CALCULATION AND THE DIVISION OF LABOR, 1750-1950

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I. The Strange Death of Calculation

The scene is a school room, in almost any epoch and any locale: it might be the house of an ancient Babylonian scribe, in which father taught son in learned lineages that stretched over centuries; or in Song Dynasty China, as students prepared for the imperial civil service examinations; or in fourteenth-century France, where an allegorized *Geometria* instructed cathedral school pupils; or nineteenth-century Prussia, whose schoolmasters had allegedly delivered a military victory over the French in 1870. In all of these classrooms, dispersed over centuries and continents, students would have been taught some version of the three fundamental cultural techniques that underlie all other cognitive practices in literate societies: reading, writing, and calculation. We have rich and vast histories of reading and writing; yet we barely have the rudiments of a history of calculation. Why not? This lecture is an attempt to answer that question.

The puzzle of why we lack a history of calculation is deepened by the fact that our oldest evidence for writing systems, for example from ancient Mesopotamia and the Mediterranean, suggests that alphabets are parasitic upon numerals. Somewhat disappointingly, many of the earliest surviving texts in Sumerian (c. 3500 BCE) and other ancient languages record not great epics like the *Gilgamesh* and the *Iliad* but rather what sound like merchants' receipts: five barrels of wine, twenty-two sheepskins, and so on. The earliest use of reading and writing appears to have been to keep track of calculations, mostly for commercial and administrative purposes. Yet today, in the age of hand-held electronic calculators and calculating apps, mental calculation has almost disappeared as a widespread cognitive practice, even from the classroom. Our online lives are dominated by reading and writing to an extent probably unprecedented in world history: these culture techniques have weathered and indeed flourished under successive media revolutions, from printing to digitalization. But calculation, the third pillar of the scribal triumvirate, has almost ceased to count as an intellectual activity. How did this happen?

II. Twinned at Birth: Artificial Intelligence and the Division of Labor

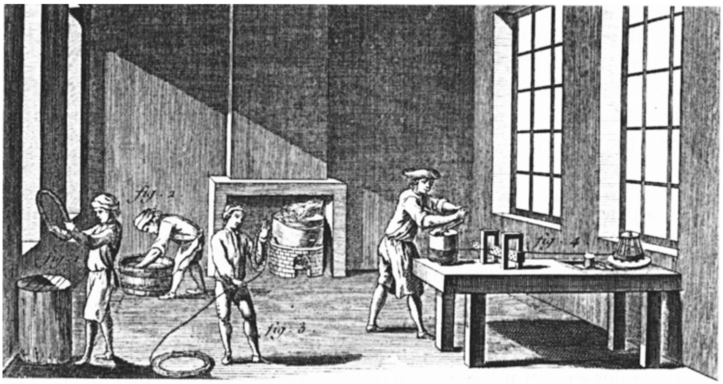

Figure 1. "Fabrication des épingles," D. Diderot & J. d'Alembert, *Encyclopédie ou Dictionnaire raisonné des sciences, des arts et des métiers* (1751–1780).

Calculation did not die a sudden death. This image (Figure 1) of how pins were made in France in the mid-eighteenth century represents the moment two concepts that made the modern world were born: the division of labor and the computer. Here is the well-known story in a nutshell, in three short acts.

Act I: This image and the accompanying article on pins in the great *Encyclopédie* of Jean d'Alembert and Denis Diderot were taken from studies made by the French engineer Jean-Rodolphe Perronet, first director of the École des Ponts et Chaussées.[1] Adam Smith, then professor at the University of Glasgow, adapted material from the *Encyclopédie* article and its sources in the famous first chapter on the pin factory and the division of labor in *The Wealth of Nations* (1776).[2]

Act II: Another French engineer, Gaspard Riche de Prony, Perronet's protegé and eventually successor at the École des Ponts et Chaussées, read Smith's account of pin-making and the division of labor, and applied those methods to the calculation of some two-hundred-thousand logarithms to at least fourteen decimal places, a project launched in 1791 during the French Revolution as a monument to the new decimal metric system. Inspired by his reading of *The Wealth of Nations*, Prony decided to "manufacture my logarithms as one manufactures pins."[3] He created a pyramid of laborers (Figure 2) divided into three classes: at the pinnacle, a few "mathematicians of distinction" who developed the general formulas for calculating the logarithms by the method of differences; at the second level, seven or eight "algebraicists" trained in analysis who could translate the formulas into numerical forms that could be computed; and at the

1 Jean-Rodolphe Perronet, *Description de la façon dont on fait les épingles à Laigle en Normandie* (1740), Bibliothèque de l'École des Ponts et Chausées, MS 2385; cited in Antoine Picon, "Gestes ouvriers, opérations et processus techniques: La vision du travail des encyclopédistes," *Recherches sur Diderot et sur l'Encyclopédie* (13 October 1992): 131-147, on 134-135. Although the plates come from Perronet, the author of the article in the *Encyclopédie* was Alexandre Deleyre, who drew on work by Perronet and others.

2 Smith's chief source was also Delyre's: the article by Henri-Louis Duhamel du Monceau, Jean-Rodolphe Perronet, and René Antoine Ferchault de Réaumur on pinmaking in Philippe Macquer, ed., *Dictionnaire portatif des arts et métiers* (Paris, 1766): Frank A. Kafker and Jeff Loveland, "L'Admiration d'Adam Smith pour l'*Encyclopédie*," *Recherches sur Diderot et sur l'Encyclopédie* 48 (2013): 191-202.

3 Gaspard de Prony, *Notices sur les grandes tables logarithmiques et trigonométriques, adaptées au nouveau système métrique décimal* (Paris, 1824), 5.

broad base, seventy or eighty "workers" knowing only elementary arithmetic who actually performed the millions of additions and subtractions and entered them by hand into seventeen folio volumes.[4]

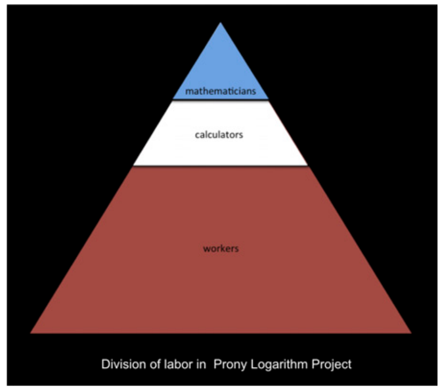

Figure 2. Pyramid of Prony logarithm project, Gaspard de Prony, *Tables des logarithmes*, Bibliothèque de l'Observatoire de Paris.

