Chapter 7

Electronic Calculators

Introduction

It was not until the mid-1930s that anyone began to think seriously of using high-speed electronic circuits in digital calculating machinery. The vacuum tube itself, a device that could switch current many times faster than electromagnetic relays, was known and heavily used for other applications for at least the previous two decades. Suggestions for why it was not applied to computing earlier and what finally triggered the change are discussed as this chapter traces the introduction of vacuum tubes into calculating machinery.

In 1883, Thomas Edison, as part of his work in developing commercial electric lighting, first noted that an evacuated tube could pass an electric current. Edison did not follow up that discovery and failed to notice the tube's ability to regulate and control currents. Not long after that discovery, J. J. Thompson explained this "Edison effect" as a boiling off of negatively charged particles (named "electrons" in 1894; hence the term "electronic") from the tube's filament, from which they would travel across the vacuum to a metal plate. In 1904, J. A. Fleming used such a "diode"—so-called because it had two working elements: a filament and a plate—to detect weak radio signals. Two years later, Lee DeForest added a third element to the diode, thereby transforming it into a device that could not only detect, but also amplify signals.

DeForest's triode touched off the first of what has become a steady stream of applications of electronics technology, which have affected the character of twentieth-century life. It transformed the radio industry by making it possible to transmit more powerful signals at higher frequencies than before, and at the receiving end it allowed extremely faint signals to be amplified and thus made intelligible. It transformed the telephone industry by permitting voice signals to be amplified and thus sent across long distances—something that hitherto had been possible only with the dot-dash signals of the telegraph. Each of these advances led in turn to further developments in communication and control.

But the calculator and accounting machines industries were not among those so rapidly transformed. One reason was that engineers who worked with the vacuum tube did not perceive it as a switch that could route electrical pulses through a circuit. Indeed, they designed circuits to minimize the tube's tendency to act as a digital switch, while maximizing its ability to produce an amplified, but smooth, continuous copy of its input.[1] The telephone engineer's goal was to get the circuit to reproduce as accurately as possible the nuances of the original signal and to minimize any tendency the tube had to latch on to either extreme of letting all or none of the available current through. Applications requiring all-or-nothing switching, as in routing telephone calls, or transmitting the discrete dots and dashes of Morse telegraph signals, were well served by electromechanical relays. Given these two apparently separate arenas of tube and relay applications, there was a general perception that tubes were ill-suited for calculators, which handled discrete digits and not continuous signals.

In the 1930s, relays and mechanical devices still served the calculating machines industry well. These devices permitted rapid calculation compared to manual methods, which satisfied most users (except for men like Wallace Eckert, L. J. Comrie, and Howard Aiken who wanted to use these machine to solve highly complex scientific problems). Furthermore, electromechanical calculating speeds were in balance with the speeds of the other activities like recording and reading data, and directing the sequence of calculations: activities still done by hand. The limits of the relay's speed to a few arithmetic operations a second did not form a bottleneck that machine designers were concerned with breaking.

First Digital Applications of Tubes

As early as 1919, Eccles and Jordan published a description of a vacuum tube "trigger" circuit that could hold one of two states indefinitely, like an ordinary relay only capable of operating much faster. Their circuit got little attention at first, but eventually it found an application in solving a problem whose nature precluded the use of slower relays. Advances in atomic physics had led researchers to an interest in recording and counting cosmic rays and related phenomena. The Geiger-Mueller counter, itself an ingenious application of a vacuum tube, allowed one to record this radiation; but to count the actual flux of particles required speeds far in excess of what relay circuits could deliver. At the Cavendish Laboratory in Cambridge, England, in 1930, C. E. Wynn-Williams built a device capable of resolving events occurring less than a millisecond apart. His circuit did not use evacuated tubes, but rather gas-filled "thyratrons," which were able to hold a state of either conducting or not-conducting, like Eccles' and Jordan's "flip-flop." The circuits were chained to one another in such a way that for every two firings of the first one, its neighbor would fire once, and so on down the chain. Thus, if there were n such circuits, the firing of the n^{th} would indicate that the first had receive 2^{n-1} events. By making the chain long enough, the speed at which the last tube fired could be scaled down to a point at which it could be recorded by a mechanical counter.[2] Such a circuit was an electronic counterpart of a mechanical register consisting of toothed wheels with a carry occurring after one full revolution of a given wheel.

By the late 1930s such "ring-counters" were well known in the physics community. Variations of Wynn-Williams's design, many using the Eccles-Jordan vacuum tube design instead of thyratrons, appeared in the literature, especially in the journal *Review of Scientific Instruments*.

With additional circuits, these ring counters could be made to calculate as well as count. As early as 1936, William Phillips, an actuary for the British office of the Manufacturers Life Insurance Company, described a machine that computed in the binary scale, which in theory was capable of very high speeds. Although the public description of it did not explicitly mention vacuum tube circuits, Wynn-Williams was thinking of using ring counters to achieve multiplication speeds of between five and ten a second.

Whatever the merits of his design, there was one basic flaw in using such ring counters for numerical calculation. Arithmetic devices, especially those used for banking, insurance, or accounting, must be exact. Ring counters, as built and used by physicists, were not. Cosmic-ray counters were perfectly acceptable if they missed a few events over a long span of time.[3] It would not do to simply build a calculator by substituting ring counter circuits for relays or gears. Nonetheless, it was from these basic concepts that some of the first electronic calculating circuits emerged.

One other development in electronics during the 1930s contributed to the perception of the vacuum tube as a digital as well as an analog device. This was the development of radar, which used pulses of radio-frequency energy to locate objects. Radar devices are fundamentally analog—they typically display the location of the object by an analogous displacement of a spot on a cathode-ray-tube. But a successful radar device requires circuits that can generate very short pulses of current, on the order of a few microseconds in duration. Such pulses had to be of a high intensity and had to be switched on and off cleanly. The intense effort devoted to radar development as World War II approached helped dispel the notion of tubes as strictly analog amplifiers, while generating a wealth of experience in circuit design that calculator designers later drew heavily from. By the late 1930s, these advances in electronic engineering combined with the ever-increasing demands for routine calculation to make the idea of electronic digital calculation at least within the realm of the practical.

