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Perpetually Laborious: Computing Electric Power Transmission Before The Electronic Computer

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INTRODUCTION

Placing Thomas Edison at the beginning of a history on electric power transmission hardly needs justification. Thomas Edison's abundant supply of pictures of himself as an inventive genius – and America's pressing demand for a myth of an ingenious inventor – combined to bestow a "Eureka" moment upon Edison's pioneering Pearl Street (New York) Station electric lighting network. But the history of the laborious computations that took place at Menlo Park and the division-of-computing labor of which Edison took advantage suggests a different view of inventive genius. The story of the computational pyramid formed by the labors of Francis R. Upton, Charles L. Clarke, and Samuel D. Mott (1879–1880) can be reconstructed from the existing literature.[1] In his reminiscences from Menlo Park, Edison's employee, Francis Jehl, detailed how Edison thought of constructing a miniaturized network to be used as a computer of the actual network. Knowing that constructing, maintaining, and using the miniature network required a considerable amount of skilled labor, Edison decided to hire an employee for it, Dr Herman Claudius. Edison enthusiastically welcomed Claudius to perform a type of computing work "requiring nerve and super abundance of patience and knowledge". Jehl remembered that the labor of constructing a miniature network of conductors, "all in proportion, to show Mr Edison what he would have to install in New York City in connection with the Pearl Street Station" was "gigantic".[2] Following the pattern of the Pearl Street Station electric lighting network, several similar networks were built in the early 1880s. In response, Edison's labor pyramid was enlarged by giving Claudius an assistant, Hermann Lemp, who performed the monotonous task of constructing the new miniature networks, which Edison needed for

1. See Robert D. Friedel and Paul Israel, *Edison's Electric Light: Biography of an Invention* (New Brunswick, NJ, 1986), pp. 120 and 124. See also, Paul Israel, *Edison: A Life of Invention* (New York, 1998), p. 179, Friedel and Israel, *Edison's Electric Light: Biography of an Invention*, pp. 36 and 148, and Francis Jehl, *Menlo Park Reminiscences* (Dearborn, MI, 1939), pp. 729–731.
2. See Jehl, *Menlo Park Reminiscences*, pp. 545–546.

computation. Inconvenient as it might be for those who assume that technological change is the product of inventive genius, electrification was, from the beginning, laboriously computed; it was not, like Athena, a deity that leapt from a godly head.[3]

Taking the history of computing electric transmission after Edison as my reference, I shall argue in this paper that the computing work required for the reproduction of the capitalist mode of production was expropriated from human labor – labor defined by the understudied work of men and women computing workers, usually referred to as "computers" or "computors". As a student of the history of computing for the period before the so-called Information Revolution – which, supposedly, was instigated after the 1940s by the electronic computer – I was surprised by the uniformity in which pre-40s authors refer to their own technical civilization as one that depended on computing. Furthermore, I was struck by the frequency of technical authors who referred to computing as "labor". This article provides the labor historian with a representative sample of the innumerable, yet understudied, pre-1940s references to the act of computing as an act of labor. But, more importantly, in thinking about how to interpret those references, instead of simply presenting a list of laborers whose role has been neglected, this article considers the mechanism by which the act of neglecting such a large and skillful population of laborers became possible.

Regarding the history of computing electric power transmission before the 1940s, most of the hundreds of articles that I considered start by introducing the reader to a crisis of computing laborers. Yet, in this pre-computing era, these very laborers employed an extensive variety of computing tools and machines! These apparatuses ranged from ubiquitous tools, such as the inexpensive and humble "slide rule", to uncommon state-of-the-art industrial and academic laboratory computing machines like the sizable "network analyzers" and its immediate ancestors, "artificial lines" and "calculating boards".

Like the miniature network that Edison hired Claudius to construct, artificial lines, calculating boards, and network analyzers – for simplicity I refer to them as analyzers – were laboratory models of the networks to be computed. Unlike many mechanical models devised and used during the same period also for the purpose of computing the transmission of electric power, the analyzers were electrical artifacts. The first calculating board of 1916 was a common wooden table upon which a set of electrical elements representing resistance was mounted. Adding electrical elements representing reactance and capacitance, and increasing the number of electrical

3. For America demanding the myth of an inventive genius and for Edison supplying it, see Wyn Wachhorst, *Thomas Alva Edison: An American Myth* (Cambridge, MA, 1981), and Charles Bazerman, *The Languages of Edison's Light* (Cambridge, MA, 1999), respectively.

elements and their interconnections as a whole, resulted in the rapid evolution of the calculating board to a room-sized artifact like the first 1929 network analyzer. Mounted on tables or library shelves, the artificial line of the late 1910s and the early 1920s provided a better computing analogy than did a calculating board, but at the cost of being more demanding in terms of the skill and the amount of labor needed to construct and maintain it. Thus, the network analyzer can be interpreted as an enlarged calculating board or as a combination of artificial lines (to make the transition from computing lines to computing networks of lines possible).

In the transition from calculating boards and artificial lines to network analyzers, analyzers were devised into subsections while peripheral components were also added to assist in the subdivision of the labor involved. Moving to the 1940s, we find pictures of a stark contrast: men sitting at control desks that were separated from the analyzer computing units that they monitored, but women standing directly before the network analyzer computing units that they set up. These pictures of the electrical analyzers predate the nearly identical pictures of the gendered division-of-computing labor that accompanied the introduction of the first, equally large electronic computers of the 1940s (see below). Revealing also is a sketch from 1944 that accompanied a *Westinghouse Engineer* editorial, which featured a man sitting at a control desk in a room made cramped by a network analyzer while boys were rushing around with the data and results.[4]

Within this article, I focus only upon the introduction of new varieties of analyzers because each new wave of these artifacts was ideologized and mythologized by the engineering professionals of that period. On each occasion, these professionals testified that the latest analyzer provided evidence of the ultimate revolution in computing technology. Here, Marxist theory can offer brevity while remaining analytically precise: of all technologies for computing electric power transmission, the one involving analyzers exemplified the highest ratio of constant to variable capital (dead to living labor, machines to humans). It follows that these moments can illustrate both the permanent technical revolution in computing and the perpetual labor crisis of computing that accompanied it.[5] I shall argue that each subsequent wave of analyzers failed to mechanize computing and thereby permanently eliminate the computing labor crisis. As a result, we find within the same technical literature that enthusiastically welcomed

4. "*Network Calculator* [...] Mathematician Par Excellence", *Westinghouse Engineer*, 4 (July 1944), front cover.

5. For the concepts of constant and variable capital, see Karl Marx, *Capital*, vol. 1, (London, 1990). For a Marxist class analysis that I found useful in thinking about the laborers involved in computing electric power transmission, see Nicos Poulantzas, *Classes in Contemporary Capitalism* (London, 1975).

each new wave of analyzers as providing the definite solution, the surprising revelation that the preceding wave of analyzers had all but solved this crisis. Certainly, each new wave of analyzers provided a momentary solution to the crisis. Given, however, the dynamic (expansive) reproduction of the capitalist mode of production, the spontaneous mechanization of the computing of one network was instantaneously turned into the basis for the construction of another, more complex network, which, in turn, immediately turned the previous wave of analyzers into something obsolete. In this dynamic, as new networks (of canals, roads, rails, electrical and electronic lines of energy and communication, etc.) brought about new computers and new computers brought about new networks, the dependence on computing labor remained intact.