Act III: Prony's project greatly impressed the British mathematician and political economist Charles Babbage, who suggested that the workers at the base of the pyramid could be replaced by "machinery, and it would only be necessary to employ people to copy down as fast as they were able the figures presented to them by the engine."[5] In his treatise *On the Economy of Machinery and Manufacture* (1832), Babbage returned to the Prony logarithm project as his primary proof that the principles of the division of labor could be applied "both in mechanical and mental operations." Indeed, Babbage argued, the calculations of Prony's third class of workers "may almost be termed mechanical," even if they hadn't been done by actual machines.[6] Human intelligence sunk to the mechanical level, kindling the idea of machine intelligence. Thus was hatched the idea of Babbage's Difference Engine (Figure 3), hailed by Babbage's contemporaries for substituting "mechanical performance for an intellectual process" and by historians as the ancestor of the modern computer.[7]

So far, so familiar. But the intertwined histories of the division of labor and mechanical intelligence neither began nor ended with this famous three-act story from pins to computers via logarithms. Long before Prony thought of applying Adam Smith's political economy to monumental calculation projects, astronomical observatories and nautical almanacs were confronted with mountains of computations that they accomplished by the ingenious

4 On the history of the Prony project, see Prony, *Notice*; Ivor Grattan-Guiness, "Work for Hairdressers: The Production of de Prony's Logarithmic and Trigonometric Tables," *Annals of Computing*, 12 (1990): 177-185; and Lorraine Daston, "Enlightenment Calculations," *Critical Inquiry* 21 (1994): 182-202. The fullest account of the calculations is given in F. Lefort, "Description des grandes tables logarithmiques et trigonométriques, calculées au Bureau de Cadastre, sous le direction de M. de Prony, et exposition des méthodes et procédés mis en usage pour leur construction," *Annales de l'Observatoire Impérial de Paris* 4 (1858): 123-150.

5 Charles Babbage, "A Letter to Sir Humphry Davy, Bart., President of the Royal Society, on the application of machinery to the purpose of calculating and printing mathematical tables," (1822), in Charles Babbage, *The Works of Charles Babbage*, ed. Martin-Campbell-Kelly, 11 vols., v.2, 6-14, on 12.

6 Charles Babbage, *On the Economy of Machinery and Manufactures* [1832], 4th ed. (London, 1835), 195, 201.

7 Henry Thomas Colebrooke, "Address on Presenting the Gold Medal of the Astronomical Society to Charles Babbage," *Memoirs of the Astronomical Society* 1 (1825): 509-512; reprinted in Babbage, *Works*, v. 2, 57-59, on 57; Martin Campbell-Kelly and William Aspray, *Computer: The History of the Information Machine* (New York, 1996).

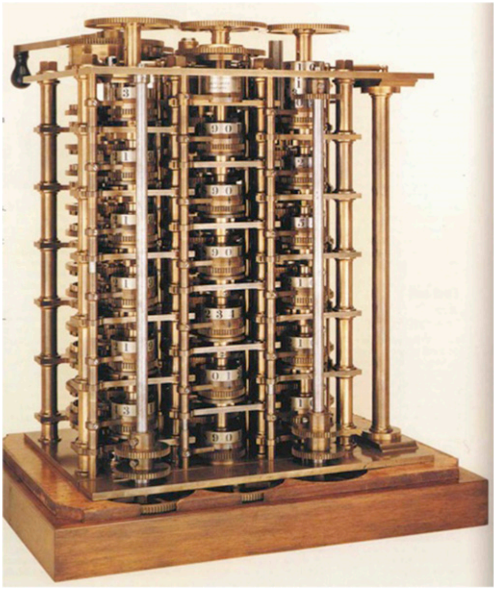

Figure 3. Modern reconstruction of Babbage's Difference Engine No. 1, 1832, (1991), Science Museum, London.

organization of work and workers. Long after Prony and Babbage and even after the spread of reliable calculating machines in the late nineteenth century, humans still played a crucial role in heavy-duty calculation (which I'll call Big Calculation, on the analogy with Big Data), and the challenge of optimizing the arrangements of humans and machines became if anything even more daunting. More reliable calculating machines like the Thomas Arithmometer (not widely marketed until the 1870s) did not get rid of human calculators; in fact, machines may have actually increased the number of humans involved. What mechanization *did* change was the organization of Big Calculation: integrating humans and machines dictated different algorithms, different skills, different personnel, and above all different divisions of labor. These changes in turn shaped new forms of intelligence at the interface between humans and machines.

In light of our current fascination with — and fear of — Artificial Intelligence, it is Babbage's inference from the mechanical nature of Prony's third tier of "mechanical" human calculators to a real machine programmed to calculate that seems to presage a future ruled by algorithms. But in fact it is the middle tier, those seven or eight "algebraicists" who translated high-flown mathematics into thousands and thousands of additions and subtractions, who should be the object of our attention. They were the ones who dissected a highly complex formula into simple, step-by-step procedures. In other words, they created the algorithms that meshed mathematics with mechanical labor by humans and ultimately with machines. From the mid-nineteenth to at least the mid-twentieth centuries, it is this kind of managerial intelligence that came to dominate factories of Big Calculation — insurance companies, astronomical observatories, railways, government statistical bureaus, naval ephemerides, accounting offices, and later military weapons research. Arguably, it is the same intelligence that still dovetails humans and machines in our own online world, in which humans interact constantly with algorithms, whether as Uber drivers, Amazon customers, or college students registering for courses. I will call the algorithmic intelligence used to organize vast calculation projects "analytical intelligence."

My exploration of analytical intelligence will focus on how the introduction of machines in the late nineteenth and early twentieth centuries changed both narrow and broad algorithms: those used to calculate and those used to organize calculation. Machines also altered the meaning of calculation and the identity of calculators. But machines did not fundamentally transform the mental burden of calculation that they had been designed to relieve. Instead, they shifted it to other shoulders — or rather, to other minds. The labor of massive calculation, a cause for complaint among astronomers, surveyors, administrators, and navigators since the sixteenth century, remained as monotonous and tedious as ever — so much so that it inspired whole new psychophysical inquiries into mental fatigue and flagging attention. At least in its first century of widespread application, roughly 1870-1970, mechanical calculation never entirely succeeded in exorcising the ghost in the machine — and a very weary ghost it was, too.

III. Calculation as Hard Labor

On an August morning in 1838, the seventeen-year-old Edwin Dunkin and his brother began work as computers at the Royal Observatory in Greenwich, under the directorship of Astronomer Royal George Biddell Airy:

> We were at our posts at 8 a.m. to the moment. I had not been many minutes seated on a high chair before a roomy desk placed on a table in the centre of the Octagon Room, when a huge book was placed before me, very different indeed to what I had anticipated. This large folio book of printed forms, was specially arranged for the calculation of the tabular right ascension and north polar distance of the planet Mercury from Lindenau's Tables. ... After very little instruction from Mr. Thomas, the principal computer in charge, I began to make my first entries with a slow and tremulous hand, doubting whether what I was doing was correct or not. But after a little quiet study of the examples given in the Tables, all this nervousness soon vanished, and before 8 pm came, when my day's work was over, some of the older computers complimented me on the successful progress I had made.[8]

8 Edwin Dunkin, *A Far-Off Vision: A Cornishman at Greenwich Observatory*, ed. P.D. Hingley and T.C. Daniel (Truro, 1999), 72-73.

Two boys sent out to support their widowed mother, the high chair and the huge ledger, the twelve hours of eye-straining, hand-cramping calculation (alleviated only by an hour's dinner break), the standardized printed forms that divided computation into steps like the manufacture of pins — it could be a vignette from Dickens, and both Airy and his predecessor in the office, John Pond, have been cast by contemporaries and historians alike in the roles of Bounderby or Scrooge.[9]

But the reality of massive calculation of the sort that went on in astronomical observatories since at least the medieval period in parts of Asia and in Europe since the sixteenth century (and since the nineteenth century in insurance offices and government statistical offices) was considerably more varied — as varied as the nature of work itself in different historical and cultural contexts. The only constant was that calculations on the large scale needed to reduce astronomical observations, compute life expectancies, and tally statistics on everything from crime to trade was indeed work: the first Astronomer Royal John Flamsteed, appointed in 1670, called it "labour harder than thrashing."[10] Before and even after the invention and diffusion of reliable calculating machines, the challenge to astronomers and other heavy-duty number crunchers was how to organize the work of deploying many algorithms, over and over again. These combined experiments in labor organization and algorithmic manipulation ultimately transformed both human labor and algorithms.

