Chapter 6

Relay Calculators

Introduction

Charles Babbage had planned to power his Analytical Engine with a steam engine—steam being the only feasible prime mover available in the 1830s. In that same decade, however, others were making discoveries that led to the electric motor: a source of motive power more compact, cleaner, quieter, and most of all, much more flexible than steam. By the early twentieth century, calculators were just one of many machines that were powered by electricity.

But electricity could do more than replace the steam engine or human arm as a source of power; it could also represent the numbers themselves that a calculator handles. Electric circuits could replace the cams, pins, gears, and levers that actually do the computation. Hollerith's electric tabulators took advantage of this property, and we have already seen how the rival Powers system, developed after 1911 to compete with Hollerith, suffered in comparison because it used electricity only for motive power.

By the 1930s, a number of inventors recognized that the ability (as well as the power) offered by electric circuits allowed one to build a machine that could not only do arithmetic, but also direct a complex sequence of calculations automatically. That, of course, had been Babbage's dream, and by 1945 that dream had come true. It came true by combining traditional mechanical calculator architecture with

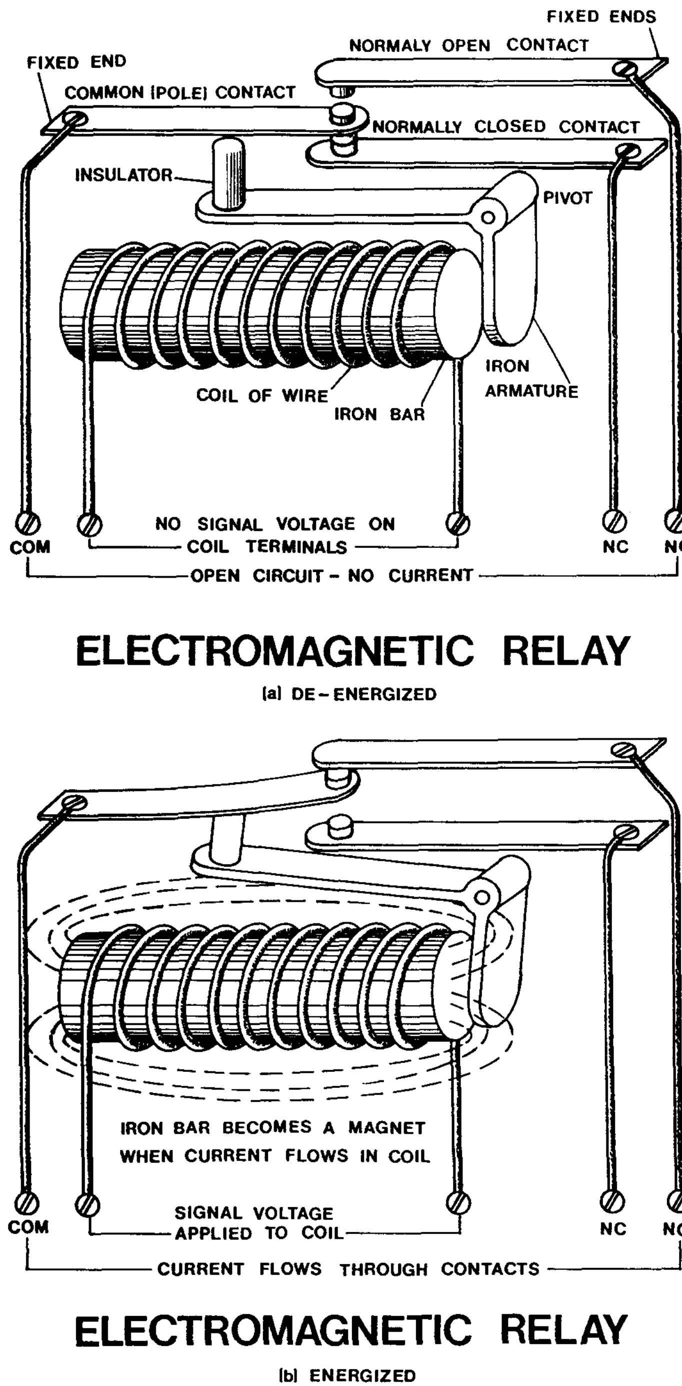

Figure 6.1. (a) Typical relay used in telephone switching. The cylinder in front is the magnet; behind are the contacts. (b) Simple relay action. Drawings: Edwin Collen.

electric circuits and motors—a combination that allowed one to build a more complex and more powerful system that maintained the reliability and precision of simpler calculators.