The aforementioned 1944 *Westinghouse Engineer* editorial heralded the replacement of calculating machines by network analyzers as the event that saved the field from a computing labor crisis. The editor informed his readership that when the plans for the electrification of the Virginia railroad were being drawn up in the mid-1920s,

> [...] two crews of three men each worked several months with a battery of adding machines making the necessary calculations [...] for the almost endless combinations of circuits and loads. Each team would work furiously for a couple of weeks and then spend the next week or so checking the results of the other team.

For the *Westinghouse Engineer* columnist, this was "a monumental task and utterly hopeless" and, as a result, "[e]lectrical systems threatened to become a Frankenstein out of [c]ontrol".[6] In the history of electric power transmission, computing revolutions came and went with an impressive frequency. Given that moments of explicit celebration of new machines are also moments of implicit disappointment in the old ones, I find that the study of these moments offers a privileged instance for making invisible human labor visible.

This contention also raises an important historiographical point. In the previous example, the network analyzer, considered by contemporary scholars to be an exemplar of an analog computer, came as a savior of the calculating machine (in this case an adding machine), now considered an exemplar of a digital computer. The *Westinghouse Engineer* editorial suggests that an essentialist demarcation between a technically superior (digital-mental) and a technically inferior (analog-material) computing technique is unfounded. Moments of shift in the emphasis from (digital) calculating machines to (analog) analyzers have been moments when the computing labor crisis became apparent. We know little about these moments because the post-40s demarcation between the analog and the

6. "*Network Calculator* [...] Mathematician Par Excellence".

digital was *a posteriori* projected to the pre-40s history of computing. As a result, analyzers are now historiographically devalued, despite their importance during their period of use. Accordingly, the computing labor crisis that marks the history of using them has yet to receive the attention that it deserves.[7]

In a few pioneering accounts of the place of human computers, the invisibility of labor is usually attributed to ceremonial introductions of computing machinery.[8] Granting the reality of this omission, it only tells us half of the story. One example may illustrate my point. In her otherwise suggestive study of the important group of women computors who worked for the ENIAC – the pioneer electronic computer of the 1940s –

7. For an elaboration, see Aristotle Tympas, "The Computor and the Analyst: Computing and Power, 1870s–1960s" (unpublished Ph.D. thesis, Georgia Institute of Technology, 2001).

8. See Jennifer Light, "When Computers Were Women", *Technology and Culture*, 40 (1999), pp. 455–483. A history indicative of the unbroken line of computors working with what we now call digital machines before, but also after the ENIAC, and the associated enlargement of the capitalist division-of-computing labor can be reconstructed by reading together the following references (in order of the chronology covered: Lorraine Daston, "Enlightenment Calculations", *Critical Inquiry*, 21 (1994), pp. 182–202; I. Gratan-Guinness, "Work for the Hairdressers: The Production of de Prony's Logarithmic and Trigonometric Tables", *Annals of the History of Computing,* 12:3 (1990), pp. 177–185; Andrew Warwick, "The Laboratory of Theory or What's Exact About the Exact Sciences?", in M. Norton Wise (ed.), *The Values of Precision* (Princeton, NJ, 1994), pp. 311–351; Mary Croarken and Martin Campbell-Kelly, "Beautiful Numbers: The Rise and Decline of the British Association Mathematical Tables Committee, 1871–1965", *IEEE Annals of the History of Computing*, 22:4 (2000), pp. 44–61; Margaret W. Rossiter, "'Women's Work' in Science, 1880–1910", *Isis*, 258 (1980), pp. 381–398; Peggy Aldrich Kidwell, "American Scientists and Calculating Machines: From Novelty to Commonplace", *Annals of the History of Computing*, 12:1 (1990), pp. 31–40; Mary Croarker, *Early Scientific Computing in Britain,* (Oxford, 1990); Paul Ceruzzi, "When Computers Were Human", *Annals of the History of Computing*, 13:1 (1991), pp. 237–244; David Alan Grier, "Gertrude Blanch of the Mathematical Tables Project", *IEEE Annals of the History of Computing*, 19:4 (1997), pp. 18–27; *idem*, "The Math Tables Project of the Work Project Administration: The Reluctant Start of the Computing Era", *IEEE Annals of the History of Computing*, 20:3 (1998), pp. 33–49; *idem*, "Ida Rhodes and the Dreams of a Human Computer", *IEEE Annals of the History of Computing,* 22:1 (2000), pp. 82–85; and Harry Polachek, "History of the Journal 'Mathematical Tables and For Other Aids to Computation', 1959–1965", *IEEE Annals of the History of Computing*, 17:3 (1995), pp. 67–74. For an example of the survival of women computors in the post-ENIAC era, see Denise Gurer, "Pioneering Women in Computer Science", *Communications of the ACM*, 38:1 (1995), pp. 45–54. For a group of male-only computors, see Jan van den Ende, "Tidal Calculations in the Netherlands, 1920–1960", *IEEE Annals of the History of Computing*, 14:3 (1992), pp. 23–33. The role of computors is generally missing from most of the available studies on the history of calculating and punched-card machines. However, some of these studies contain pictures of rooms full of working computors. For a sample of this suggestive visual record written by a professional historian, see pictures in James Cortada, *IBM, NCR, Burroughs, and Remington Rand and the Industry They Created, 1865–1956* (Princeton, NJ, 1993). For an example from a corporation that published its own history, see pictures in Edwin Darby, *It All Adds Up: The Growth of the Victor Comptometer Corporation* (Chicago, IL, 1968). For an introduction to precapitalist computors and calculators, see Arno Borst, *The Ordering of Time: From the Ancient Computus to the Modern Computer* (Chicago, IL, 1993).

Jennifer Light argues that the tasks these women performed was only programming. In doing so, Light risks severing the mental from the manual, regarding the labor the ENIAC women actually conducted. While she succeeds in inviting our attention to their unappreciated mental skill, she reproduces standard historiographical distinctions concerning the unjustifiable devaluation of the skillful manual labor when these women set switches and plugged cables.[9] In diminishing the computor's rung in the labor hierarchy, there was a relative increase in the ratio of manual to mental computing skills. Yet skill as a whole became all but unnecessary. As I understand it, we need a re-evaluation of the manual skills involved, not simply a re-evaluation of mental skills. Without such re-evaluation, the (largely) manual skills possessed by the lower computors will remain overlooked.

This historiographical strategy seems especially appropriate when the considerable differences within the ranks of computors are taken into account.[10] True, the exceptional mental-digital skills of the few top women computors were historically and (are) historiographically unappreciated. But even more unappreciated were the less digital but equally indispensable material-analog skills of many subclasses of women computors populating the pyramid of computors below them. And another facet remains disguised – history neglects the material-analog side of the skills possessed by the top women computors at ENIAC (i.e. references to their work in programming erases the significance of the actual plugging and switching over analyzing). Worse, we know practically nothing of the computing labor of a great mass of men possessing computing skills because the computing machines with which they worked are rendered historically unimportant on the grounds that their *a posteriori* designation belongs to an inferior technical class – analog computers.