Let us return to young Edwin Dunkin perched on his high chair in the Octagon Room of the Royal Observatory at Greenwich. Edwin's father William Dunkin had also been a "computer" — a word that until the mid-twentieth century referred primarily to human beings, not machines — and had worked for Airy's predecessors, Astronomers Royal Nevil Maskelyne and John Pond, to calculate tables for the *Nautical Almanac*, a navigational tool for the globalized British navy that had been produced under the direction of the Astronomer Royal since 1767.[11] Unable to supply the labor necessary to compute the *Almanac*'s numerous tables from the Greenwich Observatory's own resources, Maskelyne organized a network of paid computers throughout Britain to perform the thousands of calculations according to a set of "precepts" or algorithms, to be entered on pre-printed forms that divided up calculations (and indicated which values had to be looked up when from which one of fourteen different books of

9 Simon Schaffer, "Astronomers Mark Time: Discipline and the Personal Equation," *Science in Context* 2 (1988): 115-145. Charles Pritchard, Savillian Professor of astronomy at Oxford, wrote to Admiral Ernest Mouchez, director of the Paris Observatory, on the occasion of Airy's funeral: "Airy was buried quietly in the country: his funeral attended solely by H. Turner the Chief Assistant at Greenwich. I ought not to say it, but A. was a semi-brute: he '*sat on'* Adams, Challis & myself among other young men." C. Pritchard to E. Mouchez, 28 March 1892, Bibliothèque de l'Observatoire de Paris, 1060-V-A-2, Boite 30, Folder Oxford (Angleterre). But see also Allan Chapman, "Airy's Greenwich Staff," *The Antiquarian Astronomer* 6 (2012): 4-18.

10 William J. Ashworth, "'Labour harder than thrashing': John Flamsteed, Property and Intellectual Labour in Nineteenth-Century England," in *Flamsteed's Stars*, ed. Frances Willmoth (Rochester, 1997), 199–216.

11 George A. Wilkins, "The History of the H.M. Nautical Office," in Alan D. Fiala and Steven J. Dick, eds., *Proceedings: Nautical Almanac Office Sesquicentennial Symposium, U.S. Naval Observatory, March 3-4, 1999* (Washington, D.C., 1999), 55-81.

tables) into a step-by-step but by no means mechanical process.[12] What is noteworthy about Maskelyne's operation (which involved a computer, anti-computer, and comparer to check each month's set of calculations) was its integration into an established system of piecework labor done in the home and often involving other family members. Each computer completed a whole month's worth of lunar position or tide prediction calculations according to algorithms bundled like the patterns sent to cottage weavers to produce finished textile wares.

Just as the mid-eighteenth-century manufacturing system, in which many workers were gathered together under one roof and subjected to close managerial supervision, began to replace the family textile workshop long before the introduction of steam-driven looms,[13] so the development of Big Calculation traced a parallel arc a good half-century before algorithms were calculated by machines. The careers of William and Edwin Dunkin, father and son computers in the service of the British Astronomers Royal, span the transition between piecework and manufacturing — but not yet mechanized — systems of labor organization. William, a former miner from Cornwall, spent most of his career as a computer in Maskelyne's network, working from his home in Truro. When the computational work of the Nautical Almanac was centralized in London under the direction of its own superintendent in 1831, William was the only member of the old computation network to be carried over into the new system, a move he regretted to the end of his life because it deprived him of home and independence.[14]

Edwin Dunkin's experience as a computer began in a clerical setting like that his father had recoiled from: all the computers gathered together in a single room; fixed hours (which were significantly shortened soon after he began work at Greenwich Observatory); more supervision and hierarchy with differential pay for the various grades of computers and assistants; young personnel at the lowest ranks with a high turnover. But Airy's "system," as it was called, cannot be described as a factory of computation. Quite aside from the absence of any machines, the division of labor was loose and the possibilities for advancement significant: young computers like Edwin were also expected to shoulder their share of nighttime observing duties, and although William Dunkin was so unhappy with his prospects of social advancement as a computer that he discouraged his sons from following in his footsteps, Edwin eventually

12 Mary Croarken, "Human Computers in Eighteenth- and Nineteenth-Century Britain," in *The Oxford Handbook of the History of Mathematics*, ed. Eleanor Robson and Jacqueline Stedall (Oxford, 2009), 375-403.

13 See Georges Friedmann, "L'*Encyclopédie* et le travail humain," *Annales. Economies, Sociétés, Civilisations* 8 (1953): 53-61 on the degree to which such "grandes manufactures" were dissociated from both machines and the division of labor in the views of mid-eighteenth-century French thinkers.

14 Edwin Dunkin, *A Far-Off Vision. A Cornishman at Greenwich Observatory: 'Autobiographical Notes'*, ed. P.D. Hingley (Truro, 1999), 45.

became a Fellow of the Royal Society and president of the Royal Astronomical Society.[15] A survey of Airy's Greenwich computers and assistants reveals a spectrum of livelihoods, from teenagers hired as computers at the lowest wages, many of whom did not last long, to assistants hired straight out of university (often with strong mathematical credentials) and salaries substantial enough to support a family in solid middle-class style.[16] Maskelyne's printed forms and Airy's "precepts" structured the algorithms (and consultation of multiple tables) in a clear and rigid sequence adapted to contexts of domestic piecework and supervised office work, respectively. But neither much resembled Adam Smith's pin factory in the minute division of labor or endless repetition of the same task. Computation had not yet become "mechanical," in either the literal or figurative sense of the word.

Airy's "system" was in fact positioned between two extremes of organizing the labor of human computers in the nineteenth century. At one extreme was the American imitator of the *Nautical Almanac*, directed by Harvard mathematics professor Benjamin Peirce in Cambridge, Massachusetts. Simon Newcomb, who later became a prominent astronomer but who was largely self-educated in mathematics when he began work as a computer at age twenty-two, found working conditions decidedly casual: "The discipline of the public service was less rigid in the office [of the *Nautical Almanac*] than any government institution I ever heard of. In theory there was an understanding that each assistant was 'expected' to be in the office five hours a day. ... As a matter of fact, however, the work was done pretty much where and when the assistant chose, all that was really necessary being to have it done on time." One of his fellow computers, the philosopher Chauncey Wright, concentrated a year's worth of computation into two or three months, staying up into the wee hours and "stimulating his strength with cigars."[17]

At the opposite extreme from the laissez-faire office of the American *Nautical Almanac* was the Prony project for calculating logarithms in the decimal system initiated during the French Revolution to vaunt the advantages of the metric system. This was the moment when computation met modern manufacturing methods (though not yet machines) and could be reimagined as mechanical rather than as mental labor. By methods that Prony described as "purely mechanical," the workers performed about 1000 additions or subtractions a day in duplicate, in order to control for errors.

15 Dunkin, *Far-Off Vision*, 70-97.

16 On the careers and wages of Airy's computers and assistants see Allan Chapman, "Airy's Greenwich Staff," *The Antiquarian Astronomer* 6 (2012): 4-18.