Electromagnetic Relays as Computing Devices

Besides the electric motor which provided power, the key device of electromechanical calculators was the relay. A relay is a switch whose contacts are actuated by an electric current acting through an electromagnet. The device was originally developed to relay the dots and dashes of the Morse telegraph over long distances. (By having the original Morse signal activate a relay before it became too weak, one could transmit a message much farther—across the North American continent by the 1860s.)

Relays of this type usually have two switching states, with one activated by sending current through the magnet, the other activated by a return spring. It is basically a binary device (on or off), although one magnet can switch several contacts simultaneously. Typical relays may have up to ten sets of contacts switched by a magnet (Figure 6.1).

The telephone industry was also an early user of relays, but for a different purpose, namely switching. Telephone signals are not composed of discrete dots and dashes, like the telegraph, so they cannot be repeated by relay circuits for long distance transmission. But the telephone system can use a cascade of relays to allow an individual to select any other telephone without the need for an operator. The familiar rotary dial, first developed in America by Almon Strowger in 1890, transmits a string of discrete pulses (e.g., five pulses if the number 5 is dialed) that activates a series of relays connecting one caller's phone with another's. Unlike the simple two-position switches described above, the Strowger system uses ten-position relays—each pulse sent out by the dial advances a rotary contact by one position.

Devices of these types were in common use by the 1930s. Simple relays cost a few dollars each, and they were fairly rugged and reliable. But, for ordinary calculators, the relay offered few advantages over mechanical cams and gears. It was still cheaper and more reliable to store or add a decimal number on a train of ten-tooth gears than on a bank of multiple-contact relays. Mechanical calculators had a long heritage going back to Leibniz, during the intervening time the technology had reached a mature state of sophistication and a good deal of inertia had set in among designers. As long as one wanted only to do simple arithmetic, there was little incentive to abandon mechanical technology.

But, for something more than simple arithmetic, relays had a crucial advantage over mechanical systems, in that their circuits could be flexibly arranged (and rearranged) far more easily. One could arrange relays on a rack in rows and columns, and connect them with wires according to what one wanted the circuit to do. One could further reconfigure a relay system using a switchboard, with cables plugged into various sockets by a human operator. Going a step further, one could use a strip of perforated paper tape (originally developed to store telegraph messages for later transmission) to energize a separate set of relays that in turn reconfigured the system just as the plugboards did.

In this latter instance, the same devices—relays—perform the functions of both arithmetic and control. This seems to confer little advantage over mechanical calculators, as it appears that arithmetic and control are two different activities. But, in fact, the two are closely related, and for anything more than simple arithmetic both are required. A calculator designer who uses relays may exploit their ability to do both tasks—enabling the design of a machine with the general capabilities of Babbage's Analytical Engine, but with a much simpler overall design.

In the mid-1930s at least three individuals: Konrad Zuse in Berlin, George Stibitz in New York, and Howard Aiken in Cambridge, Massachusetts, conceived and developed calculating systems that exploited the relay's potential. In many ways their machines were different from one another, but each combined binary relays for control, other relays or electromechanical devices for number storage and arithmetic, and perforated tape for program input. And each was capable of carrying out an arbitrary sequence of elementary arithmetic operations, automatically storing and retrieving intermediate results as the need arose during a calculation. They were the fulfillment of Babbage's attempt to build an Analytical Engine, and it was relay technology that made it possible.

Konrad Zuse

Konrad Zuse, a mechanical engineering student in Berlin in the mid-1930s, was perhaps the first to make use of these properties of relays to build a working, general-purpose, program-controlled calculator. As a student, he faced problems in the analysis of load-bearing structures, like bridges or trussed roofs, whose analysis required the solution of large systems of linear equations. His textbooks taught a method (Gaussian elimination) for solving such systems, but in practice it required too much time and was too error-prone. Zuse knew little of the existing calculating machine industry, but in any case it was not a fancier calculator he wanted. Instead, he wanted a machine that could execute a sequence of simple calculations, and also store and retrieve intermediate results as needed during the solution of a problem. He recognized that, although the solution of typical problems might involve many arithmetic operations, a machine that would solve these problems would need only one calculating unit, provided it was linked to a storage unit that held and delivered initial, intermediate, and final values encountered in a solution. In addition to those two basic units, he also saw the need for a unit that stepped the other two through a sequence of operations depending on the overall plan of the problem's solution.