Atanasoff

Not surprisingly, a serious attempt to apply electronic devices to calculation occurred independently in America, England, and Germany between 1935 and 1943. But each of these applications was in a sense precocious, in that their arithmetic speeds outstripped their ability to handle input, output, and programming functions. The ENIAC, completed in 1945, shared this problem; but it struck at least a workable balance, and so may be regarded as the first working system to solve practical numeric problems at electronic speeds. Before looking at the ENIAC, we shall examine its immediate predecessors.

In the mid-1930s, John V. Atanasoff, a professor of physics at Iowa State College in Ames, began exploring the feasibility of using electronic computing circuits to help solve systems of linear equations. Such systems occur in nearly every branch of physics; furthermore, many problems described by differential or other equations can be recast and solved as linear systems. Basically, the technique for solving linear systems is straightforward and the same regardless of the number of equations or unknowns, and involves a sequence of ordinary arithmetic operations. But the number of operations grows so large that systems greater than about ten equations in ten unknowns are impractical to solve by hand. Atanasoff, like some other physicists, saw the need to mechanize this process. He first considered analog devices, then configurations of punched-card equipment, but eventually realized that the order-of-magnitude increase in speed that electronics offered was the only way to attack the explosive growth of calculations required to solve large systems of linear equations.

Atanasoff has often recounted the story of how he invented his electronic calculator. One night in the winter of 1937, he got in his car and went for a drive to clear his mind. As he later described the evening, he must have been quite agitated, for he did not stop until he arrived at a roadside tavern across the Mississippi River in Illinois, almost two hundred miles from Ames along two-lane roads. He went in, ordered a drink (something one could not legally do in Iowa in the 1930s), and collected his thoughts.

Atanasoff claims that that night he settled on the overall design of his calculator. It would be an electronic, digital machine; and it would use the binary system. Because the calculating speed had to be matched by equally high speeds for the storage and retrieval of temporary results of previous calculations, he decided on storing the numbers electronically as well. To store the digits he decided to use banks of capacitors (called "condensers" at that time), which in turn would be periodically refreshed to prevent their contents from leaking away.

Finally, he made a preliminary decision as to the arithmetic circuits themselves, although he would not actually build such circuits until 1939. His design differed from Wynn-Williams's ring counters mainly in that the holding of digits before and during an arithmetic operations would take place in banks of capacitors, not in rings of triodes. Vacuum tube circuits, consisting of only fourteen triodes enclosed in seven glass envelopes, would handle the addition of 30-bit binary numbers, while the other three arithmetic operations would be derived from addition.

The machine he envisioned would be hard-wired to carry out the arithmetic sequences to solve linear systems.[4] It did so by the method of successive elimination: first, the coefficients of one equation were multiplied by a constant, so that at least one coefficient was equal to a coefficient of the equivalent term of another equation; then the two equations were subtracted from each other. Because at least one term of each was equal to its counterpart in the other equation, the subtraction eliminated that term, and yielded a new equation having one fewer term. This process was repeated, until it yielded the value for one of the unknowns. That value could then be substituted in each of the equations, yielding a new system of equations with one fewer variables. The method could be repeated until the values of all the variables were determined.

By the end of 1939, Atanasoff and a graduate assistant, Clifford Berry, completed a prototype that could add and subtract binary numbers equivalent to about eight decimal digits of precision. The next summer, Atanasoff submitted a proposal to Iowa State College to fund the construction of a full-scale machine that would solve linear systems automatically. With a modest contribution from the college and a grant of about five thousand dollars from a private foundation, Atanasoff and Berry built a machine that functioned in every respect except for its input-output device, a novel method of punching cards at high-speed that made just enough errors to prevent an accurate solution of large systems of equations.

The most striking feature of their machine was its two drums mounted along a common shaft, each drum containing banks of capacitors that stored thirty numbers of up to fifty bits in length. (Figure 7.1) The capacitors were mounted radially, with a common contact at the center of the drum and wipers that made contact with a row of thirty on the drum's surface. One row of capacitors held the *n*th bit of each of thirty numbers; the machine therefore handled the digits of each number one at a time, or serially, but in parallel regarding all thirty coefficients of an equation. The drums rotated at about one revolution per second. The system was designed to read the charge of each capacitor (binary 1 was +40 volts, binary 0 -50 volts), and immediately refresh that charge with another set of brushes following those that read its value. Without such refreshing, the charges would leak away, but the circuits ensured that there was a more than adequate margin of safety given the speeds at which it