17 Simon Newcomb, *The Reminiscences of an Astronomer* (Boston/New York, 1903), 71, 74. Like Edwin Dunkin, Newcomb in retrospect regarded his job as a computer as the first rung on the ladder of a distinguished scientific career, "my birth into the world of sweetness and light" (1).

No machine more complicated than a quill pen was used in this herculean calculation project. What made it "mechanical" in the eyes of Prony and his contemporaries was the nature of the labor at the bottom of the pyramid — or rather the nature of the laborers. In a passage that Babbage was to repeat like a refrain, Prony marveled that the stupidest laborers made the fewest errors in their endless rows of additions and subtractions: "I noted that the sheets with the fewest errors came particularly from those who had the most limited intelligence, [who had] an automatic existence, so to speak."[18] To Babbage, steeped in the political economy of newly industrialized England, Prony's manufacture of logarithms proved that even the most sophisticated calculations could be literally mechanized. He likened Prony's achievement to that "of a skillful person about to construct a cotton or silk-mill."[19] If mindless laborers could perform so reliably, why not replace them with mindless machines?[20] But the Prony tables were never published in full and rarely used, Babbage's Difference Engine remained a party entertainment and his Analytical Engine a dream,[21] and it was a very long time before calculators like Edwin Dunkin were even reinforced, much less replaced by machines.

IV. "First Organize, Then Mechanize": Calculating Machines and the Division of Labor

If calculation was essentially mechanical, as Prony and Babbage claimed, why did it take so long for machines to actually perform these operations — especially since there was desperate demand among calculation-intensive enterprises like the *Nautical Almanac*? Any number of ingenious calculating machines had been invented and fabricated at least in prototype version since the French mathematician Blaise Pascal tried to sell his arithmetic machine (Figure 4) in 1640s, without notable success. Throughout the seventeenth, eighteenth, and nineteenth centuries inventors experimented with diverse designs and materials, but their machines remained difficult to construct, expensive to purchase, and unreliable to use, items to adorn a princely cabinet of curiosities rather than workaday tools.[22]

The first calculating machine robust and reliable enough to be successfully manufactured and marketed was the Arithmometer (Figure 5), invented by the French businessman Thomas de Colmar in 1820, but not in widespread usage until the 1870s. Even then the insurance firms

18 Gaspard de Prony, *Notices sur les grandes tables logarithmique et trigonometriques, adaptées au nouveau système décimal* (Paris, 1824), 7.

19 Charles Babbage, *On the Economy of Machinery and Manufactures* [1832], 4th ed. (London, 1835), 195.

20 Simon Schaffer has written brilliantly about the conceptions of intelligence implicit in Babbage's project, as well as the prolonged and acrimonious strife between Babbage and the engineer Joseph Clement, whom Babbage employed to build the engines: Simon Schaffer, "Babbage's Intelligence: Calculating Engines and the Factory System," *Critical Inquiry* 21 (1994): 203-227.

21 Laura J. Snyder, *The Philosophers' Breakfast Club* (New York, 2011); Doron Swade, *The Difference Engine: Charles Babbage and the Quest to Build the First Computer* (New York, 2001).

22 Blaise Pascal, "Lettre dédicatoire à Monsieur le Chancelier Séguier sur le sujet de la machine nouvellement inventée par le Sieur B.P. pour faire toutes sortes d'opérations d'arithmétique par un mouvement réglé sans plume ni jetons," in Blaise Pascal, *Oeuvres complètes*, ed. Louis Lafuma (Paris, 1963), 187-191. See Matthew L. Jones, *Reckoning with Matter: Calculating Machines, Innovation, and Thinking about Thinking from Pascal to Babbage* (Chicago, 2016) on the long and difficult history of constructing and marketing such machines.

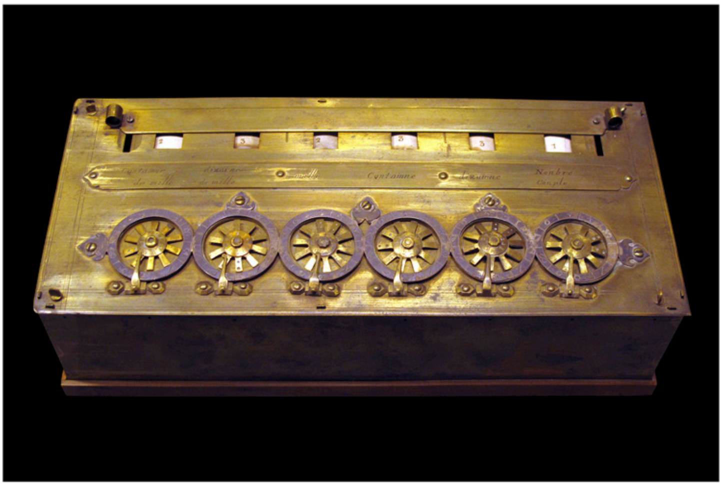

Figure 4. Pascal's "Machine arithmétique" (1645), Conservatoire des Arts et Métiers, Paris.

that were its primary purchasers complained that the Arithmometer broke down often and required considerable dexterity to operate.[23] By the second decade of the twentieth century, however, calculating machines manufactured in France, Britain, Germany, and the United States were fixtures in insurance offices, government census bureaus, and railway administrations. But a comprehensive 1933 survey of calculating machines then available admitted that for scientific purposes "mental calculation aided by writing and numerical tables" still predominated.[24]

This was more or less exactly the moment when the British *Nautical Almanac* began to introduce mechanical calculating machines into its operations.[25] The transition from the silence of the Octagon Room, broken only by the scratching of pens and the turning of pages as schoolboy Junior Computers and more senior Assistants calculated and looked up tables, to the deafening clatter of adding machines in a crowded office at the Naval College in Greenwich must have been jarring. In an urgent plea to the Admiralty for larger quarters in 1930, Superintendent L. Comrie described the scene: "We have a large Burroughs [Adding] Machine in continual use which is so noisy

23 Maurice d'Ocagne, *Le Calcul simplifié par les procédés mécaniques et graphiques*, 2nd ed. (Paris, 1905), 44-53; Martin Campbell-Kelly, "Large-Scale Data Processing in the Prudential, 1850-1930," Accounting, Business and Financial History 2 (1992): 117-140. Between 1821 and 1865, only 500 Arithmometers were sold, but by 1910, circa 18,000 Arithmometers were in use worldwide: Delphine Gardey, *Écrire, calculer, classer. Comment une revolution de papier a transformés les sociétés contemporaines (1800-1840)* (Paris, 2008), 206-212.

24 Louis Couffignal, *Les Machines à calculer* (Paris, 1933), 2.

25 Mary Croarken, "Human Computers in Eighteenth- and Nineteenth-Century Britain," in *The Oxford Handbook of the History of Mathematics*, ed. Eleanor Robson and Jacqueline Stedall (Oxford, 2009), 375-403, on 386-7. On 10 December 1928, the Admiralty approved the purchase of new Burroughs Adding Machine (Class 111700) and the lease of a Hollerith machine: Secretary of the Admiralty to Superintendent of the Nautical Almanac, 10 December 1928. RGO 16/Box 17, Manuscript Room, Cambridge University Library.

