Human Computers and their Electronic Counterparts

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In studying either the practice or the history of computing, few individuals venture into the landscape that existed before the pioneering machines of the 1940s: George Stibitz's complex calculator, John Attansoff's linear algebra machine, Konrad Zuse's Z1, Howard Aiken's Mark I. Arguably, there is a good reason for making a clean break with the prior era, as these computing machines seem to have little in common with scientific computation as it was practiced prior to 1940. At that time, the term "computer" referred to a job title, not to a machine. Large-scale computations were handled by offices of human computers.

Very few human computers made the transition to the age of electronic computers. In the mid-1940s, George Stibitz remarked that "Human agents will [soon] be referred to as 'operators' to distinguish them from 'computers' (Machines)."[1] The only large cohort of computers that became computer programmers was a group of slightly less than a dozen women at the Moore School of Electrical Engineering at the University of Pennsylvania. These women were initially trained on the school's Differential Analyzer and then moved to the ENIAC. These women are far from typical computers, as they were trained to use a large computing machine from the start. Most human computers worked only with an adding machine or a logarithm table or a slide rule.

[1] **Error! Main Document Only. Error! Main Document Only.**Ceruzzi, Paul, *Reckoners The Prehistory of the Digital Computer, From Relays to the Stored Program Concept, 1935-1945,* Westport, Connecticut, 1983.

During the 1940s and 1950s, when electronic computers were becoming more common in scientific establishments, human computers tended to view themselves as more closely to the scientists for whom they worked, rather than the engineers who were building the new machines and hence did not learn programming.

In spite of the break between human computers and their electronic counterparts, these workers illustrate many of the basic themes of the modern computer era and help us to understand the practice of computer science. In all, there are four broad ideas that can be explained by the stories of human computers. The first of these ideas is the division of mental labor, the analysis and separation of individual tasks so that they can be handled sequentially, like a conventional program, or in parallel. Parallel processing proves to be an early development in the history of human computing and it points to the second idea that can be illustrated by this era, the control of parallel processes. The great growth of human computing offices began as scientists learned how to divide computing tasks into small units, handle those units in parallel and reassemble the results.

The third theme is that of standardization. Anyone who has taught the elementary sequence in computer science has encountered, at least once, a student resisted using standard constructs, data structures or algorithms. The story of human computation shows how the computers developed standard ideas as a means of saving labor, labor that could be long and arduous. The final theme of human computers is that of professionalization, the process of defining an independent body of knowledge, practices, standards and organizations. The nature of computing as a professional occupation is currently obscure, as we live at an odd juncture in the history, where the idea that computer science might be a part of mathematics or electrical engineering is long forgotten. The traditional role of professional organizations as a promoter or computer science is slipping away, as information about computing is now more commonly dispensed by commercial presses and internet chat groups rather by a professional society. By returning to the work of human computers illustrates the need for social organizations to support a scientific endeavor.

In the end, the story of human computers is neither a quaint look at a bygone world nor a cautionary tale about how difficult computation can be. It illustrates the major themes of computation and puts on those themes, a human face.

The Division of Labor

"The greatest improvements in the productive powers of labour," wrote the Scottish philosopher Adam Smith in 1776, "seem to have been the effects of the division of labour." The division of labor occupied a central place in Smith's treatise on economics, *The Wealth of Nations.* Smith argued that the division of labor was a key step for any society to take. It increased wealth by allowing individuals to concentrate on the tasks that he or she did best. In practice, this specialization would decrease the costs of production and allow people to produce more goods. Smith acknowledged that divided labor had a long history in Europe and that the basic concepts of divided labor might be applied to scientific research. With divided labor, "[e]ach individual becomes more expert in his own peculiar branch [of science]," he wrote and "the quantity of science is considerably increased by it."

During the second half of the eighteenth century, the time when Smith was writing *Wealth of Nations*, astronomers made the first attempts to divide the labor of scientific computation into smaller pieces and find workers who might handle each piece.