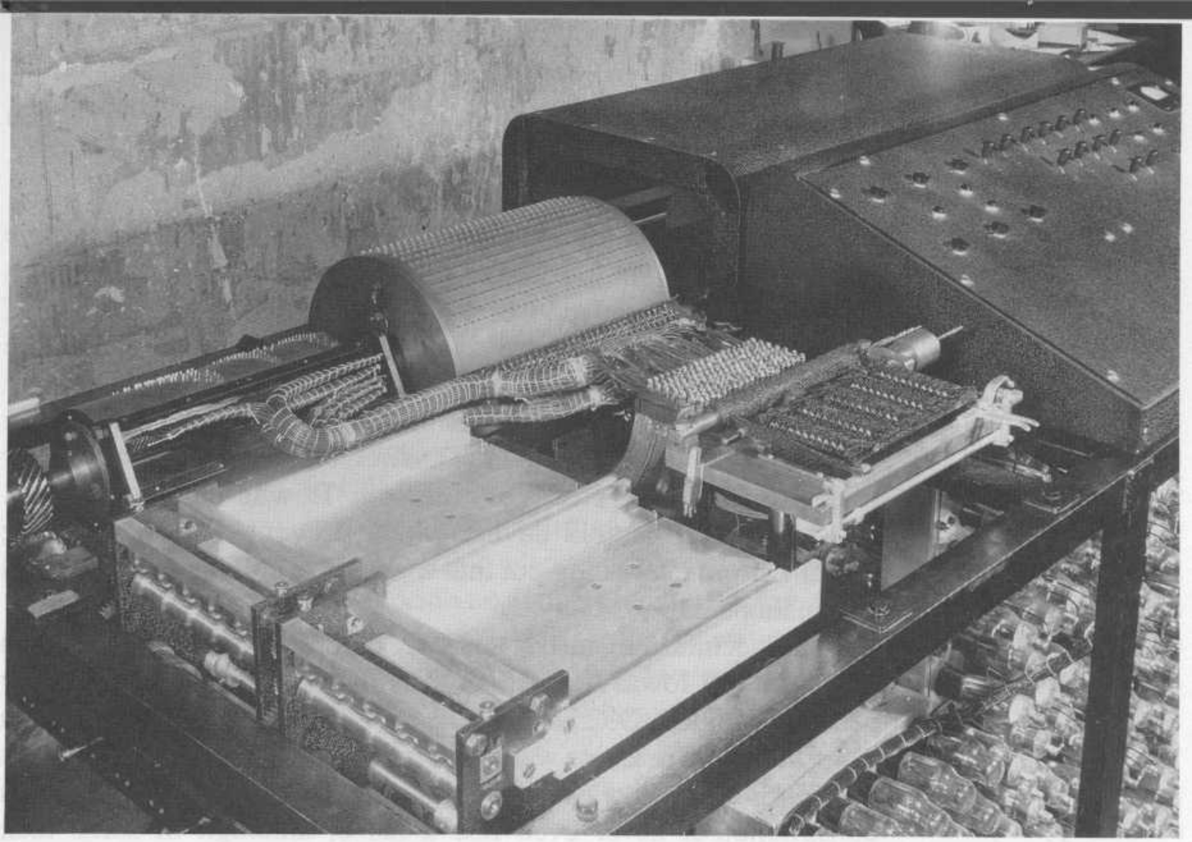

Figure 7.1. The Atanasoff calculator. Courtesy Iowa State University Archives.

operated. Atanasoff called this process "jogging"; it was the forerunner of the concept of dynamic memory so common to modern computer design.

Each drum held the coefficients of one equation of the linear system; and by a process of repeated subtraction the values on one drum were subtracted from those on the other, until one coefficient was reduced to zero. If one coefficient was not an exact multiple of the other, the machine would subtract one extra time (giving a negative coefficient value), then shift the circuits one binary place and add this new value (which would be one-half the old value of the subtrahend) to the remainder. This process would be repeated until it produced zero. In this manner, the machine was able to reduce the coefficients of the system of equations by successive elimination, using only the operations of subtraction, addition, and shifting. Although this method is similar to many modern machine implementations of binary division, Atanasoff's machine did not actually produce the quotient of the two numbers, as it kept no record of the number of times it performed the repeated subtraction.

As each pair of equations was reduced, its new coefficients were punched onto cards by a novel method of depositing a conductive spot on a card by an intense electric spark. This interim storage on cards was an integral part of the process of solving a system of equations, and it had to proceed at high speeds to remain in balance with the electronic circuits that performed the arithmetic. Ordinary card readers and punches might suffice for the initial input of a problem or the output of the final answer, but they were too slow for this intermediate storage function. It was the occasional malfunctioning of this device which prevented the computing machine from ever being put into routine use solving large systems of equations.

The machine remained at this stage of refinement until 1942, when both men left Iowa: Atanasoff for the Naval Ordnance Laboratory near Washington, D.C., and Berry for Consolidated Engineering in California. The machine was never made fully reliable and never put to use. For many years its existence was forgotten. During its construction it never even had a name, although in some later descriptions it was called the ABC for Atanasoff-Berry-Computer. Thirty years after work on the machine was abandoned, when the invention of the electronic digital computer became the subject of a lawsuit, attorneys representing one of the parties rediscovered the work. By that time, the ABC itself, save for a memory drum, had long since vanished.

Helmut Schreyer

The idea of computing with vacuum tube circuits occurred to Helmut Schreyer in Germany at the same time. Schreyer was a schoolmate of Zuse at the Berlin Technical College, where Schreyer was studying electrical engineering. He had helped Zuse with the construction of the Z1 and had suggested to Zuse the possibility of using modified film projection as a way of programming the machine. But whereas Zuse had early on favored mechanical or electromechanical computing elements, Schreyer saw that one could construct an electronic circuit that worked just like the binary relays Zuse was using, only at much higher speeds. He based his circuits on a combination of triodes coupled to gas-filled lamps (somewhat like neon light bulbs), which had well-defined voltage levels that would hold a state of either conducting or not conducting. Such circuits were slower than Eccles-Jordan flip-flops, but still much faster than ordinary relays. He designed a number of switching circuits using his so-called tube relay, and in 1941 he received a doctorate from the Berlin Technical College for a thesis on the subject.

Schreyer's thesis did not discuss the application of these relays to computing, but he did mention to Zuse the possibility of building a computer based on the Z3's design, using tubes instead of relays (recall that the Z3 was completed and working by 1941). Schreyer proposed to the German Army Command that he build a full-scale programmable electronic computer having about fifteen hundred tubes and about as many lamps. But he was turned down. The German Army Command felt the two years time Schreyer needed to complete his machine was too long: given their perception of the course of the war at that time, they chose to concentrate on projects that could be completed sooner.

Schreyer did not give up. The German army was not interested, but the Aviation Research Office (DVL) was; and they supplied him with funds to begin a more modest project: an electronic device that converted three-digit decimal numbers to and from binary. In the meantime, the Telefunken Company had developed a special tube well suited for Schreyer's designs.[5] Schreyer combined this tube with three fast-acting lamps and nine resistors to give a reliable and fast (up to 10 kHz) circuit that accepted up to three inputs and produced their logical addition (or), multiplication (and), or negation (not). The lamps were bathed in ultraviolet light to increase the reliability of their operation at high speed (Figure 7.2).

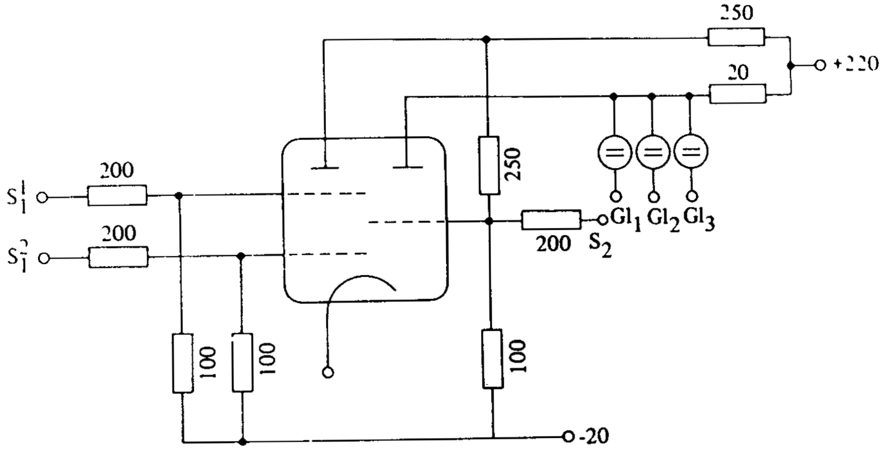

Figure 7.2. Schreyer's logic circuits (ca. 1942). Courtesy GMD, Bertin.