By 1935, while still a student at Berlin's Technical College, Zuse had sketched out a design for an automatic calculator and begun building it in a corner of his parents' apartment in Berlin. He had already decided to use the binary, not the decimal system of enumeration, with the machine itself performing the conversion between the two systems at the beginning and end of a calculating sequence, as needed. Binary arithmetic is so central to modern computer design that it is easy to overlook how radical a step this was in 1935. Nondecimal number systems were known and investigated by that time, but the established wisdom of the day among calculator manufacturers was that because human beings used decimal numbers, so should machines. Zuse, on the other hand, saw that a mechanical system could be much simpler and more reliable if its elements were designed to assume one of only two, instead of ten, values. It did not matter if the machine handled numbers in a form unfamiliar to humans; his machine would carry out a sequence of arithmetic operations, and during that sequence numbers stayed within the machine itself.

Zuse began building a machine that used mechanical computing and memory elements, with electric motors supplying power. He was familiar with electromagnetic relays, but he felt a mechanical calculator would be less expensive and more compact. Within about a year, he succeeded in building a compact and reliable storage unit, but attempts to build a mechanical calculating unit met with less success. This unit was much more complex in that it had not only to store but also carry digits from one column to another during addition. He had further decided to represent numbers in floating-point form, a form most engineers took for granted, but which further complicated his design and construction.

So in 1938, after building a small prototype (later called the *Z1*), Zuse abandoned the purely mechanical approach to calculation. He was satisfied with mechanical techniques for memory, but for calculation and control he turned to telephone relays at the suggestion of Helmut Schreyer, a former schoolmate in electrical engineering. Schreyer had worked as a movie projectionist during his student days, and from that experience he further suggested punching holes in discarded movie film as an inexpensive way to enter the program into the machine. (The basic mechanism of a movie projector, which stops each frame of film briefly as it runs through, could be adapted to read the pattern of holes punched into the film.) Zuse adopted both these ideas, but he turned down Schreyer's suggestion to build an arithmetic unit using, not relays, but much faster vacuum tubes. Zuse was working on this project entirely in his spare time with his own personal funds, and felt that vacuum tube circuits would have been too expensive. Schreyer later pursued this approach on his own, as will be discussed in Chapter 7.

With a memory fashioned out of metal plates cut with a jigsaw, a calculating unit made from secondhand telephone relays, and a programming unit that recorded on discarded movie film, Zuse and a few of his friends built a prototype of a general-purpose calculator of this radical new design. This machine, later known as the *Z2*, did not work well but nonetheless demonstrated the soundness of the principles he had developed. It worked well enough to impress the German Aerodynamics Research Institute (DVL) to give him some money to build a more substantial machine, this time using telephone relays for all its units. In 1941, he completed the *Z3*—perhaps the world's first general-purpose, sequential calculator.

The Z3 used about 1,800 relays to store sixty-four 22-digit binary numbers, as well as about 600 additional relays for the calculating and control units. The operation sequence, memory storage and recall, binary-decimal conversion, and input and output all were directed by a control unit that took its instructions from perforated 35-mm movie film. A person entered numbers and operations on a calculator-style keyboard, and answers were displayed on small incandescent lamps. A drum rotating at 300 RPM synchronized all the units of the Z3; it took between three and five seconds to multiply two floating point numbers together. The total cost of the machine was around $6,500 (mostly materials, as many hours of labor were donated by Zuse and his co-workers).

Using the Z3 to solve a problem involved first of all writing out the sequence of commands to perform arithmetic operations and send to or retrieve data from storage. This sequence was then punched into a filmstrip, using an eight-hole pattern. Once this code was prepared, initial values were entered into the keyboard in floating-point, decimal form; the machine then converted the numbers into binary, carried out the sequence, and displayed the result on the lamps after reconverting it back to decimal notation.

Zuse wrote out calculating plans to solve small systems of linear equations, to find the determinants of matrices, and to locate the roots of quadratic equations. Because of its modest memory the Z3 could not attack the problem that at the time most concerned the Aerodynamics Research Institute, namely designing enough stiffness into airplane wings so that they did not flutter like a flag at high speed—a problem in aerodynamics similar to the one that caused the Tacoma Narrows Bridge to collapse in 1940. But the Z3 was reliable and flexible enough to persuade them to grant Zuse money for a full-size machine, which eventually became the *Z4*, completed by the end of the war in 1945.