Extending the previous statement, the computor could be even a male electrical engineer as long as his work could be ideologically devalued beside the work of someone else – an "analyst" – placed above him in the pyramid of the division of labor. Hence, I understand the difference between an "analyst" and a "computor" to be relative, not absolute. What I find is a hegemony of an ideology that presented this relative difference as absolute, thereby preventing laborers from developing a shared identity to resist the devaluation of their labor power in a more effective manner.[11] For an introduction to the ideal extremes of the analyst-computor

9. See Light, "When Computers Were Women", p. 477.

10. The best testimony of the variance within computors that I know of is contained in the memorandum on the work of computors at a military facility. See Ceruzzi, "When Computers Were Human", especially the section on the subclasses of computors and the significant difference in their salaries.

11. On the mechanism of presenting relative work differences as absolute, and on how crucial it is for the capitalist mode of production, see Poulantzas, *Classes in Contemporary Capitalism*.

distinction, I quote from Vannevar Bush's influential textbook on electrical engineering mathematics: "It is entirely possible for a computer to perform the algebraic work necessary for the symbolic solution of alternating current networks in the steady state without any grasp of the philosophy of the symbolic treatment or of the mathematics or differential equations on which it is based." "It is entirely possible", added Bush, "to utilize the operational method on specific problems without the slightest idea of why and when it does or does not work. This, however, is computation and not analysis."[12]

Computing labor ranged from the labor to construct the machines to the labor to maintain them. In addition, before the labor to use the machine came the labor to educate and become educated on how to use it. This included not only education on the computing method to be selected, but also how to use this method in conjunction with the machine. To this accounting one may add the labor to link the producer of a computing machine to the user of a computing machine, a labor of intermediary individuals, or later on, of groups of individuals forming certain institutions.[13]

The history of those laboring with electric lighting and power transmission is representative of a broader tradition of computing labor. First, computing the transmission of electric lighting and power was part of a broader whole, which included the labor to compute the electric transmission of communication messages. Second, the engineering side of electric power transmission computations was related to the business part of computing (the computing taking place in the accounting department of an electric power manufacturer was, for example, linked to all aspects of electrification-related computations, including the engineering ones).[14]

12. Vannevar Bush, *Operational Circuit Analysis* (New York, 1929), p. iii. In addition to many good articles on aspects of Bush's work, there is a book-length biography of him; see Pascal Zachary, *Endless Frontier: Vannevar Bush, Engineer of the American Century* (New York, 1997).

13. The importance of the labors of intermediary agents is increasingly acknowledged in the historical literature. Their long list should include salesmen and those who trained them, important in the computing field from early on (see Cortada, *IBM, NCR, Burroughs, and Remington Rand*); consultants and members of other professional or volunteering groups, scientific and other (see Atsushi Akera, "Calculating a Natural World; Scientists, Engineers, and Computers in the United States" (unpublished Ph.D. thesis, University of Pennsylvania, 1998), whose knowledge ranged from system analysis (see Thomas Haigh, "Inventing Information Systems: The Systems Men and the Computer, 1950–1968", *Business History Review,* 75 (2001), pp. 15–61) to machine interconnection (see Onno de Wit, Jan van den Ende, Johan Schot, and Ellen van Oost, "Innovation Junctions: Office Technologies in the Netherlands, 1880–1980", *Technology and Culture,* 43 (2002), pp. 50–72.)

14. In the accounting departments of electric utilities and manufacturers the use of standard calculating and punched machinery, and an associated emphasis on a more developed capitalist division-of-labor was much more customary than in the engineering departments; see Tympas, "The Computor and the Analyst", ch. 6.

Third, the computation of the electrical phenomena of electric power transmission was developed in parallel with the computation of the mechanical phenomena of electric power transmission. For example, computing the electric stability of the current running through lines would have been meaningless without having computed the mechanical stability of the transmission towers upon which these lines hung. Fourth, the development of the "off-line" computing history that I introduce in the following pages interacted with an "on-line" computing tradition that stands at the core of what is referred to as regulation, control, and automation. In reality, the development of on- and off-line computing interacted.[15] Fifth, the history of computing power transmission took place in several related directions. For example, computing the transmission of power for civilian purposes interacted with its military analogs, namely computing the transmission of power for military purposes, which was a key component of what is known as external ballistics or "fire-control" computing. When comparing the historiography of military fire control and civilian electric power transmission, once can surmise that the individuals and the institutions involved are the same.[16] Finally, the development of computations in technical environments interacted with the development of computations in scientific environments. For example, the network analyzer, which was devised for computing electric power networks, ended up being used in many scientific contexts. The experience gained through such uses fed back into the development of the network analyzer. I focus on a technical rather than a scientific computing environment because the historiography of technical computations is the

15. For an introduction to the invisibility of human labor in the history and historiography of the technology of on-line computing through negative feedback, the core of the ideology of self-regulation (self-control, automation), see Aristotle Tympas, "An Artificial Line, or Technology as Spectrology", *Antenna: Newsletter of the Mercurians, in the Society for the History of Technology*, 13 (2000), pp. 4–5, and 10. In the *Antenna* article, the artificial line is discussed through its use as an on-line computer, i.e. as a regulator, whereas in this one I focus on its off-line use as a computer. Reading David Mindell's recent history of electronic negative feedback amplification from the perspective of labor history suggests that underneath an elusive drive for automation laid a world of intensive and extensive engineering labor. See David Mindell, "Opening Black's Box: Rethinking Feedback's Myth of Origin", *Technology and Culture,* 41 (2000), pp. 405–434.

16. Read from the perspective of labor history, the rich historiography of fire-control computing points to another ocean of human labor, ranging, for example, from the computing labor of thousands of groups of soldiers and sailors who were skillfully using an anti-aircraft gun director by tracing the movements of an invading bomber, to the computing labor of the bombardiers who used computing bombsights. A uniform problem of the existing literature is that the emphasis is placed on the technical parameters of fire-control machines at the cost of providing us with knowledge of the skill required to use them. For a sample of the labor required to construct, use, and maintain bombsights such as the one used to drop the first atomic bomb, see Stephen L. McFarland, *America's Pursuit of Precision Bombing, 1910–1945* (Washington DC, 1995).

more understudied of the two. Taken together, the interactions mentioned in this paragraph indicate that the history of laboring with electric power transmission can offer us a privileged insight to the role of human labor in the history of a broader whole of complex computational processes.