Work on the binary-to-decimal converter began in 1941 but proceeded slowly as Schreyer was called to do other work, including work on radar and on an accelerometer for the V-2 ballistic missile. In November 1943, the converter was damaged during a bombing raid on Berlin, and further work on electronic computing came to a halt. After the war, Schreyer left Germany and never again returned to computing. Thus, the priorities of the war diverted both Schreyer and Atanasoff from further progress in electronic computing, although government support for Atanasoff's computer work was somewhat greater than for Schreyer's.

The Colossus

If the war hindered progress for Atanasoff and Schreyer, it had the opposite effect on the first British steps toward electronic calculation. During the War, the British Foreign Office's Department of Communications designed a machine called the Colossus, which used high-speed electronic circuits to assist the British in decoding intercepted German radio messages that had been encrypted on a machine called the *Geheimschreiber* (Secret Writer). The first Colossus was operational late in 1943, and by the end of the war at least ten were built along the same design. The first one contained fifteen hundred vacuum tubes and operated at a frequency of five thousand pulses per second.

Unlike the two electronic calculators just described, the Colossus's logic circuits performed not ordinary arithmetic, but rather Boolean comparisons of one string of pulses with another. These operations are logically equivalent to binary arithmetic, but strictly speaking the Colossus was not a calculator. The Colossus *was* capable of high-speed internal generation and storage of data; and its sequence of operations could be modified by setting switches, while certain characteristics of the message to be decoded were entered into the machine by plugging cables. These features gave the machine a sophistication lacking in contemporary electronic and relay calculators.

The interception and decoding of German messages was a significant factor in the Allied victory, a fact kept secret until recently. The work was carried out in great secrecy at Bletchley Park, a Victorian estate about fifty miles north of London. No single person was the Colossus's inventor, but of the many who worked at Bletchley, Alan M. Turing, M. H. A. Newman, and Thomas H. Flowers were the key individuals responsible for the machine's design, construction, and method of operation. Many others played important roles, including C. E. Wynn-Williams mentioned above.

The immediate ancestor of the Colossus was a partially electronic machine called the "Heath Robinson," after a well-known British cartoon character (Americans might have called it a "Rube Goldberg"). This machine compared two streams of data entered on two paper tape readers and counted the Boolean sums or products of the holes punched on each tape with those on the other. One tape contained the encrypted German message, the other a coded representation of what the British believed the German's enciphering device did to a message (this information was itself arrived at by a combination of guesswork and mathematical theory, and by taking advantage of occasional German lapses in encrypting every message thoroughly). By performing this comparison of the two tapes over and over, each time moving one letter sequence a single place relative to the other, a clue might emerge as to the exact code the Germans had used on the particular message.[6] This clue in turn would lead to another tape with which to repeat the process, and so on until the original scrambling of letters was exactly reversed.

Because of the great number of runs needed, and because of the more general fact that the value of reading enemy messages rapidly diminishes with time, it was of utmost importance that the machine process messages quickly. The Heath Robinson's tapes fed data at the rate of up to two thousand characters per second—at this speed ordinary electromechanical tape readers were useless, and a special photoelectric reader was specially developed for this function. This reader, developed by the Post Office Research Establishment at Dollis Hill, was vital to the success of both the Heath Robinson and later the Colossi, where an even higher speed of up to five thousand characters per second was obtained.

The Heath Robinsons, however, suffered from difficulties in reading the two tapes in synchrony at high speeds. Even a slight misalignment would render the whole process worthless. Flowers, who had explored the substitution of electronics for relays in telephone circuits before he was transferred to Bletchley Park in 1942, suggested that one of the tapes be completely replaced with an internally stored table for the trial "key" tape, which could be delivered in the proper phase and sequence to the rest of the machine at high speeds. Stepping this pattern relative to the tape of the German's code could likewise be done electronically. This at once solved the problem of synchronizing the tapes and greatly reduced the Heath Robinson's "Rube Goldberg" complexity.

But as Flowers said: "My suggestion, made in February 1943, was met with considerable skepticism. The first reaction was that a machine with the number of tubes that was obviously going to be needed would be too unreliable to be useful. Fortunately, this criticism was defeated by the experience of the Post Office using thousands of tubes in its communication network. These tubes were not subject to movement or handling, and the power was never switched off. Under these conditions tube failures were very rare."[7]

The main group at Bletchley continued work on the two-tape Heath Robinsons, while engineers at Dollis Hill began almost immediately building an electronic device. After eleven months of intense effort, they completed their first model. The machine contained about fifteen hundred vacuum tubes and generated the "key-tape" data from parameters stored internally in ring counters. In early December 1943, it was put into service at Bletchley, where it acquired the name "Colossus" because of the number of tubes it contained. It soon proved to be a fast and reliable machine, producing far more useful output than the Heath Robinsons, while breaking down less often than many had feared. Its tape reader operated at a speed of five thousand characters per second, with the tape moving through it at over thirty miles an hour. The tape reader's photoelectric scanner had an ingenious double-crescent mask that produced a square-shaped pulse of current from the photocell reading the passage of light through a round hole in the tape. Special timing holes on the tape triggered an internal electronic clock, whose pulses synchronized reading the tape with comparing the internal key data, thus avoiding problems of synchronizing the two streams of data at such high speeds.

The success of the Dollis Hill engineers did not go unnoticed—in February 1944 they were told to produce twelve more machines by the summer! Flower's reaction was "flatly that it was impossible." Increasingly, the Allied ability to keep up with the German encryption depended on the Colossus's powers. Although the Germans had not caught on to the fact their messages were being read, they were slowly introducing new operating practices and a new, slightly more advanced coding machine. The code-breakers at Bletchley were always at least a half-step behind the Germans at any time, and they were facing the prospect of falling so far behind they would never catch up—just as the Allies were preparing the cross-Channel invasion.