For the Z4, Zuse retained the overall design of the Z3 but returned to a mechanical memory instead of using relays. It was the only one of Zuse's machines to survive the war. Although in the immediate postwar years it was not functional, by 1950 it was running at the Swiss Federal Technical Institute (ETH) in Zurich with a mechanical memory of 512 binary numbers, giving it a power and versatility that matched other, more advanced electronic computers of the immediate postwar era (Figure 6.2).

Americans and Britons knew little of Zuse during or immediately after the war. The result was that his work had little influence on the development of modern computing, and it remained for others to rediscover his fundamental concepts of binary, floating-point number representation and separation of memory, arithmetic, and control

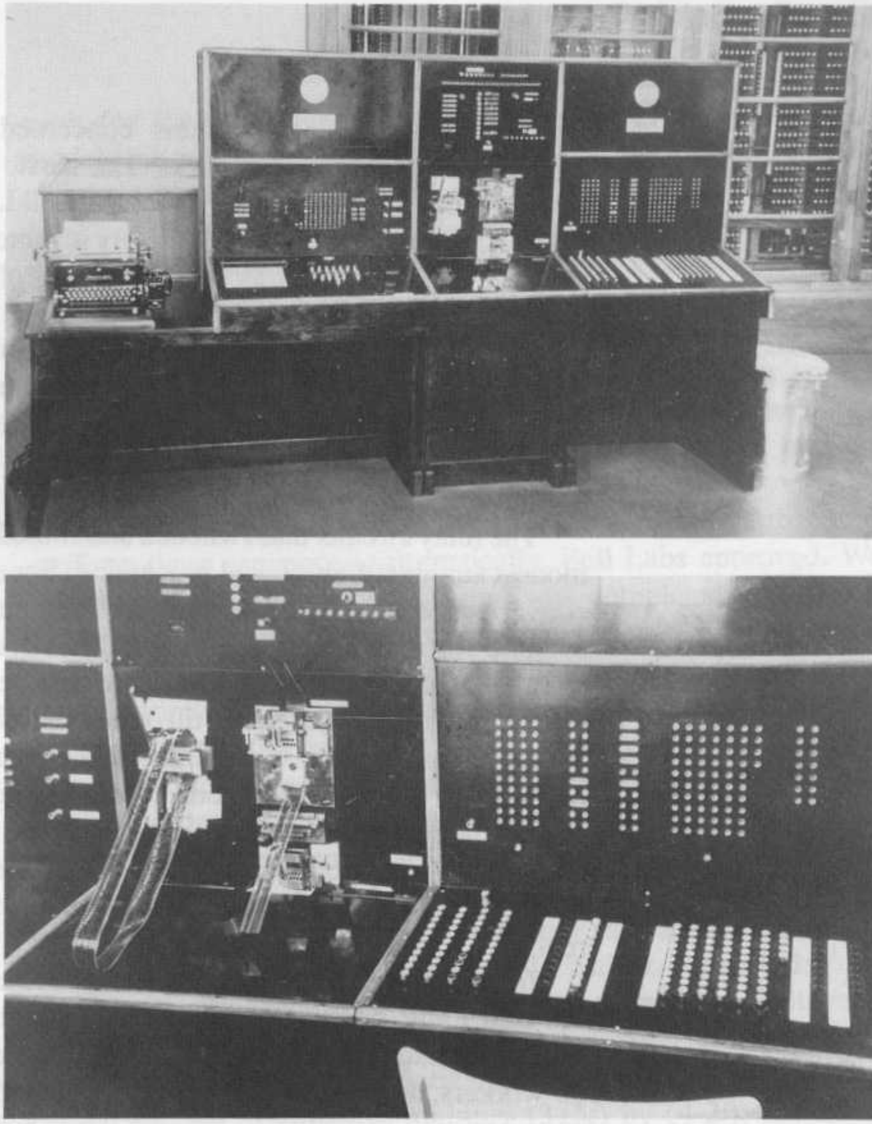

Figure 6.2. The Z4 at the Federal Technical Institute, Zurich (ca. 1950). Courtesy Konrad Zuse.

units. His Z4 influenced continental European computing in the early 1950s, but only modestly compared to several American projects, discussed below.

George Stibitz and Bell Laboratories

By the mid-1930s, Bell Telephone Laboratories was already one of America's foremost scientific research institutions, albeit with a mission closely wedded to the immediate needs of the American Telephone and Telegraph Company. Those needs centered around two technical problems concerned with establishing a nationwide telephone network. The first was the design and construction of long-distance circuits—Bell Labs was established in 1911 to investigate the use of the newly invented vacuum tube for this purpose. The second was in the design of automatic switching apparatus, which the Bell System introduced in the 1930s to replace human operators. Though long-distance circuits mainly used vacuum tubes to amplify the signal carrying the human voice, switching circuits used relays to route a call from one telephone to another. In modern terms, the first activity concerned analog circuits, the second digital.