For the most part, these early computers did calculations that could stand alone as an independent computation, even though they were part of bigger problems. In the summer of 1757, three French astronomers divided the computation of the return date for Halley's comet among themselves. The problem was difficult to compute because it was a three body problem. To properly compute the orbit of the comet, the astronomers had to compute the relative positions of the Sun, Jupiter and Saturn, as these three bodies influenced the motion of the comet. In this calculation, two of the computers shared the work of computing the orbits of Jupiter and Saturn. The third handled the orbit of the comet. It was, according to one historian of the work "the first large-scale numerical integration ever performed." It required about 3 months and produced an answer that was only 31 days from the actual date of return.[2]

The first employers of human computers were the almanac offices, the institutions that produced star charts for navigators and surveyors. In France, the almanac was produced by the Academie des Sciences and was called the Connaisance des Temps. It employed two of the astronomers who had worked on the computation for Halley's Comet. An English almanac was created in 1767. This office employed five human computers. Four computed the positions of the planets and the moon. Each set of calculations was done twice by independent workers. The fifth computer, called the comparator, looked for errors by comparing the duplicate answers.

The great advancement in divided mathematical labor came during the French Revolution in 1789, when the National Assembly developed the metric system of measurement. On the recommendation of the Academie des Sciences, the assembly

[2] **Error! Main Document Only.**Wilson, Curtis, "Appendix: Clairaut's calculation of the comet's return," in *The General History of Astronomy*, Rene Taton and Curtis Wilson, eds., Cambridge, UK, 1995, pp 83-86.

considered mandating a decimal system on all forms of measurement, including the measurement of angles. Under this rule, a quarter circle would be divided into 100 grads instead of 90 degrees. This idea created a substantial mathematical problem. The people who used trigonometry in their daily work, surveyors and navigators, employed tables of trigonometric functions in order to calculate the size of a piece of land or identify a location on the earth. Unless the government created a new set of trigonometry functions, the surveyors and navigators would have no incentive to use the new system. Without these tables, they would be forced to transform their measurements into degrees, use conventional trigonometry tables and possibly transform some of the answers back into grads.

The task of preparing the new trigonometry tables was given to a civil engineer, Gaspard de Prony. De Prony was familiar with *Wealth of Nations* and Smith's discussion of divided labor. In his book, Smith had given an example of pin manufacture to show how tasks could be divided into component parts. De Prony recognized that the computation of trigonometry tables could be divided into a series of additions through the use of calculus. He assembled a small staff, drawn, in part, from the *Connaissance des Temps,* to analyze the computations for sines, cosines and the other functions and to create worksheets that would lead other workers through the additions that would create trigonometry tables. He then hired about 90 workers to prepare the tables by completing the worksheets. This group finished 18 manuscript volumes of tables in a period of about three years.

In 1795, just as De Prony's computations were coming to their conclusion, the National Assembly decided that they would not require decimal angle measure as part of the new metric system. Once they made that decision, the new tables had limited value.

De Prony made several attempts to have them published, but was never successful. They might have been completely forgotten had they not come to the attention of Charles Babbage in the 1820s. At that time, Babbage was a member of the Royal Astronomical Society in London and engaged in the calculation of astronomical tables. He would create a computing plan for these tables and, like the Nautical Almanac Office, hire two independent computers to do the computation.[3]

Babbage found that even with two computers, his final calculations had more errors than he could tolerate so he decided that he would build a geared machine to do the calculations. He approached this problem using the ideas of De Prony as his guide. He chose to compute the tables by the mathematical method of interpolation, the calculation of values between two known values. He divided the method of interpolation into its fundamental additions and designed a machine that could perform those additions. This machine was called the Difference Engine. In promoting this machine, he compared it directly to the accomplishments of de Prony, writing that de Prony had shown how "the division of labor can be applied with equal success to mental as well as to mechanical operations." He claimed that his Difference Engine could replace most of the 90 human computers that de Prony had employed.