"FRANKENSTEINS OUT OF CONTROL": A PERMANENT CRISIS OF COMPUTING LABOR

The step-up in computing complexity involved in the transformation from Edison's direct-current short-distance distribution to alternating-current long-distance transmission was considerable. As longer transmission schemes were tried and, accordingly, as transmission by alternating current and higher voltage were chosen, the labor of calculation was dramatically increased. "Engineers", wrote Jonathan Loki in his 1932 biography of Charles Steinmetz, "as yet were almost completely in the dark about how to calculate its values under practical conditions", and "they had to use the old faithful cut-and-try". "This", explained Loki, "was the dragon which Steinmetz undertook to tame".[17] For Leonard Reich, Steinmetz's Calculating Department was the "most important" research organization at General Electric during the 1890s.[18] However, a mere decade later, calculation was already too big a task for one department because of the frantic increase of the distance of alternating current transmission, and the Calculating Department could not catch up with the aggressive demand. Steinmetz's Calculating Department was dismantled and calculation became a distinct function within each department.[19]

Moving from the 1880s (Edison) and the 1890s (Steinmetz) to the 1900s, proposals for laying and interconnecting lengthy sections of electric lines into complex networks gathered speed. Engineers hastily sought to solve the ensuing computing labor crisis, and, in order to do so, devised more elaborate computing models of the networks to be build. The "artificial lines" and the "calculating boards" were typical examples of such models of the years between the 1900s and the 1920s.

Considerable labor was required to design, construct, and operate the artificial line. In his 1911 description of Union College's smooth artificial line, J.H. Cunningham described in detail the work required during each phase. In some instances, the mismatch between design and construction appeared quite mysterious. "A great amount of trouble", reported Cunningham at a 1911 AIEE conference, "has been caused by the breaking

17. See Jonathan Norton Leonard, *Loki: The Life of Charles Proteus Steinmetz* (New York, 1932), p. 131.

18. Leonard Reich, *The Making of American Industrial Research: Science and Business at GE and Bell, 1876–1926* (Cambridge [etc.], 1985), p. 58.

19. Ronald Kline, *Steinmetz: Engineer and Socialist* (Baltimore, MD, 1992), Part 2.

of tubes. After being completed and placed on the racks they would crack with no apparent cause." The solution to this problem inspired an extended research program on computing coils at MIT in the early 1920s.[20] Constructing an artificial line was so laborious that in many cases it required years. And the methods were never fail-safe; for example, the Harvard artificial line required many experimental trials before permanent installation. The engineers developing the University of Washington's artificial line resisted presenting their line at an AIEE conference until they tinkered with it for three years. Once the original designer left the company, the Telluride Power Company invested many additional years to complete their project. In 1923 Dellenbaugh presented MIT's artificial line, yet they had begun their construction as early as 1920.[21] Maintenance and operation were also affected by unpredictable instabilities. For example, in 1912 Arthur Kennelly and H. Tabossi reported that changes in temperature could produce serious disturbances. Inferring from the case of the broken Union College line coils, skill proved necessary even for mounting an artificial line. Mounting Harvard's line was not problem-free either. Evidently, details could make considerable difference – such as first carefully mounting the line's coils on a shelf and then arranging them vertically so that they were alternately perpendicular to one another because laying them so could minimize the unwanted action from mutual induction.[22]

Problems of this kind are what Dugald Jackson, the director of MIT's Electrical Engineering Department, had in mind when he referred to the history of the artificial power line as a "struggle".[23] Kennelly, the world's expert on the artificial power line, unceasingly emphasized the need to focus attention while laboring with seemingly unimportant details. In his textbook, he cautioned about the difference that improper plugging could make. Considering that some units would deviate considerably from the

20. See J.H. Cunningham, "Design, Construction, and Test of an Artificial Transmission Line", *AIEE Transactions,* 30 (1911), pp. 245–256, 251; and F.S. Dellenbaugh, "Artificial Lines with Distributed Constants", *AIEE Transactions*, 42 (1923), pp. 803–823.

21. See Arthur E. Kennelly and H. Tabossi, "Artificial Power-Transmission Line", *Electrical World,* 59:7 (17 February 1912), pp. 359–361, 359; Edward C. Magnusson and S.R. Burbank, "An Artificial Line with Adjustable Line Constants", *AIEE Transactions*, 35 (1916), pp. 1137–1153, 1138; George H. Gray, "Design Constructions and Tests of an Artificial Power Transmission Line for the Telluride Power Company of Provo, Utah", *AIEE Transactions*, 36 (1917), pp. 789–831, 791–792; and Dellenbaugh, "Artificial Lines with Distributed Constants".

22. Kennelly and Tabossi, "Artificial Power-Transmission Line", pp. 359–361.

23. Dellenbaugh, "Artificial Lines with Distributed Constants", p. 821. On Jackson and the MIT-General Electric partnership, see Bernard W. Carlson, "Academic Entrepreneurship and Engineering Education: Dugald C. Jackson and the MIT-GE Cooperative Engineering Course, 1907–1932", *Technology and Culture*, 29 (1988), pp. 536–567; and Karl L. Wildes and Nilo A. Lindgren, *A Century of Electrical Engineering and Computer Science at MIT, 1882–1982* (Cambridge, MA, 1985).

designed average, he suggested that it was better to place them away from the generator-end of the line because it was "very disconcerting to observers and computers to find certain sections far off the average".

In his 1925 *Bell Laboratories Record* article, Hoernel included a photo of two young men, Breivogel and Northrup, plugging an artificial communication line. They performed a job similar to what women computors would do in the 1940s when arranging ENIAC.[24] Underpaid electrical engineering undergraduates performed tasks such as winding coils, graduate and research assistants constructed the remainder and conducted a few experiments, while research directors made most experiments and designed nearly all the apparatus. For example, in the spring of 1910, Becker and Grover – two seniors in Union College's Department of Electrical Engineering – constructed 150 tubes. One could surmise that when the tubes broke, that engineers could demand better products. More than ten years later, L. Becker worked as a research assistant at MIT and supervised making coils with distributed constants. In the 1920s, M. Gardner and E. Arnold, two research assistants, carried out the first MIT tests with the artificial lines. Frederick Dellenbaugh, Jr, Director of MIT's Electrical Engineering Research Division, created the design for the single-phase line, while many extensive tests were carried out by his graduate students, Scott, Van Ness, and Jackson, who were supervised by Jones, another research assistant. Coffin and Buckner documented the design of the three-phase artificial line in their MIT graduate thesis and groups of graduate students later performed the test work.[25]

Upon experiencing the workings of computing pyramids, most students of electrical engineering later sought to reproduce them to their advantage. From 1900 to 1910, Kennelly and his dissertation advisee, Vannevar Bush, offer the classic example of a "top analyst". Another of Kennelly's graduate students from the 1910s, Edith Clarke, also offers the classic example of an electrical engineer who struggled to enter the electrical engineering computing pyramid from below, i.e. from the ranks of the computors. Sexism contributed considerably to an essentialist demarcation between analysts and computors. The fortunes of a female electrical engineer, Clarke – who had the same age, intelligence, and desire to learn as did her counterpart Bush – can help us to understand how such demarcation could be created.

In his 1919 letter to Steinmetz, Dugald Jackson recommended Clarke as an expert in power transmission analysis:

24. For Kennelly, see Arthur E. Kennelly, *Electric Lines and Nets: Their Theory and Electrical Behavior* (New York, 1925), pp. 220–221. On plugging the ENIAC, see Light, "When Computers Were Women".

25. See Cunningham, "Design, Construction, and Test of an Artificial Transmission Line", p. 249, and Dellenbaugh, "Artificial Lines with Distributed Constants", p. 805.