Flowers promised to have at least one new Colossus working by the first of June, and once again the Dollis Hill group did the "impossible." They met the deadline (the first of the new machines was not working the evening of May 31, but was set right by an engineer overnight). What was more, the new Colossus incorporated a number of improvements over the first, not the least of which was its ability to process not one, but five streams of data from the tape in parallel, thus increasing its speed fivefold. And unlike the original Colossus, the new model contained circuits that could automatically alter its own program sequence. If it sensed a potentially meaningful pattern, a circuit permitted it to redirect its stepping through the internal table in such a way that would more quickly find a path to a solution. Within a decade, this ability became a defining feature of digital computers.

By V-E Day in May 1945, a total of ten Colossi were in use at Bletchley. Design changes continued to be made, but after the first one, each of the following contained about twenty-four hundred tubes, twelve rotary switches, and about eight hundred relays. Input of tabular data was made by plugging cables into pairs of sockets, which in turn directed the firing of ring counters. The pattern stored in these rings was compared with the pattern read from a tape, according to various Boolean operations. Usually the bit streams were added modulo-2, but a number of other functions were possible if so desired by the cryptanalysts.

After each pass the comparison was repeated, only with one pattern offset by one position relative to the other, as set by a rotary switch. The results of the comparison, as well as the positions of the rotary switches, were printed out on a typewriter for further processing by the human cryptanalysts at Bletchley. The Colossus did not produce a decoded message, but rather an intermediate text that required further work, not always leading to success.

The Colossus's place in the history of the invention of the computer is hard to fix. Compared to other machines of the day, it was both more and less than what we now recognize as a digital computer. It performed all logical functions electronically at very high speeds, stored data internally in high-speed, fixed, and alterable stores, and stepped through a sequence of operations also at electronic speeds. In a rudimentary way, it could also alter that sequence.

But it was a machine capable of attacking one and only one problem: the analysis of German messages, which themselves were encrypted in a specific way. The Colossus did not perform ordinary arithmetic, nor could it solve other logical problems not cast in the same mold as those for which it was designed. Its greatest legacy—besides the enormous contribution it made to the Allied war effort—was that those who worked on it gained an experience with computing circuits that allowed them after the war to design and build a number of general-purpose electronic computers. These computers, built at Manchester, Cambridge, and London, were among the first to be placed in operation anywhere. In the context of the postwar evolution of digital computer architecture, the Colossus had less influence. The computers built after the war were general-purpose devices that could perform numerical or logical work, but they were immediate descendants of machines that had been built for numerical work, not from logic machines like the Colossus. The architecture of the modern stored-program computer hardly resembles that of the ENIAC, but it evolved from the ENIAC—a special-purpose electronic computer optimized for certain numerical problems.

The ENIAC

Of the machines described above, only the Colossus was able to take advantage of high processing speed, by balancing it with a fast photoelectric tape reader and plugboard programming. The first machine that could solve complex numerical problems electronically, and whose programming was flexible enough to allow it to solve a variety of such problems, was the ENIAC, completed in late 1945 at the Moore School of Electrical Engineering at the University of Pennsylvania. The ENIAC is the most famous of the early computers, but not always for the right reasons. It deserves its fame not for its electronic circuits, which several other machines already had, nor for its architecture, which although ingenious and full of promise was rejected by subsequent designers. One should rather remember the ENIAC as the first electronic machine to consistently and reliably solve numerical problems beyond the capability of human and in many cases relay computers as well.

The ENIAC owed its existence, like the Colossus, to the pressures of the Second World War. It grew out of the need by the United States

Army to compute firing tables for ordnance then being employed in the field. The rapid deployment of various new types of artillery to widely dispersed battle fronts strained the capabilities of the Army's Ballistic Research Laboratory (BRL) at Aberdeen, Maryland, to supply field officers with firing tables, without which the guns were useless. After 1935, the BRL began to employ a variety of methods for preparing these tables, including one method that used differential analyzers of the type described in Chapter 5. At the Moore School in Philadelphia, there was one such analyzer; teams of human computers (many of them recent graduates of women's colleges in and around Philadelphia) also prepared tables using mechanical calculators. Although each of these methods worked, none was able to produce firing tables fast enough for the Army's needs after the United States's entry into the war in 1941.

Against that background at the Moore School, John Mauchly conceived of an electronic calculator that he felt would be able to compute tables much faster than any other method. Like the teams of human computers, his would be a digital machine, solving the differential equations of ballistics by numerical methods. But like the Differential Analyzer in which the integrators were connected via servomechanisms and cables, this machine would have a flexible arrangement for interconnecting its individual units, thereby allowing it to be used to solve a wide variety of problems.

John W. Mauchly (1907-1980) received a Ph.D. in Physics from Johns Hopkins in 1932 and from 1933 to 1940 taught physics at Ursinus College outside Philadelphia. While at Ursinus, he pursued an interest in meteorology and began investigating mechanical aids to assist with a problem he had a long interest in, namely correlation between weather and sunspots or other periodic solar activity. He built a small electrical analog computer to assist with the analysis of weather data, and began searching the literature for information on other mechanical aids to calculation.

Mauchly also explored the use of punched-card equipment, and for a while considered building a special-purpose harmonic analyzer like Kelvin's tide predictor. Sometime around 1940, he began considering the use of vacuum or gas-filled tubes for counters and storage of numbers. He was familiar with cosmic-ray counters then in common use by physicists, and at that time he also built one or two vacuum tube circuits to explore these concepts.

In December 1940, Mauchly attended a meeting of the American Association for the Advancement of Science, where he presented a paper on the weather analysis he did using his analog computer. Atanasoff was among those who heard the talk, and afterward he introduced himself and told Mauchly of the electronic machine then being built in Iowa. The two men corresponded frequently on the subject of computing, and in June 1941, Mauchly drove out to Iowa to visit Atanasoff for five days. While there as Atanasoff's guest, Mauchly examined the partially completed machine, and the two had long discussions about its details, as well as about the general philosophy of calculator design.