Babbage is almost universally acknowledged as the first person to have conceived of the programmable computer but if you trace his influence on those who created the first electronic computers in the 1930s and 1940s, you will find that the path

[3] Computers used the term "plan" rather than "program" to describe their instructions for calculation. The term "program", in its modern sense, was introduced by the staff who worked on the ENIAC computer.

is filled with problems. Babbage never completed his Difference Engine. His later, more sophisticated machine, the Analytical Engine, was unknown to most of the early electronic computer designers. Those who did know of the work, drew few ideas from it. However, if you trace Babbage's influence through human computers and the division of labor, his importance is much more obvious. Though Babbage never completed his Difference Engine, others were able to build such a device and used it to good effect. The American Nautical Office tested a difference engine in 1857, though they never adopted it for production work. Almost seventy five years later, the director of the British Nautical Almanac discovered a commercial accounting machine that could be used as a difference engine. He quickly purchased one for his office and used it to produce tables for his publication. The American Nautical Almanac Office purchased a similar machine in 1940 and used it both to produce an almanac and to create tables for the military during the second world war. Both directors were familiar with Babbage's discussions on divided labor and the importance of divided labor in computation.

Babbage described de Prony's method of divided labor for computation in his book *On the Economy of Machinery and Manufactures*(1835). This book was widely read by those who created and managed factories in the 19th century. More than one critic has noticed that it updated the ideas of Adam Smith for the early machine age. In spite of its wide circulation, de Prony's computing office was not often duplicated. In effect, there were few problems that required such a large computing staff and such a complete division of labor. Most calculations could be handled by a staff of 8 to 12 computers and a judicious use of "aids to computation" such as logarithm tables or, after the 1890s, of adding machines. De Prony's computing office was recreated only once, in 1938, when the United States Government established the Mathematical Tables Project.

The Mathematical Tables Project was a solution to a social problem rather than a scientific one. It was created by a relief agency, the Works Project Administration, as a means of employing out-of-work clerks in New York City. At its height, it employed a computing staff of 450 individuals, most of whom knew little arithmetic beyond the basic rules of addition. The project created 28 volumes of mathematical tables, numerous smaller tables and literally thousands of special computations for various agencies during the second world war. It operated until 1948. During its last years, it operated as a surrogate for the ENIAC electronic computers. Several scientists, including John von Neumann, used the group in order to estimate how quickly the ENIAC might handle their problems.

Managing Computers

Scientists learned to manage large staffs of human computers at the same time that they learned to divide mathematical labor and assign it to individual computers. These scientists had to develop methods that would control production, keep the workers on a deadline and help identify mistakes in the final results. The first managerial tool that they developed was the worksheet, a piece of paper that described each step of the calculation and had blank spaces for the computers to fill with their work. Such worksheets were used by the first director of the Nautical Almanac, Nevil Maskelyne, in the 1770s. Maskelyne would prepare worksheets by hand, drawing a grid on one side of a sheet of paper and writing instructions down the margins. Occasionally, he would illustrate the calculation with a little diagram on the back of the paper. Maskelyne would send these sheets to his computers through the mail. The computers would complete the forms at their leisure and return them to Maskelyne by the same method.

Through the early nineteenth century, most computers worked in their homes. The scientist who employed these computers would coordinate production either by sending instructions through the mail or by occasionally meeting with the computer. This managerial technique saved the expense of separate computing facility but it did not allow much discipline over the computers. Computers could easily delay calculations and refuse to respond to letters. One computer of the 1850s was especially frustrating to the director of the American Nautical Almanac. When the computer refused to answer any letters, the director wrote to a mutual friend, "Will you do me the kindness to explain to [the computer], who does not understand the subject that his relation to me as a public officer, he receiving compensation from the government under an appointment conferred by me with authority required that he should keep me informed of his condition or if he finds that inconvenient or impracticable, that he had better resign his appointment which it will give me pleasure to renew, when he is again ready for work."[4] Eventually, the American Nautical Almanac pulled all of its computers into a central computing room. This practice had been introduced by the British Almanac in 1833 and had been followed by the establishment of a central computing facility at the Greenwich Observatory a few years later. Through these computer rooms, scientists could enforce a more rigorous discipline on their workers, though the discipline of the nineteenth century was still fairly informal and relaxed. One computer of the American Almanac computers recalled that that "In theory there was an understanding that each assistant was "expected" to be in the office five hours a day."[5]

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[4] **Error! Main Document Only.**Charles Henry Davis to Thomas Sherwin, Principal Boston High School, July 5, 1850, Papers of the Nautical Almanac Office, Records of the Naval Observatory, Library of Congress.