> Dr Kennelly tells me that Miss Clarke has been an uncommonly competent student in Mathematics and allied branches, and that she has done excellent research in connection with the characteristics of power transmission as represented by our artificial transmission lines. She is proposing to communicate with you for the purpose of seeing whether there may not be a need for such a mind as hers in connection with your work.[26]

Regardless, the best that Clarke could do upon completing her 1919 thesis, entitled "Behavior of a Lumpy Artificial Line as the Frequency is Indefinitely Increased", was to upgrade her status to "computor". The relationship between alternating current frequency and computing accuracy was the thorniest issue during the 1910s. Unless we turn to the ideology that perpetuated women's inferiority, which contributed to the division-of-labor pyramidization, we cannot explain why Edith Clarke could not find any job as an electrical engineer. Yet, Clarke's career was, as the knowledgeable James Brittain commented, "remarkable". In 1918, Clarke was the first woman to earn an electrical engineering degree from MIT and was awarded her MS in 1919. Although she obtained these degrees, Clarke fought a battle to move, first, from computor to the rank of the electrical engineer, and, subsequently, to move from engineer to the superior rank of the analysts.[27] Clarke contributed substantially to electrification computing technology. Evidently, her exposure to artificial line-related computing began well before earning her MS. After her first year as an engineering undergraduate in 1911 at the age of 28, George Campbell, who had computed the principle of the loading coil by using an artificial line, hired her for the summer as a computer assistant.[28] For most of that decade, Clarke worked as a computor in crash projects devoted to computing the long distance transmission of communication. The division of labor between analysts like Campbell and computors like Clarke – and among the various computors like Clarke and her colleagues – confirms what we know about other, non-engineering computing projects that employed computors in both governmental and private contexts, scientific or otherwise. In all these cases, we find a division-of-computing labor

26. For Dellenbaugh and Bush, see Karl L. Wildes and Nilo A. Lindgren, *A Century of Electrical Engineering and Computer Science at MIT, 1882–1982* (Cambridge, MA, 1985), p. 68. For Jackson's letter see Edith Clarke's file at the General Electric Archives (Schenectady, New York).

27. See Edith Clarke, "Behavior of a Lumpy Artificial Line as the Frequency is Indefinitely Increased", (unpublished manuscript, Massachusetts Institute of Technology, 1919); James E. Brittain, "From Computor to Electrical Engineer: The Remarkable Career of Edith Clarke", *IEEE Transactions on Education*, E–28:4 (1985), pp. 184–189; and Edward L. Owen, "Edith Clarke: Pioneer Woman Engineer", *IEEE Industry Applications Magazine*, 1:3 (1995), pp. 40–43.

28. On how Campbell employed the artificial line, see James E. Brittain, "The Introduction of the Loading Coil: George A. Campbell and Michael I. Pupin", *Technology and Culture*, 11 (1970), pp. 36–57.

pyramid, with the women computors remaining invisible even though they may have possessed a college education. After a period of unemployment following her graduation from MIT, Clarke herself organized and managed one such computing pyramid at General Electric from 1919 to 1921.[29]

We know the names of some computors like Clarke and the mathematician Gertrude Blanch because there was something remarkable in both women that had nothing to do with their work as computors. Like Clarke, Blanch started as a top computor to become a top analyst. Had she not become an analyst, Clarke might have also been unknown. For more examples of women computors who worked to produce engineering computations in general and electric power transmission in particular, i.e. for computors who remain historiographically invisible, one would have to pay attention, literally, to the footnotes of computing treatises authorized by male analysts. A footnote in one of Kennelly's handbooks on electrical engineering computations in the 1910s offers a representative example. Kennelly wrote this handbook series to present computations based on artificial lines. They included a book with computing equations (applications of hyperbolic functions to electrical engineering), a book with computing tables (tables of complex hyperbolic and circular functions), a book with computing graphs (chart *Atlas* of complex hyperbolic and circular functions), and a book on the theory, mode of construction, and uses of artificial lines. In the 1914 preface to the first edition of his handbook on electrical engineering computing tables, Kennelly proudly stated that to solve the same electrical engineering computing problem, "to a like degree of precision without aid from these functions, and by older methods, would probably occupy hours of labor and cover several sheets of computing-paper".[30]

Valuable computing labor could be saved by using Kennelly's tables. But vast computing labor had been appropriated to produce these handbooks in the first place. In an explanatory appendix, Kennelly confessed that the steps between computations were larger than he originally intended because his applications for financial assistance were unsuccessful. Without financial assistance, Kennelly's computational

29. For Clarke's talk, see Edith Clarke, "Trends in Power System Analysis", *Midwest Power Conference Proceedings*, 7 (1944), pp. 172–180. For her work as a computor and as a manager of computors, see Brittain, "From Computor to Electrical Engineer: The Remarkable Career of Edith Clarke", and Owen, "Edith Clarke: Pioneer Woman Engineer".

30. Arthur E. Kennelly, *The Application of Hyperbolic Functions to Electrical Engineering Problems* (New York, 1925) (first edited in 1912 and re-edited in 1919); *idem*, *Tables of Complex Hyperbolic and Circular Functions* (Cambridge, MA, 1914), *idem*, *Chart Atlas of Complex Hyperbolic and Circular Functions* (Cambridge, MA, 1914), and *idem*, *Electric Lines and Nets: Their Theory and Electrical Behavior*. For the quoted passage see, *idem*, *Tables of Complex Hyperbolic and Circular Functions*, Preface.

project was enormous; for example, to control against errors, all computing of the tables were computed twice by using two different formulas of the computing equation. All the tables were subsequently reduced to graphic form in the book with the computing charts – which Kennelly called the *Atlas* – by marking off each entry of the tables on its proper chart with a sharp needle. Then a ruling pen was drawn through the successive punctures. The graphs (charts) of Kennelly's *Atlas* of electrical engineering were not a passive picture of the tables, because in the process of drawing errors were discovered and rectified. Thus, computing tables were computed three times before they were set in type. After this, the tables were proofread three times again. As Kennelly explained, if the two initial computations differed, "the steps of the computation were gone over afresh".[31] Who provided the devaluated labor power required for this project, given that money was scarce? We cannot learn the answer to this question by reading Kennelly's preface, in which he mentions some of his fellow electrical engineering analysts who exercised an indirect influence on his computing project. To learn who exercised the direct influence we would have to stumble luckily across the appendix footnote on page 209. There, in small letters, Kennelly wrote that he "desired to express his acknowledgment" to four women computors for "the care and painstaking efforts of his assistants engaged in computation, namely Miss Ethel Smith, A.B. Radcliffe, 1911, Miss A.F. Daniell, A.B. Radcliffe, 1911, Miss Mary M. Devlin, A.B. Radcliffe, 1912, and Miss Hope M. Hearn, A.B. Radcliffe, 1912".[32] If Edith Clarke's case points to the internal limit within the electrical engineering computing pyramid, their cases point to the external limit of this pyramid. In other words, since they lack a meaningful history, we can only elaborate on Clarke's exceptional case.