The relay circuits that switched and routed calls also performed a modest amount of numerical processing. For example, some circuits converted the number dialed by a customer into another number more suitable for automatic switching. Other circuits might temporarily store a dialed number while the system searched for an open line from one central office to another. Still other relay circuits operated display panels revealing information about the internal workings of the network. In short, the telephone company's relay circuits performed all the functions of an automatic calculator, although they did not "calculate" in the ordinary sense of the word. With a few modifications, one could easily make an ordinary calculator out of relays.

In 1937, George R. Stibitz (b. 1904), a research mathematician at the Bell Labs, brought some relays home one evening and built a battery-operated device that added two binary digits together. His co-workers, however, were not impressed with his Model K. (Stibitz gave it this whimsical name because it was built on his kitchen table.) They reasoned that any practical relay computer, using binary arithmetic, would need perhaps hundreds of relays, thus making it both bulkier and more expensive than the commercial mechanical calculators then in use at the Labs.

But what Stibitz realized was that a relay calculator could perform not just one but a sequence of calculations, with relay circuits directing the order and storing interim results as needed. Specifically, it could perform the sequence of operations required to perform multiplication and division of complex numbers: two mathematical operations that researchers elsewhere at the Labs frequently performed in connection with filter and amplifier design for long-distance circuits.

Complex arithmetic manipulates numbers in pairs, one number each for the "real" and "imaginary" parts. Electrical engineers modeled the performance of alternating current, amplifier, and filter circuits with complex numbers. For them both parts were equally "real": the first number represented a signal's amplitude or strength, the second its phase or relation to time. At Bell Labs in the 1930s, a roomful of human "computers" figured complex number quotients and products using commercial mechanical calculators. The calculations themselves are straightforward enough: a complex multiplication requires about six simple arithmetic operations, while complex division requires about a dozen operations, and each requires temporary storage of a few intermediate results.

Stibitz proposed building a machine out of relays that would perform these sequences automatically. Bell Labs approved. Work began in the early fall of 1939 and was completed that October. Initially the Complex Number Computer, as it was called, performed only complex multiplication and division, but later a simple modification enabled it to add and subtract as well. It used about 450 binary relays and ten multiposition, multipole relays called "crossbars" for temporary storage of numbers. The machine used the decimal system with the decimal point fixed at the beginning of each number. Internally, four binary relays coded each digit, using a code that represented a decimal digit n by the binary code for $n + 3$; this simplified the problem of digit carry and subtraction (excess-three binary coded decimal is still called "Stibitz-code" today). The machine handled ten-digit numbers in its registers, but displayed and printed eight-digit answers. It used "prefix" notation: that is, operators keyed in the arithmetic operations before they keyed in the operands. For example, to multiply (3+5i) by (4-2i), the operator would key in

M +.3 +i .5 +.4 -i .2 =

The "M" stands for multiply. Note the location of the decimal point before each of the four numbers. The machine would actually be calculating (.3+.5i) x (.4-.2i), and print the answer 0.22000000 +i 0.14000000. The operator would have to scale the results accordingly. Complex multiplication took about forty-five seconds.

The Complex Number Computer was kept in an out-of-the-way room in the labs, where few ever saw it. Persons accessed it remotely using one of three modified teletype machines placed elsewhere. Only one keyboard could control the machine at any one time, but assuming a person would use it only briefly to do a calculation, no one would have to wait too long. As with the mechanical and human system it replaced, the engineers themselves did not usually operate the machine, but instead gave their problems to human operators who keyed in the numbers and recorded the answers.

Stibitz carried this idea of remote, multiple access one step further. In the fall of 1940 the American Mathematical Society met at Dartmouth College in Hanover, New Hampshire, a few hundred miles north of New York City. Stibitz arranged to have the Complex Number Computer connected by telephone lines to a teletype unit installed there. The Complex Number Computer worked well, and there is no doubt it impressed those who used it. The meeting was attended by many of America's most prominent mathematicians, as well as individuals who later led important computing projects (e.g., John von Neumann, John Mauchly, and Norbert Wiener). The Dartmouth demonstration foreshadowed the modern era of remote computing, but remote access of this type was not repeated for another ten years (until done by the National Bureau of Standards, in 1950).