When he returned, Mauchly enrolled in a special summer course in electronics at the Moore School designed to acquaint professionals with the recent developments in electronics that were expected to play a role in the war. Mauchly completed the course and stayed on at the Moore School as an instructor. His correspondence with Atanasoff and others at that time reveals a growing conviction that a calculating machine using vacuum tubes and digital circuits was indeed both feasible and potentially useful—not only for meteorology but also for a range of problems the military might be interested in, including the preparation of firing tables. Correspondence continued through 1941 and into the next year, but tapered off after that, and the two men went their separate ways.

In December 1941, the United States entered the war, and the Ballistic Research Lab pressed on with even greater urgency in computing firing tables. At the Moore School, Mauchly met J. Presper Eckert, who at the timewas studying for a master's degree in electrical engineering and who had already done significant work on several advanced electronics projects, including the Moore School's Differential Analyzer.

By the time he met Eckert, Mauchly had conceived of an electronic calculating machine that would eventually become the ENIAC. His visit with Atanasoff and their exchange of letters suggest that Atanasoff's work was a spark that ignited Mauchly's growing interest in digital electronic devices. The fact that in Iowa Mauchly saw another physicist building such a complex machine might have helped convince him that his own, independent ideas were not all that farfetched (it might easily have seemed so at Ursinus, where Mauchly had few colleagues with whom he could discuss such grand schemes).

Many years later, the issue of who deserved credit for the invention of the computer became the subject of a court case, *Honeywell vs. Sperry Rand*. Briefly, the court case arose because Sperry Rand held a basic patent on the computer (# 3,120,606).

Honeywell challenged its validity and thus Sperry's right to collect royalty payments from other computer manufacturers. The patent itself was for the ENIAC, and was applied for in 1947 by Mauchly and several other members of the ENIAC team. Sperry Rand acquired the rights to this patent after its merger in 1955 with Remington Rand, which had in 1950 acquired the Eckert-Mauchly Computer Corporation. The patent was finally granted in 1964, although Sperry Rand had been collecting royalties prior to that time. In 1973 Judge Earl Larson of the U.S. District Court for Minnesota ruled the patent invalid, primarily due to Atanasoff's prior work and his influence on Mauchly.

Mauchly strongly denied the influence of Atanasoff. The ENIAC had a very different structure from Atanasoff's machine. Most of all, the ENIAC was designed to solve different problems, and it could be reconfigured to solve a range of such problems—something that Atanasoff's machine could not do. If Atanasoff is the inventor of the electronic digital computer, as the courts judged in 1973, then it is in the restricted sense outlined here. At the same time, evidence uncovered at the trial reveals that prior to his visit to Iowa, Mauchly had only vague and ill-defined ideas about how to use vacuum tubes to build circuits that could perform digital calculation. Atanasoff, by contrast, was skilled at circuit design and had a thorough understanding of the difference between electronic circuits used for analog as opposed to digital applications.[7] However, the ENIAC's circuits were not derived from Atanasoff's. Atanasoff deserves credit as one of the persons who made the electronic digital computer a reality, but he is not the "inventor" of the digital computer.

In August 1942, Mauchly wrote a brief memorandum on "The Use of High Speed Vacuum Tube Devices for Calculating," in which he outlined his thoughts on the feasibility of such machines. That memo received little immediate response, but by the following spring, as the problem of computing firing tables mounted, the Army was more willing to entertain Mauchly's notion. In April 1943 he and Eckert submitted a formal proposal to the Army for the Construction of an "Electronic Diff. Analyzer," with "diff." standing for "difference" but intentionally abbreviated to suggest a kinship with the analog Differential Analyzer already familiar to the Army. The proposal was accepted, funds were made available, and design and construction begun. A year later, the basic design was complete—and the name was changed to ENIAC, for Electronic Numerical Integrator and Computer.

The heart of the ENIAC, and the first part its creators began designing, was a set of accumulators in which numbers were both stored and added.[8] Eckert and Mauchly were familiar with thyratron scaling circuits used by physicists, but rejected that design because it could not guarantee enough accuracy. They settled instead on a ring counter having ten positions for each of the decimal digits, but which stored each digit in an Eccles-Jordan flip-flop. The result was an electronic counterpart to a mechanical calculator's decimal wheel, with one flip-flop corresponding to each tooth of the wheel. In the ring counter, the state of one (and only one) flip-flop would be different from all the others. When the ring received a pulse or train of pulses, the flip-flop having the different state would cycle around the ring accordingly, sending out a carry pulse to the next ring counter if it passed through the nines position (Figure 7.3).

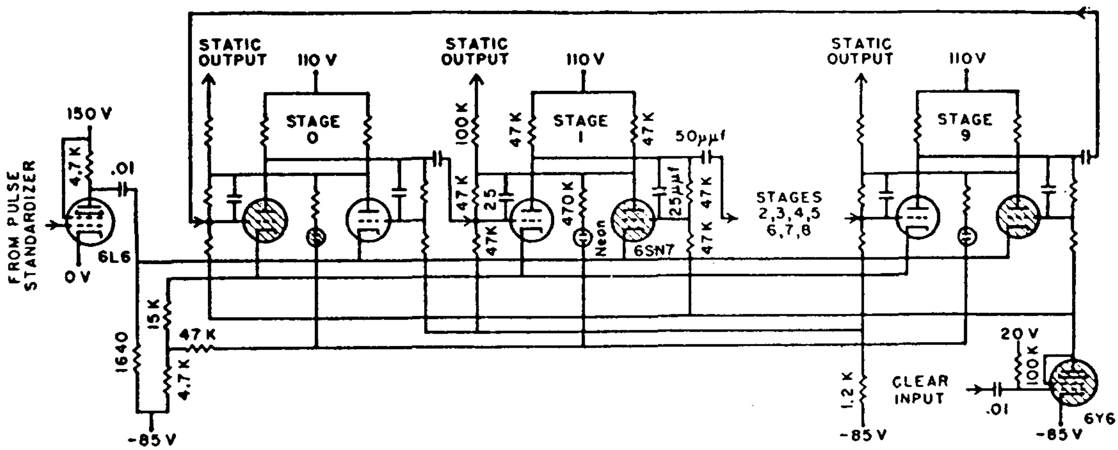

Figure 7.3. ENIAC's ring counter. Courtesy IEEE.