The computational project that Kennelly completed in the 1910s, with the publication of his series of handbooks, actually started much earlier. The first mention of the potential use of artificial lines in the context of power transmission goes back to 1895. We get an idea of how much computing labor would eventually be stored in Kennelly's computing handbooks by considering how impressed the 1895 discussants were who noted the vast work required to produce a single computing graph. One of the discussants, the physicist Arthur G. Webster, began his comments by acknowledging that computing required much labor:

> Not being an engineer myself, and not knowing engineers as well as I wish I did, I had supposed that an engineer was an extremely busy man and that he was mostly occupied in doing practical things which brought him in a certain amount of very pleasant returns which are not open to people in my position. But I came to the conclusion that there are engineers who delight in doing other things, who

31. Kennelly, *Tables of Complex Hyperbolic and Circular Functions*, p. 102.
32. *Ibid.*

> are willing to do arithmetic, which I may say for myself I find a terrible grind. If I have been fortunate enough to get certain experimental results and put them down in my notebook, when it comes to working the calculations over, I should prefer to send them several hundreds miles rather than do it myself. But I have come to the conclusion that business is probably a little slack in Philadelphia. I have always had the impression that there were more hours in the day in Philadelphia than in New York. But I see that there must be many more days in the week, and if I might take the liberty I should be glad to ask Mr Kennelly privately how long it took him to draw that diagram. I was extremely interested in that part.[33]

In his reply, Kennelly proudly shared the story of the machine that he imported in order to plot Plate 1: "In order to draw that diagram", explained Kennelly, "we had to send to Europe for a machine. We could not find anywhere in this country a machine which would draw the lines accurately enough." Yet, the machine could not draw the lines by itself. A human was needed to guide it. Kennelly, however, mentioned nothing in public about the computing labor required to produce Plate 1. The computing labor story was indeed to be discussed "privately".[34]

Kennelly argued that:

> [...] it may be said that hyperbolic functions [...] have risen from the state of theory [...] to a stage of practical utility; because problems which would take hours of labor to solve by other methods, may be solved in a few minutes by the use of the hyperbolic tables and curve sheets.

He appraised his computing artifacts by portraying them as "a practical engineering tool of great swiftness and power". For comparison, as was customary, he contrasted his computing technology to computing by a slide rule. The savings in living labor seemed impressive: "In fact, with the atlas [containing the computing graphs] open at the proper chart, any complex hyperbolic function can be read off within a few seconds of time, ordinarily, to at least such a degree of precision as is offered by a good 25-centimeter slide rule."[35] However, Kennelly's comparison failed to note a whole series of parameters (e.g. portability of the slide rule, specificity of slide-rule scales to concrete computing works, and, above all, price, which could determine who would be the owner of the means of computing production) that persuaded electrical engineers to prefer a slide rule to everything else. This preference held for many subsequent years. An incredible variety of slide rules, including those that calculated electric power transmission, would remain for years the most popular computing

33. Edwin Houston and Arthur Kennelly, "Resonance in Alternating Current Lines", *AIEE Transactions*, 12 (1895), pp. 133–169, 160–161.
34. *Ibid*., p. 168.
35. Kennelly, *Application of Hyperbolic Functions to Electrical Engineering Problems*, p. vii.

artifact, and the tools always provided the standard reference of computing comparisons.[36]

In presenting Westinghouse's first calculating board, W. Woodward explained that it was constructed for cases "when calculations are very lengthy and in a few cases practically impossible".[37] The mechanical method of computing with a calculating board is "convenient", clarified R. Evans in an attached 1919 *Electric Journal* article, but "the initial cost" and its unavailability demanded that progress in new mathematical-analytical methods was also necessary.[38] Evans kept returning to advances within analytical methods "to reduce the labor of calculations" when the board was not available,[39] while others kept improving the calculating board since "analytical solutions are laborious".[40] Only ten years after the introduction of the first calculating board to remedy these laborious calculations, the Westinghouse engineers introduced another calculating board, an alternating current variety, as a device that "would reduce to a minimum the tedious mathematical calculations now involved".[41] The story was identical for the General Electric electrical engineers. After introducing their first calculating board in 1916 as a solution to computing "complexity",[42] and after justifying a series of modifications as solutions to the fact that "the mathematical methods were very laborious and often impossible of application",[43] they and their MIT partners would, by 1925, find that "the size and complexity of present-day power systems have increased to the point where the prediction of the behavior of the system by analytical methods is more and more difficult" and the calculating table is "too inaccurate".[44] By 1930, they were prepared to introduce their own alternating current calculating board – baptized the "network analyzer" and ceremoniously presented at MIT to emphasize how revolutionary a machine it was. It too was offered as the solution to "lengthy and usually impracticable mathematical calculations".[45]

36. See Tympas, "The Computor and the Analyst", ch. 7.

37. W.R. Woodward, "Calculating Short-Circuit Currents in Electric Networks: Testing with Miniature Networks", *Electric Journal*, 16 (1919), pp. 344–349, 345.

38. Robert D. Evans, "Analytical Solutions", *Electric Journal*, 16 (1919), pp. 345–349, 346.

39. *Idem*, "Analytical Solution of Networks", *Electric Journal*, 21 (1924), pp. 149–154, 150.

40. I.T. Monseth and R. De Camp, "Short-Circuit Calculating Tables: Of the Variable Resistor Unit, Direct Current Type", *Electric Journal*, 23 (1926), pp. 299–305, 299.

41. H.A. Travers and W.W. Parker, " An Alternating Current Calculating Board", *Electric Journal,* 27 (1930), pp. 266–270, 266.

42. Anon., "A Device for Calculating Currents in Complex Networks of Lines", *General Electric Review*, 19 (October 1916), pp. 901–902, 901.

43. W.W. Lewis, "Calculation of Short-Circuit Currents in Alternating-Current Systems", *General Electric Review*, 22 (February 1919), pp. 140–145, 140.

44. H.H. Spencer and H.L. Hazen, "Artificial Representation of Power Systems", *AIEE Transactions*, 64 (1945), pp. 72–79, 72.

45. H.I. Hazen, O.R. Schuring, and M.F. Gardner, "The MIT Newtork Analyzer", *AIEE Transactions*, 48 (1929), pp. 1102–1114, 1102.

In 1935, those at Commonwealth Edison reported "savings approximately eight times is installed costs in two years of operation".[46] In his sales pitch, General Electric's Robert Treat claimed that "by using this specialized algebra machine the saving in labor is so great that many problems may now be solved fairly rapidly which would not be undertaken at all without it".[47] Several variations were introduced throughout the 1930s, all as a response to the evidently persistent need for "longhand methods", which were "generally laborious – frequently, sufficiently laborious to greatly curtail the scope of the study and at times to prevent the study being made altogether".[48] Amidst the Great Depression that offered an abundant supply of labor, the computing labor crisis persisted. General Electric's R. Slinger introduced another network analyzer variant because "longhand calculations requires an infinite amount of patience and an almost prohibitive amount of time".[49] Reports on improvements made it into the late 1940s and beyond.[50] A balanced and inclusive account of the impressively long list of uses for calculating boards and network analyzers was offered by General Electric's H. Peterson and C. Concordia immediately after the war: "[w]ithout the use of these modern devices", they remarked in 1945, "many investigations would not be undertaken simply because the amount of work and time required to arrive at satisfactory quantitative conclusions would be prohibitive".[51]

The same finding was reported with flourish during the same year in an article in the *General Electric Monogram*, entitled "Beyond Human Calculation":

> In one of the General Office buildings in Schenectady there is a door that might well be marked "through this portal pass power company representatives from all over the world": The door is labeled simply "A–C Network Analyzer". This means little or nothing to the average passer by; but to power company men it means the solution of problems too difficult for human calculation, and the savings of many thousand dollars.