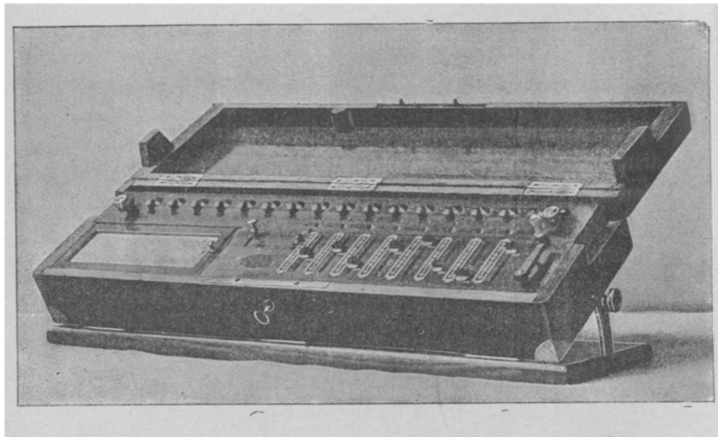

Figure 5. Thomas de Colmar, Thomas Arithmometer c. 1905, from Maurice d'Ocagne, *Le Calcul simplifié par les procédés mécaniques et graphiques*, 2nd ed. (Paris, 1905), 46.

that no degree of concentration is possible in the room where it is working. It is essential, for the sake of the other workers, that the machine should have a room to itself." And why was the office so crowded? Because use of the machines dictated that work previously parceled out to "outside workers" — retired staff members, their relatives, clergymen and teachers seeking to pad their modest incomes — should now be assigned to "ordinary junior market labour with calculating machines" instead of to "the old-time highly-paid computers who knew nothing but logarithms and who often worked in their own houses." Such lower-paid workers needed "closer supervision," and the expensive machines could not leave the office.[26] And who were these cheap workers who operated the new machines under the gimlet eye of their supervisor? No longer boys fresh from school as in Edwin Dunkin's day but rather a half-dozen unmarried women (British Civil Service regulations prohibited hiring married women) who had passed a competitive examination in "English, Arithmetic, General Knowledge and Mathematics."[27]

Ironically, the machines introduced with the intention of cutting costs, saving labor, speeding up production, and, above all, alleviating mental effort had at least the initial effect of hiring more workers, spending more money, disrupting production, and increasing mental effort — especially for the supervisors charged with reorganizing how calculations were done in order to integrate human and mechanical calculators into a smooth, efficient, and error-free sequence. Take the case of the Hollerith machine that Superintendent Comrie was keen to lease for at least six months to make an ephemeris of the Moon. In addition to the circa £264 for the rental itself, there would be the additional expense of £100 for 10,000 punch cards, plus the extra "wages of four girls for six months, and two girls for an additional six months" to punch in the numbers and operate the machine, amounting to another £234 — and did I mention the extra £9 added to the electricity bill? That's a grand total of £607, compared to £500

26 Superintendent of the Nautical Almanac to the Secretary of the Navy, 28 October 1930. RGO 16/Box 17, Manuscript Room, Cambridge University Library.

27 Secretary of the Admiralty to the Superintendent of the Nautical Almanac, 23 November 1933. In a letter from the Superintendent to the Secretary of the Admiralty, 14 April 1931, the Superintendent sees no reason why women could not also be employed at the higher-level post of assistant but recommended that the positions of Superintendent and Deputy Superintendent "be reserved for men, especially in view of the fact that the greater part of the calculation is now performed by mechanical means." RGO 16/Box 17, Manuscript Room, Cambridge University Library.

per year for the same calculations using the old methods. Instead of calculating 10,000 sums of figures taken from seven different tables, it would now be necessary to punch twelve million figures onto three hundred thousand cards in order to run them through the Hollerith machine. The superintendent must have anticipated some raised eyebrows at the penny-pinching Admiralty when he sent in these figures, for he hastened to acknowledge that "a heavy initial cost" would be justified by subsequent increases in "speed and accuracy and saving of mental fatigue obtained by using the tabulating machines."[28]

"A true calculating machine," ran one definition circa 1930, is one that "suppresses in its operation all that could genuinely demand a mental effort."[29] But like Freud's return of the repressed, mental effort and fatigue tended to return through the back door. Quite apart from the fatigue endured by the women who punched the cards, a point to which I'll return, there was the effort of rethinking the division of labor in the millions of calculations necessary to produce the Nautical Almanac. As we have seen, observatory directors and almanac superintendents had been analyzing the work of calculation into multiple steps and matching steps to degrees of mathematical skill, from schoolboys to Cambridge Wranglers, since the eighteenth century.

But with the influx of new workers to operate the calculating machines in the 1930s, the superintendent and deputy superintendent found themselves confronted with a supervisory crisis: how could the new staff and new machines be meshed with the old staff and their tried-and-true methods? There were the difficult but invaluable Daniels brothers, who were the only staff members trusted to proofread tables but deemed "temperamentally unfitted to supervise subordinate staff" and "too stereotyped in their habits to adapt themselves to the use of machines." Miss Stocks and Miss Burroughs, who were charged to transform heliocentric into geocentric coordinates using Brunsviga calculating machines, required three months *each* of private tuition in computing from the Superintendent.[30]

Trying to justify why, despite the sizeable investments in new machines and personnel, the *Nautical Almanac* was still twelve months behind schedule, Superintendent Comrie explained to his bosses at the Admiralty that the supervisor's preparation of the work for the machines and their operators now constituted "20 or 30 per cent of the whole [calculation]." Whereas previously computing the ephemeris of the Moon at transit consisted of simply telling one W.F.

28 Superintendent of the Nautical Almanac to the Secretary of the Admiralty, 4 May 1928. RGO 16/Box 17, Manuscript Room, Cambridge University Library.

29 Louis Couffignal, *Les Machines à calculer* (Paris, 1933), 7.

30 Superintendentent of the Nautical Almanac (L. Comrie) to the Secretary of the Admiralty, 9 February 1937. RGO 16/Box 17, Manuscript Room, Cambridge University Library.

Doaken, M.A. "'Do the Moon Transit,' and four or five months later the printer's copy would be handed over," now the work had been divided up among "six or seven people, to whom perhaps 100 to 120 different sets of instructions are given."

But the bottom line was the bottom line: the new methods were at least 20% cheaper than the old. If the *Nautical Almanac* was not going to revert back to the luxurious staffing scheme of their German counterparts, who employed eleven Ph.D.s, then cheaper staff (i.e. women), machines, and, most important, constant and creative supervision would be necessary. New algorithms disrupted old methods of calculation on at least two levels. First, the machines rarely calculated in the way that humans had been taught to or even in the way indicated by theoretical mathematical solutions. For example, the Seguin machine multiplied not by iterating additions but rather by treating numbers as polynomials of powers of ten.[31] The best rules for mental calculation were not those for mechanical calculation — and different machines used different algorithms. Second, meshing the mental, mechanical, and manual aspects of calculation required supervisors to invent new procedural algorithms that divided a problem like the lunar transit into small, explicit steps. When Comrie complained, as no doubt all superintendents before and after him did, about how much of his time was nibbled away by administrative duties, it was not scientific work to which he longed to return: "My mind should be free from administrative worries, so that I can exploit methods, devise improved arrangements of computations, and collate and supervise the work of individual members of the Staff."[32] Here was analytical intelligence concentrated to its doubly algorithmic essence: calculation and the division of labor simultaneously rethought to accommodate machines and the allegedly mechanical workers who operated them — all in the name of cost-cutting.