[5] Newcomb, Simon, **Error! Main Document Only.** *The Reminiscences of an astronomer*, Boston, 1903, p 74.

Once scientists began building computing offices, their next step was to develop broad methods of computation so that the staff could be kept busy by working on different kinds of problems. Throughout most of the nineteenth century, almanac computers and observatory computers were considered different kinds of mathematical workers. Observatory computers generally spent their days reducing data, taking the positions of stars and planets, as recorded by observers at telescopes and converting them into absolute coordinates in the celestial sphere. This kind of work was considered fairly elementary and commanded less pay than the more sophisticated orbital calculations that were handled by almanac computers. Yet, almanac calculations tended to be seasonal and often did not require a full year's effort by a computer. By combining observatory computations and almanac calculations, an astronomer could keep a computer fully occupied throughout the year.

The U. S. Naval observatory was one of the first institutions that required computers to handle both observatory data reduction and orbital calculations for an almanac. In the 1890s, the director of this combined computing facility, Simon Newcomb, suggested that this computing operation should be pushed one step further. He proposed that American scientists should join together and create an "Institute for the Exact Sciences". He argued that this institute should help scientists build mathematical models for both the physical and newly developing social sciences. The centerpiece of this organization would be a large computing room that would provide free calculating services to the world's scientists. Newcomb was the best known American scientist of his day and perhaps the only individual with a reputation sufficient to lead such an organization; but he soon found that there was little enthusiasm for his project.

Mass Produced Computing Machines

Through the end of the nineteenth century, most human computers did all of their work by hand. Other than a paper and pen, the only tool that they would regularly use was a table of logarithms. Geared adding machines had first appeared nearly two hundred years before, but few of the early adding machines were employed by human computers. These machines were too expensive and too fragile to be used in regular calculation. Human computers began to acquire adding machines only after the appearance of mass produced machines in the 1880s. The first machine to be widely used by computers was the Arithmometer of Thomas de Colmar.

De Colmar, an actuary, marketed his machine to insurance companies and commercial firms but it soon found its way into observatories, almanac offices and university laboratories. "With the Arithmometer at hand," wrote one scientist, "the work [of scientific calculation] becomes rather amusement than labour, especially to those at all fond of ingenious and beautiful mechanism."[6] These machines allowed computers to handle problems that were previously considered too lengthy to undertake. The most of influential of these methods was that of least squares. Astronomers used least squares to prepare highly accurate calculations of orbits but the technique had applications far beyond astronomy. Least squares calculations introduced organized calculation into surveying and social statistics. Surveyors used the technique to adjust their work and minimize errors in their final presentations. Statisticians used the method to analyze data, to find underlying factors that seemed to influence physical and social phenomena. The method of least squares was promoted by Myrick Doolittle, the head of the computing division of the U. S. Coast and Geodetic Survey. Doolittle developed a particularly efficient plan for doing least squares computations. Least squares moved

[6] Jevons, W. Stanley, "Remarks on the Statistical Use of the Arithmometer, *Journal of the Statistical Society of London*, Vol. 41, No. 4, December 1878, p 597-601.

into statistical practice through the efforts of George Snedecor, a mathematician at Iowa State College, and Henry A. Wallace, a news paper publisher in Des Moines. The two wrote a well-circulated book on least squares calculations. Snedecor created a large staff of human computers at his college and trained them in the method of least squares.