This "modern electrical brain" was presented as an "infallible arbiter" that "in a few hours can perform calculations that ordinarily require weeks or months". According to the *General Electric Monogram* article, more than

46. T.G. Leclair, "Board Earns Eight Times Its Cost", *Electrical World*, (23 November 1945), pp. 28–29, 28.
47. Robert Treat, "Critical Analysis of System Operation Improves Service and Saves Money", *General Electric Review*, 41 (July 1938), pp. 306–311, 307.
48. H.P. Kuehni and R.G. Lorraine, "A New A–C Network Analyzer", *AIEE Transactions*, 57 (1938), pp. 67–73, 67.
49. R.N. Slinger, "Network Analyzer Points", *Electrical World*, (16 July 1938), pp. 30–32, 30.
50. W.A. Morgan, F.S. Rothe, and J.J. Winsness, "An Improved A–C Network Analyzer", *AIEE Transactions*, 68 (1949), pp. 891–897.
51. H.A. Peterson and C. Concordia, "Analyzers [...] For Use in Engineering and Scientific Problems", *General Electric Review*, 48 (September 1945), pp. 29–35, 29.

Figure 1. Electrical engineers renting and using a network analyzer in the early 1940s. A General Electric 480-cycle A–C network analyzer set-up for the Virginia Public Service Co. in March 1941.
General Electric Archives (Schenectady, New York), Filing no. 170D, 8851; used by permission

100 companies and industrial power companies and concerns had rented it to carry out more than 300 hundred investigations. In its 7-year tenure at the Central Station Engineering Division, the network analyzer had become "a proving ground for engineers' ideas".[52]

The fate of the network analyzer was not, however, different from that of the machines already considered above. On a more cautious note than that of the promotional *Westinghouse Engineer* (1944) and *General Electric Monogram* (1945) editorials, which ideologized the network analyzer as the ultimate "brain", an *Electrical World* editor warned (1946) that it was "no substitute for brains and must be operated by engineers who can recognize a problem, plan, analyze and carry through its investigation".[53] John Casazza's memoirs, offered on the occasion to protest the transition from the network analyzer to the electronic computer, suggest that computing with the network analyzer was not "beyond human calculation", in fact the opposite is true. "The skill of the person doing the network analyzer analysis", argued the veteran electrical engineer, "was enhanced considerably" by "short-cut methods". He

52. "Beyond Human Calculation", *General Electric Monogram*, 22:1 (1945), p. 25.
53. Braymer, "Today's Network Calculators Will Plan Tomorrow's Systems", p. 52.

added, "along with the development of this skill came a better fundamental understanding of how the network operated". This understanding for Casazza was akin to "surgical skills", having to do with "ability to go into a network and search only the specific answer needed". Although disagreeing with what he perceived to be a substitution of digital "speed for brains", Casazza clarified that computing with the network analyzer, a machine promoted as the "brain", the brains were actually human.[54]

The ongoing interconnection of regional networks into inter-regional pools, national and international, was creating a computing complexity that exacerbated the pressure for advance towards the digital direction. In the mid-1940s, paralleling the plans for establishing numerous network analyzer laboratories, the electrical engineering community kept an open eye for alternatives. The analyzers, informed Philip Jennings and George Quinan, engineers at the Puget Sound Power and Light Company, "have afforded welcomed relief from tedious calculations", but since they were not located conveniently, power engineers still had to use "longhand methods". Their method involved a "large amount of labor" – labor that could be, hopefully, mechanized by the use of digital electromechanical machinery (punched-card machines).[55] L. Dustant, an engineer at the Federal Power Commission, ran tests on how to replace the network analyzer with calculating machines and punched-card machinery.[56] Electrical engineers needed not merely the mechanization of the old techniques of hand calculation, but development of new techniques. A decade later the complaints became loud and clear. "With the expansion and increase in complexity of power systems throughout the country", wrote D. Johnson and J. Ward of the University of Washington and Purdue University respectively, "a more accurate and less time-consuming means of determining the transient stability characteristics of power networks is required". The network analyzer, which they were now calling an "analog computer", was introduced by the two engineers as an exemplar of the past – the "immediate past", but, nevertheless, the past.[57]

It was only on the condition of existing precalculation that the digital was advantageous. In the absence of such precalculation, engineers like Bonneville's Rodney Brown and William Tinney stopped short at simply outlining the requirements for the successful introduction of the digital.[58]

54. John A. Casazza, *The Development of Electric Power Transmission* (New York, 1993), p. 78.

55. Philip D. Jennings and George E. Quinan, "The Use of Business Machines in Determining the Distribution of Load and Reactive Components in Power Line Network", *AIEE Transactions*, 65 (1946), pp. 1045–1046, 1045.

56. L.A. Dunstan, "Machine Computation of Power Network Performance", *AIEE Transactions*, 66 (1947), pp. 610–624, 610.

57. J. B. Johnson and J. B. Ward, "The Solution of Power System Stability Problems by Means of Digital Computers", *AIEE Transactions*, 76 (1957), pp. 1321–1329.

58. Rodney J. Brown and William F. Tinney, "Digital Solutions for Large Power Networks", *AIEE Transactions*, 76 (1957), pp. 347–355, 347.

Even if we assume that appropriate digital hardware was available at competitive cost, producing the software to run on such a machine was definitely emerging as a key issue. The first programs for computing electric power transmission addressed the needs inadequately. Westinghouse's Long, Byerly, and Rindt, welcomed the "tremendous power of large-scale digital computers" only to admit that their use could only be partial due to the lack of appropriate programs to run them.[59] As late as in 1963, in discussions of the first digital computer programs for computing the complex problems like the stability of electric power transmission, engineers acknowledged that there was still a "serious limitation" in the field.[60] In his 1957 introduction to using digital computers for the easier short-circuit calculations, M. Lantz, who was with the Bonneville Power Administration, clearly stated that the advantages of the digital – speed, accuracy, and the ability to be operated without highly trained professional personnel" – rested in necessary "pre-calculation".[61]

The best way to relate how much and what kind of labor was involved in the shift from analog hardware (analyzer) to digital software of the computer is to study the panel papers on these artifacts within the volumes of the *Proceedings of the American Power Conference* during the 1950s and 1960s. By way of introducing to the continuity between working with the old analog network analyzer and the new digital computer, I refer to what several General Electric's network analyzer old-timers had to report about "training electric utility engineers in the application of digital computers". For G. Carter, C. Concordia, and F. Maginnis, who had experimented with early digital computers in 1946,

> [...] the engineer must have had some actual experience in problem reduction, flow diagramming, programming, and checking out if he is to be in good position not only to recognize the possible applications but also to distinguish between those that are really worthwhile and those that are not yet economically feasible.