Pressure to trim costs in order to justify the purchase of expensive machines and hiring of more staff to operate them was even more intense in calculation-heavy industries, like the railroads. At the same time the *Nautical Almanac* in Greenwich was experimenting with Hollerith and other calculating machines to streamline astronomical calculations, the French Chemins de Fer Paris-Lyon-Méditerranée (C.F.P.L.M.) was introducing them to keep track of freight shipments and moving stock. In a 1929 article, Georges Bolle, head of accounting at the C.F.P.L.M. and graduate of the École Polytechnique, France's elite engineering school,

31 Louis Couffignal, *Les Machines à calculer* (Paris, 1933), 41, 78.

32 Superintendentent of the Nautical Almanac (L. Comrie) to the Secretary of the Admiralty, 14 October 1931, 25 January 1933, 30 September 1933. RGO 16/Box 17, Manuscript Room, Cambridge University Library.

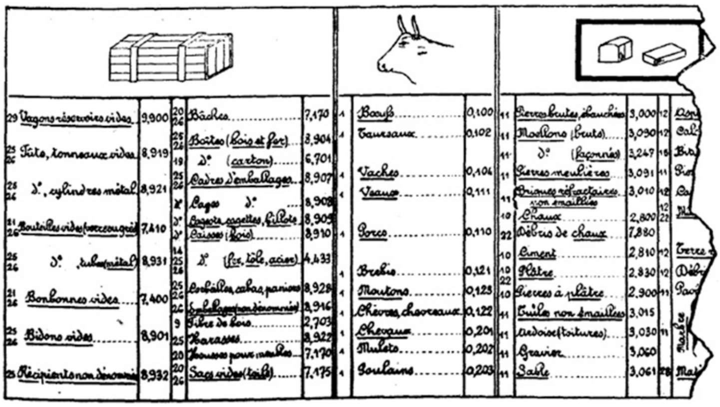

Figure 6. Icons for C.F.P.L.M freight, from Georges Bolle, "Note sur l'utilisation rationelle des machines à statistique," *Revue générale des chemins de fer* 48 (1929): 190.

explained that the economic advantages of the new machines were "really incalculable" — but only if every single detail of the workflow had been meticulously thought out in advance, from how to maximize the use of all of the forty-five columns of a Hollerith punch card to devising icons (Figure 6) for the kind of freight most frequently transported to speed up coding of the information by the machine operators. No detail of the process was too small to escape the supervisor's scrutiny, not even the numbering of freight categories: "Every detail must be meticulously examined, discussed, weighed in work of this kind." As in the case of the Nautical Almanac, the use of machines entailed centralizing the workplace (in Paris, of course) and hiring the cheapest labor consistent with the qualifications of "much orderliness, care, concentration, and good will" (women, of course). The economic advantages of a cheap work force were apparently so great that Bolle thought that all the difficulties involved in abandoning old methods — not least the cost of the machines themselves — paled by comparison. But these gains could only be achieved by a vast effort of organization: "The study of every problem to be solved by machines requires very laborious mental effort [*un travail cérébral très laborieux*], a considerable amount of reflection, observations, and discussions to mount the projected organization and make sure that all works well ... ."[33] Or, in his lapidary motto: "First organize, then mechanize."[34]

V. Mechanical Mindfulness

However different in their design, materials, power, and reliability, all calculating machines, from the seventeenth to the mid-twentieth century, promised to assuage human intelligence, not replace it.[35] The inference drawn from the capacity of machines to calculate was not that machines were intelligent but rather that at least some calculation was mechanical, in the sense of being mindless. But it was a peculiar sort of mindlessness, one that required the utmost efforts

33 Georges Bolle, "Note sur l'utilisation rationelle des machines à statistique," *Revue générale des chemins de fer* 48 (1929): 169-195, on 175, 176, 179, 190.

34 Quoted in Louis Coffignal, *Les Machines à calculer* (Paris, 1933), 79.

35 As Matthew Jones notes, calculating machines, in contrast to automata, rarely inspired visions of machine intelligence in the eighteenth century, despite the fascination of materialist philosophers like La Mettrie with thinking matter: Matthew L. Jones, *Reckoning with Matter: Calculating Machines, Innovation, and Thinking about Thinking from Pascal to Babbage* (Chicago, 2016), 215-218; Lorraine Daston, "Enlightenment Calculations," *Critical Inquiry* 21 (1994): 182-202, on 193.

of attention and memory. This was most dramatically displayed by a wave of psychological studies devoted to calculating prodigies on the one hand and to the operators of calculating machines on the other. These two groups might once have been viewed as opposite ends of a spectrum: number geniuses versus number dunces. But the spread of calculating machines had simultaneously devalued the mental activity of calculation without eliminating the monotonous effort of concentration traditionally associated with it. As a result, the psychological profiles of the virtuosi of mental arithmetic and the operators of calculating machines converged in strange ways.

The history of eighteenth and early nineteenth-century mathematics boasts several calculating prodigies who later became celebrated mathematicians, including Leonhard Euler, Carl Friedrich Gauss, and André-Marie Ampère.[36] Anecdotes circulated about their precocious feats of mental arithmetic as early signs of mathematical genius. But by the late nineteenth and early twentieth centuries, psychologists and mathematicians insisted that such cases were anomalous: great mathematicians were rarely calculating virtuosi, and calculating virtuosi were even more rarely great mathematicians. It is significant that these arguments featured prominently in treatises on calculating machines: if calculating was a mechanical activity, then minds that excelled at it were perforce mechanical. Lightning calculation, whether performed mentally or mechanically, was now more akin to dexterity than to creativity.

Alfred Binet, professor of psychology at the Sorbonne and pioneer of experimental investigations of intelligence, subjected two calculating prodigies to a long series of tests in his laboratory in the 1890s and concluded on the basis of his results and a review of the historical literature on such virtuosi of mental arithmetic that despite much individual diversity they constituted a "natural family": they were sports of nature, born into families with no previous history of such prodigies; grew up in impoverished circumstances; exhibited their talents at an early age but were otherwise unremarkable, even backward in their intellectual development; and even as adults resembled "children who did not age." In contrast, mathematicians like Gauss, who had dazzled parents and teachers with feats of mental arithmetic at a young age, allegedly lost these abilities as their mathematical genius matured. Binet went so far as to query whether the accomplishments of the calculating prodigies were so remarkable even as mere "number specialists." In

36 Edward Wheeler Scripture, "Arithmetical Prodigies," *American Journal of Psychology* 4 (1891): 1-59, offers a historical overview of the phenomenon.

Figure 7. Synchronized machines. From: Louis Couffignal, *Les Machines à calculer* (Paris: Gauthier-Villars, 1933), 63.

a competition with four cashiers from the department store Bon Marché, who were used to toting up prices in their heads, one of Binet's calculating prodigies lost to the best of the Bon Marché clerks when it came to multiplication by small numbers, although he surpassed them all in solving problems involving more digits. Binet concluded that what was truly prodigious about calculating prodigies were their powers of memory and "force of attention," at least as applied to numbers.[37]

It was exactly this focused attention, at once monotonous and monothematic, that the operators of calculating machines were expected to sustain for hours on end. The unbearable strain of attention required of human calculators had long been a bone of contention between them and their employers. Despite his zeal to increase calculating productivity, Airy had in 1838 reduced the working day of the computers from eleven hours to eight. Attempts to add an hour of overtime in 1837 in order to complete calculations for Halley's Comet provoked a rebellion on the part of the computers, who protested that even the regular nine-to-five hours were "more than sufficient for the oppressive and tedious application of the mind to continued calculation."[38] In 1930, outgoing *Nautical Almanac* superintendent Philip Cowell wrote his successor Leslie Comrie that "anyone who worked really hard for five hours could not possibly do more," adding parenthetically: "it may be different with your machines."[39]

It was indeed different with machines, but even the efficiency-obsessed Bolle at the French railways thought that a working day of six-and-a-half hours of punching 300 cards, each with forty-five columns, was the maximum that could be expected from Hollerith machine operators, and then for only fourteen consecutive days per month (see Figure 7).[40] As a 1931 psychological study devoted to the performance of French railway operators on Elliot-Fischer calculating machines observed, bodily gestures could become automatic with

37 Alfred Binet, *Psychologie des grands calculateurs et joueurs d'échecs* (Paris, 1894), 91-109. The two calculating prodigies studied by Binet, Jacques Inaudi and Pericles Diamandi, were both the subjects of a commission of the Académie des Sciences that included Gaston Darboux, Henri Poincaré, and François-Félix Tisserand, who recruited the help of Binet's teacher Jean-Martin Charcot at the Salpêtrière, who in turn recruited Binet.