A unit of ten ring counters stored a ten-digit decimal number. Because a carry mechanism was built in, the unit could also perform addition and subtraction. One set of counters, together with circuits that gated pulses into and out of it, made up one accumulator. Each accumulator required 550 tubes; it was the need for reliability that dictated this rather large number of tubes to handle a single ten-digit number. The whole ENIAC, with twenty accumulators, a multiply-divide unit, and other units for control and input-output, contained about 18,000 tubes and consumed 150 kilowatts of power.

Besides the twenty accumulators, the ENIAC contained a separate unit that performed multiplication and division, a bank of ten-position switches that stored up to one hundred numbers for use during a calculation, and standard IBM punched-card readers and printers for input and output. A separate cycling unit delivered electronic pulses at 100 kHz to all other units to keep them synchronous. The basic machine cycle, or addition time, was 200 microseconds; a multiplication took 14 cycles or 2.8 milliseconds.

If the ENIAC's number registers were akin to those found in mechanical calculators, its method of programming was a direct descendant of the Differential Analyzer's. Cables, plugged into large plugboards distributed throughout the machine, directed the sequence of operations, while a cycling unit orchestrated the overall flow of instructions. This method, though cumbersome and time-consuming when it came to configure the ENIAC to solve a new problem, was nevertheless the only feasible way to exploit its high arithmetic speeds. The ENIAC's accumulators were capable of adding five thousand numbers a second; no electromechanical input device (save possibly the Colossus's paper tape reader) could have supplied instructions to it at that rate. It took up to two days to make all the necessary connections that set up the ENIAC to solve a new problem; once set up, it might solve that problem in minutes.[9]

In programming the ENIAC by plugging cables, its users were literally rewiring the machine each time, transforming it into a special-purpose computer that solved a particular problem. In a sense this is what happens whenever one programs a modern computer; only with the ENIAC, as with the Differential Analyzer from which the concept was derived, the changes were made by a person rather than automatically by the computer itself.

The important point is that however time-consuming the setup period was, it allowed the ENIAC to solve a wide range of mathematical problems, including many that its designers never anticipated. It was not fully a "general-purpose computer"—for example, it could not solve large systems of linear equations as Atanasoff's machine was designed to do. But its ability to be reconfigured to perform an almost limitless sequence of steps, including iterative loops of operations, sets the ENIAC apart from the other electronic calculators described thus far, and places it astride the categories of "calculator" and "computer."

The ENIAC was completed late in 1945 (well after the end of the war) and publicly dedicated in February 1946. The dire predictions that a machine with so many tubes could never be reliable did not come true: Eckert had carefully designed all the circuits so that the tubes drew far less current than they were rated for. And once completed, the ENIAC's operators left the tube heaters on all the time, preventing the extreme temperature changes that cause filaments to burn out. After an initial run-in period, the ENIAC routinely ran up to twenty hours between tube failures—not as good as some relay calculators, but during those twenty hours the ENIAC could do more work than a relay machine could do in months. Like the Colossus, ENIAC's speed allowed it to tackle problems that in practice were insoluble by any other method. From the very start, the ENIAC solved a steady stream of problems in a variety of fields; its first job was a still-classified problem relating to a design of the hydrogen bomb. In fact, the ENIAC was kept so busy at first that its installation at the BRL's Aberdeen Proving Ground was delayed a year. It was finally moved, in 1946-47, to Aberdeen, Maryland where it computed firing tables reliably until it was shut down in 1959. Also while at Aberdeen it solved a number of other problems, ranging from number theory to meteorology, that demonstrated its versatility and power.

There is no question that the machine was successful in doing the kind of work it was designed to do, but the ENIAC's shortcomings of limited memory size and tedious programming were apparent from the start. These two deficiencies were remedied to a limited extent by two modifications to the machine's original design.

At Aberdeen, the ENIAC was modified in 1948 so that the pulses that directed its program sequence came not from cables laboriously plugged into plugboards, but rather from one of the banks of switches originally intended to be used as a function table. It was done by exploiting a symmetry of the ENIAC's design, namely that cables carrying numbers from one unit to another contained eleven channels (for the ten decimal digits plus the sign), the same as the number of program channels the cycling unit delivered to each unit. In that a program pulse in the ENIAC was electronically identical to a number pulse, it was easy enough to route the pulses delivered by a function table onto the 11-wire program trunk. Eckert has stated that he purposely designed this symmetry into the ENIAC from the start, but in any case it was not exploited until after 1948. Its effect was to shorten the setup time greatly, while slowing down the execution time somewhat (because steps could no longer be executed simultaneously in different parts of the machine).

In 1953, a mass storage device was fitted, which increased the ENIAC's memory capacity from 20 to 120 numbers. This device used small magnetic cores, whose direction of magnetization represented a binary value analogous to the flip-flops of a ring counter. This modification, together with the internal storage of the machines's instructions in numerical (albeit nonalterable) form, foreshadowed two salient features of nearly every computing machine built thereafter.

To summarize, the ENIAC was a transitional device that incorporated many of the features of what we now define as computers: high processing speed, flexible (and from 1948, internally stored) programming, and the ability to solve a wide range of problems in practice insoluble by any other means. But at the same time, it exhibited many of the features—and the inherent limitations—of calculators: a tedious method of setup, internal use of decimal instead of binary numbers, and the use of accumulators that performed the dual functions of storage and arithmetic.

But the most important thing was that it worked, and worked well. Its existence was well publicized from 1946, and news of the ENIAC helped dispel the skepticism about the feasibility of electronic calculation. Its place as a milestone in computer history has become controversial, especially since the 1973 legal judgement declaring Eckert and Mauchly's patent on the ENIAC invalid.

Other Electronic Calculators

It was from the ENIAC team that the concept of the modern stored-program computer emerged. As its designers recognized the ENIAC's deficiencies, they wisely chose not to abandon the project (cf. Babbage) but rather deferred their ideas for a new design to the future. That design produced the EDVAC, and later a host of other computers that embodied the stored-program principle. But for almost ten years, even well after the advantages of the EDVAC-type design were recognized, other electronic calculators continued to be built. A few of these deserve a brief mention here.