Computing machines forced human computers to develop a new set of skills. Almost all of these machines were designed for commercial work, for dealing with monetary calculations. In order to do scientific calculations, with their decimal numbers, complex mathematics and long divisions, computers often had to follow fairly detailed instructions. Though some individuals felt that calculating machines should be designed expressly for scientific, most computers felt that the commercial machines were best computing tools, in spite of their drawbacks. "[Commercial machines] are the product, not of a single and, perhaps, not too experienced designer but of a group of experts," wrote L. J. Comrie, the director of the British Nautical Almanac in the 19020s. He further noted that, compared to special purpose scientific machines, "spare parts and expert service are readily available" and that these machines had prices "that are economical as compared with the overhead costs of design and construction on a small scale."[7]

Comrie became well known for his skill at computation and his ability to adopt commercial machines for scientific purposes. He was the almanac director who discovered the accounting machine that could operate as a difference engine. He also developed procedures for doing scientific calculations with IBM punched card tabulators. The first tabulators that he employed were little more than adding machines, yet he

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[7] Comrie, L. J., "Inverse Interpolation and Scientific Applications of the National Accounting Machine," *Journal of the Royal Statistical Society,* Vol. 3 No. 2, 1936, p 87-113.

showed how they could do the full range of arithmetical operations and could be used for orbital calculations.

Computing As a Formal Discipline

Between 1925 and about 1945, L. J. Comrie was perhaps the world's leading expert in scientific computation. For many of those years, he served on the Mathematical Tables Committee of the British Association for the Advancement of Science. This committee created tables of mathematical functions and publishing reference works on computation. It also served as a coordinating body, an organization that collected information about calculation. In the United States, the National Academy of Science operated a similar group, called the Subcommittee on the Bibliography of Mathematical Tables and Other Aids to Computation. This organization was concerned with documenting the literature of computation, both the methods of calculation and mathematical tables that could be used to simplify hard problems. Through the late 1930s, there was no unified literature of numerical methods. Scientists published their computational ideas in the journals of astronomy, electrical engineering, optics, statistics and other fields.

Beginning in about 1939, the Subcommittee on Mathematical Tables and Other Aids to Computations moved to identify computation as an independent discipline. As an independent discipline, it would be applicable to all forms of scientific practice. It would have a standard set of computational methods that could be used for problems in any form of scientific practice. It would have a single literature that could be used as a reference by anyone undertaking scientific computation. Finally, it would have a recognized way of training new computers. The leader of this effort was R. C. Archibald, the chair of the Subcommittee. He was aided in his efforts by Comrie, though Comrie's contributions were limited by the fact that he was an ocean away from Archibald and that he was undertaking computations for Great Britain's effort in the second world war.

The centerpiece of Archibald's efforts was a new journal, named after his committee, *Mathematical Tables and Other Aids to Computation.* The first issue of the journal appeared in the in winter of 1943. The first several issues were produced almost exclusively by Archibald. "R. C. A. greatly regrets the apparent necessity for numerous personal contributions in this issue, as well as in the second." He wrote in his introduction to the debut number. "It seems certain that elimination in this regard shall be noticeably operative in the third and later issues."[8] His prediction proved true, as the journal quickly attracted a large audience. By 1945, *Mathematical Tables and Other Aids to Computation* had a subscription list of 300 and had published twelve of material. Its efforts were aided by a number of the war-time computing groups, notably the Mathematics Tables Project in New York City. Though the Mathematical Tables Project had originally resembled the computing organization of Gaspard de Prony, it had acquired adding machines during the war, reduced its computing staff and operated as the general computing office of the American Office of Scientific Research and Development. It taught classes on computation, sponsored seminars on new computing methods and circulated mimeographed textbook on computation.

The efforts to establish computing, as practiced by human computers, as an independent discipline, reached its peak at the end of the second world war. The U. S. Navy and U. S. Army provided funds to operate the Mathematical Tables Project as an independent computing office. The subcommittee on Mathematical Tables and Other

[8] Archibald, R. C, "Introductory," *Mathematical Tables and Other Aids to Computation*, Vol. 1, No. 1, 1943, p i.

