted as the fundamental carriers of negative charge. The Cambridge school of electromagnetic theory continued on, reaching its crescendo with Larmor's "own"[11] Electronic Theory of Matter, wherein all mass was electromagnetic in origin. Now even Cambridge had no time for traditional Maxwellian concepts, although the extent of Larmor's departure from Maxwellian theory was interpreted differently by different parties. Much like Maxwell's beloved country estate Glenlair, by the early-20th century the framework of Maxwellian theory had collapsed and the age of electron theories (of varying sorts) had begun. We are left with a period of at best 15–20 years from the early-1880s until the beginning of the 20th century at the latest during which theoretical physics in Britain was concerned with recognizably Maxwellian electromagnetic concepts. This is a short time period for Maxwellian concepts to exert much influence, but unfortunately considering the history of electrical engineering during this period only further narrows the window of opportunity.

Scientifically trained electrical engineers do not appear to have lagged much behind theoretical physicists in adopting one or another electron theory. Nevertheless, during the heyday of Maxwellian theory many engineers remained happily ignorant of or even antagonistic towards any general theory of electromagnetism.[12] Let's remember where this project started; engineering is not applied science. It is naive to expect that the electrical technologies developed during the short time in which Maxwell's electromagnetic theory reigned should necessarily have been created with much, if any thought towards the formal physical theory. Much of the successful electrical technology of the period was designed and maintained by practitioners with no knowledge of abstract theory. The premier electrical technology that arrived during this span of time, practical wireless telegraphy, i.e., radio, is perhaps the most famous example. Guglielmo Marconi had no working knowledge of Maxwellian theory and his

[10] Hertz and Thomson (1893, p. 21).
[11] Darrigol (1994).
[12] Hong (2001); Hunt (1983).

most critical innovation, grounding his transmitter and receiver, was inspired by the tacit knowledge of practical telegraphers.[13] At best Maxwellian theory inspired radio technology by suggesting the existence of electromagnetic waves, but other than the fact of their existence (which is more appropriately credited to Hertz), no knowledge or concepts passed from Maxwell to Marconi.

And yet, even if technology is not applied science, science obviously does influence technology and there are still some narrow avenues for future research. Oliver Lodge had some limited impact on the trajectory of radio, and given his status as a committed Maxwellian, his work on the concept of syntony might be a source of connection.[14] John Ambrose Fleming, a student of Maxwell's, worked as Marconi's scientific advisor as he geared up to send signals across the Atlantic. By this time Fleming had already adopted Larmor's Electronic Theory of Matter, although the extent to which he maintained certain Maxwellian conceptions remains open.[15] It is worth investigating to what extent electrical engineers were able to preserve Maxwellian concepts even after accepting Larmor's electron. Nevertheless, even if one or more of these examples panned out none is particularly striking. Maxwellian theory was slowly adopted and after a short time its unique electromagnetic conceptions were quickly sterilized, leaving only a skeleton of mathematics. Being pared down to mathematics is not necessarily redemptive. Arguing that the Victorian context is preserved within Maxwell's equations themselves is certainly not impossible, but it is a considerably more difficult task. Ultimately, there is little evidence to support the claim that Maxwellian theory had much direct influence on the technological foundations of our electrical world.

How strange then that in our electrical present, where Maxwell's equations are still critically useful tools of scientists and engineers, they once again find themselves unmistakably enmeshed with adapted versions of the same political and economic forces that shaped Maxwell's theory in the middle-Victorian era. Connected now through modern technologies and networks, Maxwell's equations still cannot escape their attachment to colonialism, economic exploitation, and environmental devastation. We are now in an age of wireless, AM and then FM radio, over-the-air and satellite television, cell phones, WiFi, and Bluetooth, if we limit ourselves to a selection of only wireless *communication* technologies. Maxwell's electromagnetic theory was once connected to the grandest technological manifestation of Britain's imperialist vision, its global submarine telegraph network. As Faraday first noted, these submerged cables acted like giant capacitors, making the ocean itself the other conductive plate. To manage its overseas territories Britain had captured the oceans

[13] Hong (2001, p. 21).

[14] Aitken (1985).

[15] Fleming seemed to view Larmor's theory as a "supplement" not a challenge to Maxwell's. Hong (2001, pp. 193–194).

Figure 4.1: Cable Landing at Lopez Island, Washington

and turned them into colonial technologies. Now Maxwell's equations are tied to a sort of extra-dimensional colonialism. The electromagnetic spectrum first hinted at by Maxwell's theory is now new territory to be conquered and exploited. Frequency bands are typically owned by governments and licensed to private carriers or withheld for particular public interests. Much as the British government utilized submarine cables and thus the oceans themselves in an effort to control its sprawling empire, modern day governments command the electromagnetic spectrum, controlling the dissemination of information across frequency bands and then delegating that control to private corporations. The global supply chains that make possible cheap modern electronics are exploitative in much the same way as the Victorian cable industry. Millions of gutta trees were cut down to feed the Victorian cable industry's insatiable appetite for insulation material, while today the mining and refining of rare earth elements that make possible modern electronics leave choking clouds of smog and poisonous lakes of processing waste. Although radio eventually blunted the submarine cable boom, undersea data cables now make up the backbone of the internet, once again putting the various corners of the world in communication with one another. Like their Victorian counterparts, these cables constitute yet more tons of waste deposited into the oceans. Unlike the gutta-percha insulated cables of the

19th century, modern undersea cables are not the direct cause of any environmental crises. However, tons of polyethylene plastic shielded cables filled with petroleum jelly criss-crossing the ocean floor serve as an effective avatar for the microplastic and oil fueled disaster we have created.

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