38 Wesley Woodhouse to the Lords Commissioners of the Admiralty, 10 April 1837. RGO 16/ Box 1, Manuscript Room, Cambridge University Library.

39 P.H. Cowell to L. Comrie, 13 September 1930. RGO 16/ Box 1, Manuscript Room, Cambridge University Library.

40 Georges Bolle, "Note sur l'utilisation rationelle des machines à statistique," *Revue générale des chemins de fer* 48 (1929): 169-195, on 178.

practice, but "attention to the work must be continuous and concentrated. The operator is obliged to check her machine incessantly, to verify the names on the pieces of paper, to make sure that the elements of the calculation are correct." Each calculation involved sixteen separate steps, from inserting the paper into the machine to clearing all the numbers before the next calculation. In the view of the psychologists who tested the operators, it was impossible to sustain such intense levels of attention for a long period "without rest" (see Figure 8).[41] Commenting in 1823 on the advantages of Babbage's Difference Engine for computing mathematical and astronomical tables, English astronomer Francis Baily had envisioned how the "unvarying action of machinery" would solve the problem of "confining the attention of the computers to the dull and tedious repetition of many thousand consecutive additions and subtractions,"[42] and over a century later, in 1933, calculating machines were still being defined in terms of the suppression of mental effort.[43] Yet the calculating machines that had held out the promise of relieving the mental effort of attention had in the end exacerbated it.

Figure 8. Test results of best operator. J.-M. Lahy and S. Korngold, "Séléction des operatrices de machines comptables," *Année psychologique* 32 (1931): 131-149, 143.

Paradoxically, mechanical calculation had become intensely mindful, at least by the standards of the day. Turn-of-the-twentieth-century psychologists were unanimous that the ability to muster voluntary attention for tedious but necessary tasks was the essence of the conscious act of will — and the highest expression of consciousness.[44] Théodule Ribot, professor at the Collège de France, speculated that it was the ability to sustain attention for boring work that distinguished civilized from savage peoples and "vagabonds, professional thieves, prostitutes." Like the psychologists who had tested the calculating machine operators, Ribot emphasized that the exercise of voluntary attention was always accompanied by a sense of effort, an abnormal state that "produced rapid exhaustion of the

41 J.-M. Lahy and S. Korngold, "Séléction des operatrices de machines comptables," *Année psychologique* 32 (1931): 131-149, on 136-137.

42 Francis Baily, "On Mr. Babbage's New Machine for Calculating and Printing Mathematical and Astronomical Tables, *Astronomische Nachrichten* 46 (1823): columns 409-422; reprinted in Charles Babbage, *The Works of Charles Babbage*, ed. Martin-Campbell-Kelly, 11 vols., v.2, 45-56, on 45.

43 Louis Couffignal, *Les Machines à calculer* (Paris, 1933), 21.

44 William James, *Principles of Psychology* [1890] (New York, 1950), 2 vols., vol. 1, Ch. 11; Wilhelm Wundt, *Grundzüge der physiologischen Psychologie* (Leipzig, 1874), ch. 18. For an overview of early twentieth-century psychological research on attention, see Hans Henning, *Die Aufmerksamkeit* (Berlin, 1925), especially 190-201.

organism."[45] Calculation was a routine task given to experimental subjects by psychologists in order to test the strength of voluntary attention and resistance to mental fatigue.[46] Results suggested wild fluctuations in attention as subjects became fatigued, their minds wandered, and errors literally added up. In the context of the classroom or the laboratory, the dread of the tedious task was observed to grow with fatigue, allegedly sometimes to the point of "milder forms of insanity."[47] In the context of mechanical calculation, the operators' fatigue also caused fluctuations in attention and an alarming propensity to error. But there was no getting rid of the operator, as a 1933 treatise on the latest calculating machines emphasized: "In the comparative study of modern machines, it is impossible not to take into account the manner in which the operator intervenes [in the calculation]."[48] All that could be done was to organize the work of calculation so as to minimize the discretion of the operator — but at the same time to maximize her unflagging attention to her monotonous task: mechanical calculation made mindful.

VI. Conclusion: Algorithms and Intelligence

I began with a simple question: why don't we have a full-dress history of calculation, the oldest of all cultural techniques in literate societies? We now have at least the beginnings of an answer: over a period of about 170 years, roughly from 1800-1970, calculation was demoted from intellectual to mechanical activity — even if people were still crucially involved in its execution. The well-known story with which I began traced an arc from Adam Smith's pin factory to Babbage's Difference Engine via Prony's logarithm tables: from the division of labor to Artificial Intelligence. Much of the credibility of this story depends on the connection Babbage himself drew between the mechanical labor of Prony's bottom tier of calculators and a machine — one that remained largely imaginary for over a century after Babbage conceived it.[49] For reasons at once material, conceptual, and commercial, the first era of widespread mechanical calculation,

45 Théodule Ribot, *Psychologie de l'attention* (Paris, 1889), 62, 95, 105.

46 Alfred Binet and Victor Henri, *La Fatigue intellectuelle* (Paris, 1898), 26-27.

47 John Perham Hylan, "The Fluctuation of Attention," *Psychological Review* 2 (1898): 1-78, on 77.

48 Louis Couffignal, *Les Machines à calculer* (Paris, 1933), 67, 72.

49 The most successful realization of a calculating machine of the Difference Engine sort was realized by the Swede Georg Scheutz and his son Edvard in 1853 but never mass-produced. Michael Lindgren, *Glory and Failure: The Difference Engines of Johann Müller, Charles Babbage, and Georg and Edvard Scheutz* (Cambridge, MA, 1990). As late as 1905, a survey of calculating machines relegated Babbage's vision of an Analytical Engine to "fairyland": Maurice d'Ocagne, *Le Calcul simplifié par les procédés mécaniques et graphiques*, 2nd ed. (Paris, 1905), 88.