The IBM SSEC

IBM equipment was used with little modification for the ENIAC's input-output devices. Although the head of IBM, Thomas Watson, Sr., hardly foresaw the future trend toward electronic computers, he did embark on an ambitious project to build an electronic computer for IBM. This machine was finished quickly, by 1948, and was called the SSEC, for Selective Sequence Electronic Calculator. Its design was a hybrid of traditional IBM punched-card technology, Howard Aiken's ideas, and some of what IBM gleaned from the ENIAC and the Moore School staff. Wallace Eckert directed the overall project, while Frank Hamilton, one of the builders of the Harvard Mark I, was the chief engineer at IBM's Endicott, New York plant. Hamilton was reluctant to build a fully electronic machine, and the result was an awkward architecture of a high-speed electronic store holding only eight, 20-digit decimal numbers, together with a much slower relay store that held 150 numbers. A third store, consisting of an array of paper-tape devices, held an additional twenty thousand numbers. Like the ENIAC, the SSEC was huge, occupying a prominent windowed showroom at IBM's New York offices on 57th St. The machine did incorporate a number of innovative features, including the ability to store and even modify instructions in the 8-number electronic store, but the awkward compromises of its design gave it few of the advantages, while retaining most of the disadvantages of both relay and vacuum tube technology. It did solve a number of problems at a time when few other machines of its size were operating reliably (and of these few, most were under strict control of United States military organizations).

Wallace Eckert used the SSEC for astronomical work; his computation of tables of the Moon's position helped to guide the Apollo astronauts twenty years later. The SSEC was dismantled in 1952, after a modestly productive but short life.

The Aviation Industry Calculators

By 1950, a general consensus was beginning to emerge as to the best way to build an automatic calculating machine. It was agreed that the machine should have a large-capacity read-write memory in which both program instructions and data are stored. It should use the binary system, and its circuits should be electronic.

But there were serious difficulties in getting such machines completed and working. In particular, the question of how to construct a memory of adequate capacity and sufficient speed was unresolved (and remained so until the perfection of the magnetic core in the mid-1950s). Meanwhile, the need to solve large systems of linear equations, and linear and nonlinear differential equations was growing, especially within the booming aviation industry. In the United States this industry was centered in Southern California, where its engineers took the initiative in designing several electronic calculators that had unique and interesting designs and performed a lot of computation for them for many years.

In 1951, engineers at Northrop Aircraft developed a machine in many ways reminiscent of Atanasoff's machine, in that it used a rotating drum on which successive approximations of the solution to a problem were computed and stored. They called their machine "MADDIDA" for Magnetic Drum Digital Differential Analyzer.[10] The original model was built under an Air Force contract for the Snark guided missile project, but after the completion of a prototype in 1949, Northrop built a production model, of which at least ten were installed by the early 1950s. The production model contained about one hundred tubes; its drum stored about ten thousand 29-bit binary numbers. The MADDIDA's processor consisted of twenty-two circuits that performed numerical integration iteratively on pieces of data, at an addition speed of ten microseconds.

Despite its limitations, the MADDIDA was a successful machine and was highly regarded by those who used it. For Northrop engineers the important point was that with it they were getting solutions to their problems (while the BINAC, a stored program computer they contracted from Eckert and Mauchly for the Snark project, never worked at all for them.) The MADDIDA's ability to deliver solutions to problems was clearly more important to Northrop. Besides their MADDIDA, three or four other companies made and sold similar devices through the early 1950s. After about 1955, manufacturers of stored-program computers learned to produce simple, compact, and reliable machines, thereby taking away the MADDIDA's *raison d' etre*. Meanwhile, its designers went on to found a host of computer companies on the West Coast, including Computer Research Corporation, ElectroData, and Teleregister. These companies formed the basis for much of the dynamic computer industry in California during the next decade.

Another machine developed at Northrop and used heavily by the aviation industry was an adaptation of IBM accounting equipment. Northrop engineers coupled an IBM Type 604 calculator to a Type 402 accounting machine, which they controlled through a plugboard device of their own design. The combination worked well, and later IBM extended the concept by adding a type 521 summary punch and a type 941 memory unit, which gave the system an ability to store up to fifty 10-digit decimal numbers. IBM marketed this system as the Card Programmed Calculator, or CPC; nearly seven hundred were installed and used until the late 1950s. Its type 604 calculating unit used vacuum tubes operating at 50 kHz, performing eighty multiplications a second. Programming was carried out by a combination of plugboards and punched cards, with conditional branching and loops of up to ten lines of instructions possible. For companies like Northrop, the CPC filled the need for computing power at a time when good commercial stored-program computers were unavailable.

Conclusion

The high speeds of electronic circuits offered dramatic increases in the power of mechanized arithmetic, but also brought forth serious design challenges. The variety of calculator designs described in this chapter reveals that there was little agreement on how best to use vacuum tubes. One serious problem was the perceived unreliability of tubes compared to relays; as it turned out, engineers like Presper Eckert found ways to design tube circuits that were even more reliable than relay circuits. More serious was the integration of high arithmetic speeds with the speeds of input, output, and programming. Each of the machines just described addressed this issue in a different way, with varying degrees of success. None of them achieved a good balance among the various functions. Only with the adoption of the stored-program concept was this problem adequately met, allowing the technology of electronic calculating circuits to realize its potential.

Notes

1. In British Commonwealth countries the vacuum tube is called a "valve," a name which might further suggest its function as a regulator of the flow of current, as well as an all-or-nothing switch.

2. By connecting the chains of thyratrons in rings, one could count in any number base besides binary, with the base determined by the number of tubes in each ring.

3. This is generally true of counters: consider an automobile odometer, which counts the total miles a car has traveled. It is usually off by a few percent due to numerous factors, but for its use in an automobile the error is tolerable.

4. The sequence was fixed for this process and did not need to be altered.

5. This tube enclosed a tetrode, having two grids, and a triode in the same glass envelope.

6. The exact nature of this clue and how it was observed is still kept secret, but it is derived from the statistical properties of a sequence of letters that in some way represents a meaningful message.

7. Indeed, Atanasoff was the first to use the word "analogue" to describe that type of computer ; "digital" was first used by George Stibitz in 1942.

8. The 1943 proposal called for the ENIAC to have ten accumulators; later this was doubled to twenty.

9. Because the input of data was through punched cards and not cables, it was easy to have the ENIAC solve a set of problems in which the basic operation sequence remained unchanged. This was the kind of operation the designers had intended, although with the end of the war the ENIAC assumed a much different role that required the frequent changing of its programs.

10. Unlike Atanasoff's computer, MADDIDA stored digits on the drum magnetically and was dedicated to solving differential equations.

Further Reading

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