The Complex Number Computer lacked an ability to carry out a sequence of operations other than those for complex arithmetic; however, Bell Labs used it for many years. Its success encouraged Stibitz to propose more ambitious designs that included an ability to modify the calculator's operations by perforated tape. At first the Labs turned down his proposals, but with the entry of the United States into the Second World War in December 1941, Bell Labs shifted its priorities toward military projects that involved more computation than its peacetime research. Most of their wartime accomplishments were in the design of analog computers, as described in the previous chapter. But they also built five digital relay computers for military purposes, and one more after the war's end for their own use, making a total of seven digital machines counting the Complex Number Computer.

The first of these calculators for military use was the Relay Interpolator, installed in Washington, D.C. in 1943 and later known as the Model II. It mainly solved problems related to directing antiaircraft fire, which it did by executing a sequence of arithmetic operations that interpolated function values supplied to the machine by paper tapes. Like the Complex Number Computer, it was a special-purpose machine; however, its arithmetic sequence was not permanently wired but rather supplied by a "formula tape" cemented into a loop. Different tapes therefore allowed one to employ different methods of interpolation. The Model II could not do much besides interpolation, but as interpolation is a process that lends itself to the solution of many problems in science and engineering the machine was kept busy by other government agencies long after the war ended. The machine was dismantled in 1961.

The next two machines, the Models III and IV, were identical machines, the first installed in 1944 at Fort Bliss, Texas, and the second in early 1945 in Washington. These machines also used paper tapes for data and formula input, with the arithmetic sequence supplied by a loop of paper tape. The Models III and IV, like the Model II, also solved problems relating to the aiming and tracking of antiaircraft guns. They were, however, more sophisticated machines, having the ability not only to perform interpolation but also to evaluate the ballistic equations describing the path of the target airplane and of the antiaircraft shell. An additional paper tape directed which of those functions the machine was to evaluate. Thus, the Models III and IV were the first of the Bell Labs digital calculators to have some degree of general programmability, although neither was a fully general-purpose calculator.

The largest computer in the series was the Model V, of which Bell Labs built two copies for the military in 1946 and 1947. Each contained over nine thousand relays and, like Zuse's Z3 and Z4, handled numbers expressed in scientific notation. The store could hold up to thirty numbers, and paper tape readers fed in both program steps and numerical data. A flexible and elaborate control unit allowed more than one tape loop to direct the machine while it was running, based on the results of a calculation just completed. This gave the Model V the ability to "branch" on a condition, modifying its own program instead of plodding down the same path each time.

This ability to branch to different sequences of instructions is a key to the power of the modern computer. Although branching had been recognized by Ada Augusta (and perhaps by Babbage as well), the practical difficulties of implementing it on a machine programmed by essentially linear paper tapes had prevented its use by earlier calculator designers. Relay calculators installed branching by means of multiple tape readers and loops of tape, which made for a rather baroque overall design.[1] A desire to circumvent the difficulties of providing conditional branching on machines like the

Model V was a major reason why computer designers adopted the principle of internal program storage that characterizes modern computer design.

A relay has a tendency to fail intermittently because of dust or dirt on its contacts. Therefore, all Bell Labs machines after the first employed a system whereby not four but seven relays encoded each decimal digit. The relays were grouped like the beads on a Chinese abacus, with one set of five relays having a unit's weight, the other two a weight of five—the so-called bi-quinary system, viz:

Table 6.1. The Bell Labs bi-quinary system of relays

Decimal digit	Bi-quinary code
0	01 00001
1	01 00010
2	01 00100
3	01 01000
4	01 10000
5	10 00001
6	10 00010
7	10 00100
8	10 01000
9	10 10000

As Table 6.1 shows, for each digit one and only one relay in each group is "on"; a separate set of relay contacts checked this condition and stopped the machine if it found otherwise. This arrangement was a forerunner of error-correcting codes now common in digital computing and communications.