"Without such training", they explained, "there has been a tendency to go to the extremes of thinking that either all or none of his problems were suitable computer applications".[62] To provide such training, they started a digital computer course at General Electric, which, by 1963 had graduated over 100 engineers.[63] The passage to the digital was all but effortless.

59. R.W. Long, R.T. Byerly, and L.J. Rindt, "Digital Computer Programs in Electric Utilities", *Electrical Engineering*, (September 1959), pp. 912–916, 912.
60. A.J. McElroy and R.M. Porter, "Digital Computer Calculation of Transients in Electric Networks", *AIEE Transactions*, 82 (1963), pp. 88–96, 95–96.
61. M.J. Lantz, "The Digital Computer and Power System Short-Circuit Calculations", *Electrical Engineering*, (November 1957), pp. 981–983, 981.
62. G.K. Carter, C. Concordia, and F.J. Maginnis, "Training Electric Utility Engineers in the Application of Digital Computers", *Proceedings of the American Power Conference*, 25 (1963), pp. 834–847, 835–836.
63. *Ibid.*, p. 837.

Engineers considering converting to the digital computer would have to labor hard, since the course was intensive.[64]

In 1959, Westinghouse engineers reported a service through its analytical department, which was organized around paying for the use of an electronic computer in the same manner that the use of the network analyzer.[65] Their problem in developing such a service suggests that the change in the technical vocabulary has left the process of the dynamic reproduction of the computing labor crisis intact. "The necessary work", admitted the Westinghouse engineers, "in preparing for a program release could delay the actual release by many months from the time when the program would be available for use on a service bureau basis."[66] In this case, I interpret one typical early instance of the computing labor crisis known as the "software crisis". The software crisis surfaced when one more machine – the computer introduced in the 1940s – soon turned out to be more of the same. By the late 1950s, a decade after the emergence of the analog-digital demarcation, digital won the battle. Yet, by then the software–hardware split had emerged, and along with it, the associated "software crisis", which is a computing labor crisis that has marked the history of computing since then.[67]

CONCLUSION

The most celebrated attempt at constructing a calculating machine during early industrial capitalism was that of Charles Babbage. Despite several studies that insightfully relate Babbage's calculating machines to his views on capitalist industry, it has to date escaped attention that there are actually computors in Babbage's scheme. Babbage called them "attendants", and, as the term implies, he thought of them as exercising no influence in the computing process.[68] As is well known, Babbage failed to have such a machine constructed. The first commercially available calculating machine of industrial capitalism, the Thomas de Colmar Arithmometer, was similar in principle to one of the infamous first calculating machines of merchant capitalism, that of G.W. Leibnitz. Leibnitz introduced his machine by arguing that "it is unworthy of excellent men to lose hours like slaves in the labor of calculation, which could safely relegated to anyone else if the

64. For a brief historical overview on the introduction of digital computers to the context of computing electric power networks, see Glenn W. Stagg and Ahmed H. El-Abiad, *Computer Methods in Power System Analysis* (New York, 1968), pp. 1–2.
65. Long, Byerly, and Rindt, "Digital Computer Programs in Electric Utilities", p. 916.
66. *Ibid.*
67. For an introduction to the history of the software crisis, see Paul Ceruzzi, *A History of Modern Computing* (Cambridge, 1998).
68. On Babbage's attendants, see Charles Babbage, *The Exposition of 1851: Views of Industry, The Science and the Government of England* (London, 1851), p. 169.

machine were used".[69] This indicates that from before the beginning, the calculating machine existed as a split between "excellent men" and a "slave", who could be "anyone else". As, however, there are no slaves in capitalism, those to populate the lower places in the hierarchy of computing with such machines were searched in the ranks of devaluated free workers.[70] These free workers could be women computors like the ones mentioned above, victims of the hegemony of an ideology that blended successfully the time-honored ideology of sexism with that of technological determinism.

The fact that one can find so many references to the computing labor crisis suggests that there were many computing laborers involved in the history of pre-40s computing. Labor historians might choose to place emphasis on political struggles in which these workers become involved – struggles of a classic political form (e.g. unions) or struggles exemplifying other forms of political resistance and organization (struggles more passive than unionism, but, at times, even more effective, e.g. careless use of sensitive computing machinery). Seeking to reach common ground with labor history after starting from history of technology, I suggest a less standard approach. In addition to retrieving as many as possible of those technicians that were consciously hidden by the (visible) writings of their masters,[71] I propose that we interpret the role of technicians by what their masters unconsciously wrote in their most visible writings. Accordingly, in the pages above, I have relied extensively on what top-ranking electrical

69. Leibnitz quoted in David Eugene Smith, *A Source Book in Mathematics* (New York, 1929), pp. 180–181.

70. From the rich literature on the blend of technological determinism and sexism, I find useful Katherine Stubbs's account of the technocratic rhetoric that aimed both at mechanizing work and, at introducing women as physiologically suitable for it, on the grounds of them being naturally tolerant to repetitive-monotonous jobs requiring manual dexterity. Stubbs refers to industrial female work in general, but what she finds seems appropriate for introducing to the general context of the labor of the lowest-ranking human computors (the majority of whom were women), whose work was uniformly considered to be the *par excellence* province of manual dexterity, tolerance to monotony, and undemanding intellectually; Katherine Stubbs, "Mechanizing the Female: Discourse and Control in the Industrial Economy", *Differences*, 7 (1995), pp. 141–163. For a introduction to how women's intellect was, from the commencement of modern capitalism, ideologized as suitable to such tasks, see Lorraine Daston, "The Naturalized Female Intellect", *Science in Context*, 5 (1992), pp. 209–235. In her study of Gaspar De Prony's division-of-computing-labor scheme, Daston focuses specifically on the effects of this ideology in the compound attempts at mechanizing calculation while devaluating it as unworthy intellectually. Daston's references to nineteenth-century bureaucratic projects of calculation that were inspired by De Prony's scheme – works that included the employment of women computors – conveniently sets the stage for the literature on women computors in subsequent contexts. See Daston, "Enlightenment Calculations".

71. For an original argument about the consciously hidden "invisible technicians", see Steven Shapin, *A Social History of Truth: Civility and Science in Seventeenth-Century England* (Chicago, IL, 1995).

engineers had to say about the computing labor crisis within electric power transmission on the occasion of introducing new analyzers.

In studying the repeated attempts at mechanizing "electrical computations", I find evidence of the prevalence of a mode of producing computations marked by the restless introduction of computing machines – each of which introduced with much clamor as, supposedly, to bring about an end to human labor – before it was silently withdrawn to make room for the perennially cacophonous introduction of a subsequent device. I would suggest that we give serious attention to the hypothesis that the information revolution (of which the computing revolution is a core component) is integral to capitalism as a whole. Specifically, I suggest that the popular divide between an industrial and an information revolution (and the associated assumption for a passage to a post-capitalist order) is perhaps untenable: the industrial revolution was, from the beginning, an information revolution.[72]

72. For an introduction to the broader historiography of the information revolution that is sensitive to the continuity beyond the analog-digital demarcation see Greg Downey, "Virtual Webs, Physical Technologies, and Hidden Workers: The Spaces of Labor in Information Internetworks", *Technology and Culture*, 42 (2001), pp. 209–235.