Aids to Computation held a conference on computation at the Massachusetts Institute of Technology that assembled most of the leading war-time computers. However, to those computers who were paying attention to the postwar plans, the future of the human computer was far from certain. First, the demand for scientific computation was falling rapidly. War industries and agencies had employed several thousand computers between 1940 and 1945 but they had little use for these employees after the end of the war and released them. Second, the new electronic computer promised to replace the human computers. By the summer of 1946, it was clear that human computers would have only a limited role in the post-war world. These workers were not invited to the conferences on electronic computers. Only a few found positions as programmers. The knowledge that they accumulated in the journal *Mathematical Tables and Other Aids to Computation* became part of the literature of numerical analysis. The journal itself was renamed *Mathematics of Computation*. The last major effort of the human computers was a publication called *Handbook of Mathematical Functions*, a book that described how to evaluate complicated mathematical expressions. It was published in the mid-1960s, a time when the computer industry was growing rapidly. Even though half of the pages were filled with the old mathematical tables, it became one of the best selling scientific books of all time.[9]

Conclusion: The Legacy of Human Computers

By the early 1950s, most of the war time computers had vanished, Commonly, these computers took positions as clerks, salespeople, bookkeepers, teachers or mothers after leaving their computing jobs. The programmers that took the place of

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[9] See, Grier, David Alan, "Irene Stegun, the Handbook of Mathematical Functions and the Lingering Influence of the New Deal," submitted to the *American Mathematical Monthly.*

human computers did a different task yet they rediscovered some of the most fundamental lessons of hand computers. Programming taught its practitioners how to divide large activities into small steps and then write the code to handle each step.

The other lessons of the human computer were repeated both in the social organizations around electronic computers and in the computers themselves. The computing centers of the first decades of the computing era, bore at least a superficial resemblance to the computing floors of the Nautical Almanac Offices, Observatories and the Mathematical Tables Project. The early programmers also learned the lessons of L. J. Comrie, the lessons that taught how to use a business machine to do scientific work, how to make a small computer behave like a big computer, how to make any machine do more than it was intended to do. Finally, the issues of professional organizations appeared shortly after the University of Pennsylvania announced the ENIAC computer. By early 1948, the first computer scientists were asking how they could disseminate information about computing machines, how they could train new programmers and how they could control entry to this new field.

Those stories of electronic computers that appeared in the press of the late 1940s and early 1950s, spoke of electronic brains, miracle machines and unrealistic expectations for what these devices could do. By the time that the public began to get a clearer understanding of how computers operated, they had generally forgotten the contributions of human computers; yet, the problems faced by the early computer scientists faced had parallels in the issues encountered by human computers in the 17th, 18th and 19th centuries.

Selected Bibliography:

This paper is based upon the author's book *When Computers were Human*, Princeton University Press, 2005. A considerably fuller description of all computing groups mentioned in this article can be found there.

Babbage's *On Machinery and Manufacture* is available over the internet from Project Gutenberg.

Examples of Computing Plans can be found in the published tables of the Mathematical Tables Project. The Mathematical Tables Project published 28 volumes of tables and at least one can usually be found in any college library. Sadly, they are not catalogued in a standard manner but are often found listed under the authorship of Arnold Lowan, the Works Project Administration or the Mathematical Tables Project. A complete list of these tables can be found at Grier, David, "The Math Tables Project: The Reluctant Start of the Computing Era," *IEEE Annals of the History of Computing,* vol. 20, no. 3, p. 33-50..

The book, *A Handbook of Mathematical Functions*, (Abramowitz and Stegun, Washington, D. C., National Bureau of Standards, 1964) was written by former human computers and suggests the kind of work that they did.

The journal of human computers, *Mathematical Tables and Other Aids to Computation*, is available electronically through JSTOR. It also contains many interesting reports of early electronic computers.

L. J. Comrie has yet to be given the biography that he deserves. The best exposition of his life can be found in Croarken, Mary, *Early Scientific Computing in Britain*, Oxford University Press, 1992.

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