The Model V was a powerful, general-purpose calculator that could and did solve problems in a variety of areas of physics, mathematics, and engineering—many of these problems related to classified wartime work. But at the same time it represented the end of the line for relay technology applied to computing, as its computing power was in many ways offset by increased complexity, cost, bulk, and power requirements. Bell's engineers frankly admitted that their Models III and IV, which had less programming power, represented a better balance between the users' needs and the relay's inherent abilities. The last machine of the series, the Model VI built for Bell's own use in 1949, abandoned the dual-processor and master control programming facilities of the Model V, its designers believing the increased complexity was not worth the trouble or expense. By 1949, it was clear that computing's future lay in the direction of vacuum tube circuits and program input from an internal store instead of a paper tape. Bell Labs did not design or produce electronic computers at that time, but its relay machines were nonetheless an important bridge from the mechanical calculator to the electronic computer.[2]

Howard Aiken and the Harvard Computation Laboratory

The same year that Stibitz was experimenting with relay circuits on his kitchen table, a Harvard graduate student named Howard Aiken began looking for ways to adapt existing calculating machines to help him with calculations for his dissertation research in physics. Aiken began by taking a thorough look at existing calculator technology and its history; he also studied the capabilities of commercial punched-card and calculating machines. He saw that they had sophisticated powers, but primarily for business and accounting applications. For the scientific applications he had in mind (specifically for his thesis on space charges, which required the numerical solution of differential equations) their capabilities were inappropriate. For example, business equipment handled positive values rarely greater than a million, and rarely with more than two places to the right of the decimal point. But scientific problems involved positive and negative numbers of a much wider range and decimal precision; they also used functions like sine, cosine, and logarithm, which business machines did not supply.

Most important, scientific calculations often required iterative solutions, in which the results of a previous calculation are recycled as input data for a subsequent stage in the approximation of a solution. But typical punched-card installations did not permit this kind of approach. With punched-card machines, if one were to evaluate, say, a payroll formula for employees, one would first multiply the number of hours worked by the hourly rate for each employee, producing a new deck of cards as output. This deck would then be submitted to another machine (or to the first machine after making some wiring changes) to compute the deductions for each employee, and so on. Only at the very last step in this process would one have a complete evaluation of the entire formula—and at this step one would have it for every employee (cf. Chapter 4, section 2). Aiken wanted a machine that could compute the whole formula for each value of n, before going on to the next iteration. That implied that the machine would have to alter the arithmetic operations it performed on each input value automatically. And as he intended to use it for problems in which the value of the independent variable was incremented by a constant amount each time, he also wanted the machine to automatically increment the variable and step through the process without human intervention. Implicit in that requirement is the further ability to stop processing upon reaching the desired number of iterations.

Aiken sketched out these ideas in a memorandum entitled "Proposed Automatic Calculating Machine," written in 1937. He discussed these issues, stating above all that the proposed machine had to automatically carry out sequences of different operations. The picture that emerged from this 1937 proposal is one of a set of commercial punched-card machines linked to one another by cables, with separate units for input of initial data, storage and retrieval of interim results, and control of the sequence of operations by the rest of the machine. His proposal also stressed the machine's ability to print the results of its work without the need for manual typesetting or proofreading—this of course would eliminate one of the main sources of errors in printed tables, as Babbage had astutely noted a century earlier.

Aiken tried to interest calculating machine firms in his proposed calculator, but had little success at first. The Harvard astronomer Harlow Shapley then suggested that he approach IBM by way of T. H. Brown, a professor at the Harvard Business School who was on good terms with IBM's chairman, Thomas J. Watson. Watson had already initiated the use of IBM machines in scientific work at Wallace Eckert's lab in New York (cf. Chapter 4); he believed that collaboration with Aiken would lead to a similar involvement at Harvard. Watson assigned the experienced and respected IBM engineer James W. Bryce to implement Aiken's proposal; Bryce in turn assigned three engineers and the facilities of IBM's Endicott, New York plant. Aiken spent the summers of 1941 and 1942 in Endicott, where he sketched out what he wanted his machine to do, but it was the IBM personnel who actually designed and built the machine, using existing IBM punched-card technology. IBM also paid most of the estimated half a million dollars the machine cost.

The Automatic Sequence Controlled Calculator (ASCC)—so named to call attention to its method of evaluating formulas—was completed in Endicott early in 1943 and moved to Harvard the next year. It was covered with an attractive stainless-steel and glass enclosure, and on August 7, 1944 was publicly unveiled at an elaborate ceremony attended by Watson, Aiken, President Conant of Harvard, and a number of other VIP's. The ASCC thus became the first large-scale automatic digital calculator made known to the public. News of its dedication was overshadowed by the war, but nonetheless many newspapers and popular scientific journals reported the event. Some reports found their way to Germany, where Konrad Zuse heard them as he was building his own Z4.