Figure 9. Women computers of NASA's Jet Propulsion Laboratory. Photograph by NASA, JPL-Caltech. Used by permission.

roughly from 1870 to at least the early 1960s, was one that meshed the intelligence of humans and machines. Increasingly, the human computers who operated the machines were women, actively recruited by observatories in Greenwich, Paris, and Cambridge, Massachusetts, already in the 1890s, and ubiquitous for decades thereafter wherever Big Calculation took place, from insurance offices to government censuses to weapons projects (see figure 9).[50] Although some of these institutions, such as the Harvard College Observatory, took advantage of the women's advanced training in astronomy and mathematics, the chief attraction of female labor was that it was cheap: even women with college degrees were paid significantly less than their male counterparts.[51] Indeed, the principal motivation for introducing calculating machines in the first place was usually to cut costs for Big Calculation, as we have seen in the scientific context of the British Nautical Almanac office and the industrial context of the French railway. Babbage the political economist would surely have approved.[52]

But would Babbage the prophet of automated intelligence have been equally impressed? Certainly, the boundary between "mechanical" and "mental" work had been blurred, but this had already occurred in Prony's logarithm project, before any actual machines had been used

50 David Alan Grier, *When Computers Were Human* (Princeton, 2006); Christine von Oertzen, "Machineries of Data Power: Manual versus Mechanical Data Compilation in Nineteenth-Century Europe," *Osiris* 32 (2017): 129-150.

51 Dava Sobel, *The Glass Universe: How the Ladies of the Harvard Observatory Took the Measure of the Stars* (New York, 2016); Allan Chapman, "Airy's Greenwich Staff," *The Antiquarian Astronomer* 6 (2012): 4-18, on 16.

52 "[W]e avoid employing any part of the time of a man who can get eight or ten shillings a day by his skill in tempering needles, in turning a wheel, which can be done for sixpence a day; and we equally avoid the loss arising from the employment of an accomplished mathematician in performing the lowest processes of arithmetic." Charles Babbage, *On the Economy of Machinery and Manufactures* [1832], 4th ed. (London, 1835), 201.

in massive calculation projects. The impact of calculating machines into the daily work of observatories and insurance offices seems not to have made the machines seem more intelligent — Artificial Intelligence in our sense — but rather to make the human calculators appear more mechanical. Emblematic of this shift was the plunging prestige of calculating prodigies: by the late nineteenth century, such talents were no longer early signs of mathematical genius but the stuff of vaudeville acts. Calculating prowess was no longer correlated with human intelligence nor did it endow calculating machines with anything like Artificial Intelligence.

Calculating machines did not eliminate human intelligence in Big Calculation, but they did shape it in new ways. First, at the level of the calculating algorithms built into the gears and levers of the machines, the operations of arithmetic had to be reconceived in ways that corresponded neither to mental arithmetic nor mathematical theory. What was optimal for human minds was not optimal for machines, and as the machines became more complex in terms of moving parts, the divergences became more pronounced. Second, at the level of the procedures required to mesh human and machines in long sequences of calculation, whether in the offices of the Nautical Almanac or the French Railways, tasks previously conceived holistically and executed by one calculator had to be analyzed into their smallest component parts, rigidly sequenced, and apportioned to the human or mechanical calculator able to execute that step most efficiently — where efficiently meant not better or even faster but cheaper.

In a sense, the analytical intelligence demanded by human-machine production lines for calculations was no different than the adaptations required by any mechanized manufacture: mechanical weaving looms did not operate the way human weavers did; the sequencing of human and mechanical labor in a textile factory also required breaking down tasks in new and counter-intuitive ways. In another sense, however, the analytical intelligence applied to making human-machine cooperation in calculation work was a rehearsal for an activity that would become known first as Operations Research and later computer programming.[53]

The interaction of human and mechanical calculators also modified intelligence, both the concept and the thing, in more subtle ways. In whichever way calculation had been understood, as intellectual accomplishment or drudgework, and by whoever performed, whether Astronomer Royal or schoolboy computer, it had been intensely, even

53 Judy L. Klein, "Implementation Rationality: The Nexus of Psychology and Economics at the RAND Logistics Systems Laboratory, 1956-1966," *History of Political Economy* 48 (2016): 198-225.

tediously mindful. Calculators from Kepler to Babbage complained of the mental strain imposed by the calculation of astronomical tables; inventors of calculating devices and machines since Napier and Pascal had promised a respite from labor that was at once monotonous but unremittingly attentive. Practice speeded up the rate of calculation, but it could not be allowed to become automatic and almost unconscious (as repetitive bodily gestures on the factory assembly line could) without increasing the risk of error. However, the spread of more reliable calculating machines not only downgraded the intellectual status of calculation; it also severed the connection between mindfulness and accuracy: by the early twentieth century, automation had become the guarantee of, no longer the obstacle to error-free calculation. Reversing a centuries-long history of erratic calculating machines, the results of which often had to be checked by hand, improvements in design and precision machining had by the 1920s made automatic calculation and accurate calculation synonymous.[54]

Yet a ghost lingered in the machine: the human operator. As even enthusiasts for the new generation of calculating machines admitted, the efficiency and accuracy of the results depended crucially on the dexterity and attentiveness of the humans who entered the numbers, pulled the levers, punched the cards, and cleared the tally, all in precisely the correct, rhythmic order. The operators may no longer have performed the actual calculations, but the vigilant attention demanded by their task was every bit as wearisome as the mental labor that had motivated the invention of calculating machines in the first place. Mental fatigue among operators was evidently so great that their working hours were shortened, in defiance of the iron rule of economy that had justified the introduction of calculating machines in the first place. In contrast to other forms of repetitive factory or clerical work that subjected human operators to the tempo of machines, the gestures involved in the use of calculating machines could not be mastered to the point of becoming unconscious, fingers playing automatically over the typewriter keyboard as the mind wandered. It was just this anomalous combination of routine and unwavering concentration that made calculation, with or without machines, so exhausting. Calculating machines, even reliable ones, did not banish mindfulness and monotonous attention from Big Calculation; they simply displaced these mental exertions to other tasks and people.

Calculating machines placed new demands on human intelligence, but did they pave the way for Artificial Intelligence? They did arguably

54 Matthew L. Jones, *Reckoning with Matter: Calculating Machines, Innovation, and Thinking about Thinking from Pascal to Babbage* (Chicago, 2016), 244-245; Louis Couffignal, *Les Machines à calculer* (Paris, 1933), 47.

55 On the visions of Leibniz, Stanhope, Condillac, and others, see Matthew L. Jones, *Reckoning with Matter: Calculating Machines, Innovation, and Thinking about Thinking from Pascal to Babbage* (Chicago, 2016), 4-5, 197-199, 215-225; Lorraine Daston, "Enlightenment Calculations," *Critical Inquiry* 21 (1994): 182-202, on 190-193.

expand the domain of algorithms, by forcing a rethinking of how to optimize Big Calculation at every level, from the innards of the machines to the organization of work flow to the attentive interaction with the machines. But making calculation even more algorithmic, in the sense of following standardized, step-by-step procedures, is a long way from making intelligence algorithmic. For that to happen, the reduction of intelligence to a form of calculation had to seem both possible and desirable. Although there are historical precedents for such visions, which made calculation and combinatorics the template for all intellectual activity, calculating machines did not advance their cause.[55] On the contrary, the effect of making calculation mechanical was to disqualify it as an intelligent activity. It would require a complete reconceptualization of both calculation *and* intelligence in order to make Artificial or Machine Intelligence something other than an oxymoron. It is only with the benefit of twenty-twenty hindsight that calculating machines and Artificial Intelligence belong to the same story. If sometime in the first half of the twentieth century calculation ceased to be a form of intelligence, sometime in the latter half of the twentieth century intelligence ceased to be intellectual, no longer a matter of mental processes accessible to the thinking subject — the twinned birth of the cognitive sciences and Machine Intelligence.

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