The ASCC was long and slender: 51 feet long, 8 feet tall, and only 2 feet deep. By 1944 standards it was awfully large for a "calculator," but today it would be dwarfed by typical mainframe installations with their rows of tape and disk drives. It had that shape because all its individual calculating units were powered (and synchronized) by a constantly turning drive shaft that ran along its base—not unlike a nineteenth-century New England textile mill. Numbers were transferred by relay circuits, which activated clutches that coupled the drive shaft to one of seventy-two sets of wheels called "accumulators." By activating the clutch connected to an accumulator for, say, five units of time, the number 5 was added to whatever contents were already in that unit. A typical addition took about one-third of a second.

The seventy-two accumulators were adapted from similar devices found in IBM punched-card machines, and comprised both the ASCC's store and mill—that is, they both stored numbers and performed nearly all of the arithmetic operations needed to solve a typical problem. Like punched-card machines, the accumulators used fixed decimal arithmetic, although they could store and add numbers having many more digits—twenty-three digits plus sign, with the decimal point fixed after the twelfth digit. (Commercial punched-card machines handled numbers from eight to twelve digits in length.) Numbers were inputed by paper tape or cards, or by setting a bank of manual switches (Figure 6.3); the calculating sequence was entered by a 24-column, punched-paper tape (Figure 6.4).

Additional equipment included a separate device for multiplication (and division) and a device for interpolating function values supplied on paper tapes. A device similar to the interpolator supplied logarithmic and trigonometric functions. Two "electromatic" typewriters provided output.

The key piece of the ASCC was its sequence control unit. This device read 24-column paper tapes containing the operation sequences needed to solve a problem. The columns were grouped into three fields: out-, in-, and miscellaneous-field. The first specified from which accumulator or other unit a number was to be taken. The second specified where it was to go (the terminology is the reverse of today's). The third, or miscellaneous field could specify a number

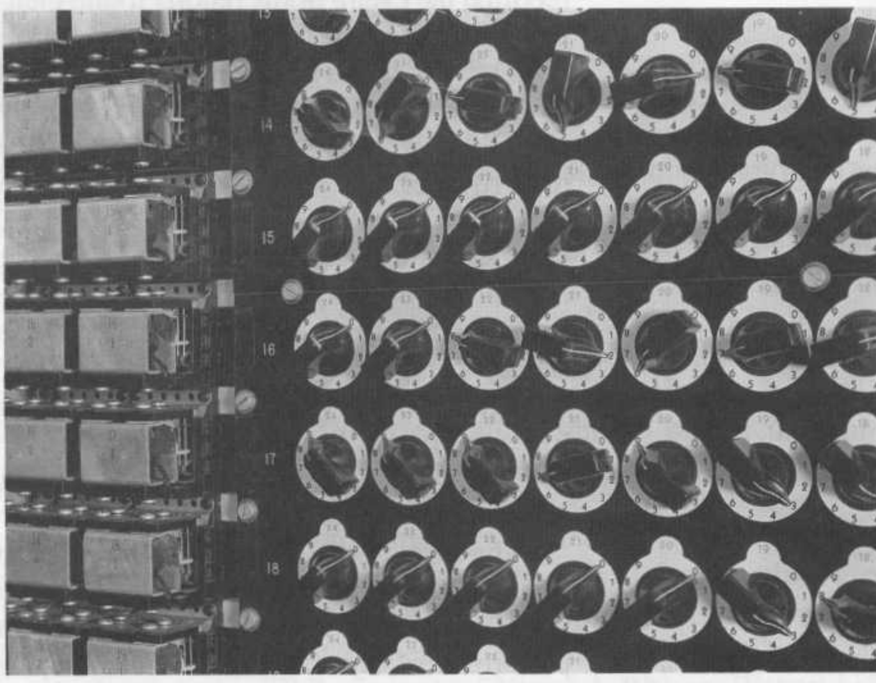

Figure 6.3. A bank of manual switches on the Automatic Sequence Controlled Calculator, used for input of constant numerical values. Courtesy Cruft Laboratory, Harvard University.

of operations, but it was not strictly speaking used as an operation field. A number routed to a given accumulator would automatically be added to whatever was already in it; hence, there was no need to give the command "add," but only a command (punched into the third field) to continue with the next operation. Typical operation sequences for the ASCC consisted of a long series of transfers from one accumulator (or input device) to another, with the command to "continue" punched in the miscellaneous field. Even multiplication was handled in this way: the multiplier unit was given an address, which was punched into the in-field when one wanted to use it.

Aiken assembled a small staff of mathematicians and technicians to service and program the ASCC. Support for the machine's daily operations came from the Navy; hence most of this staff were either fresh recruits or recently commissioned Naval officers. One of the latter was Grace Hopper, who had taken leave as an instructor in

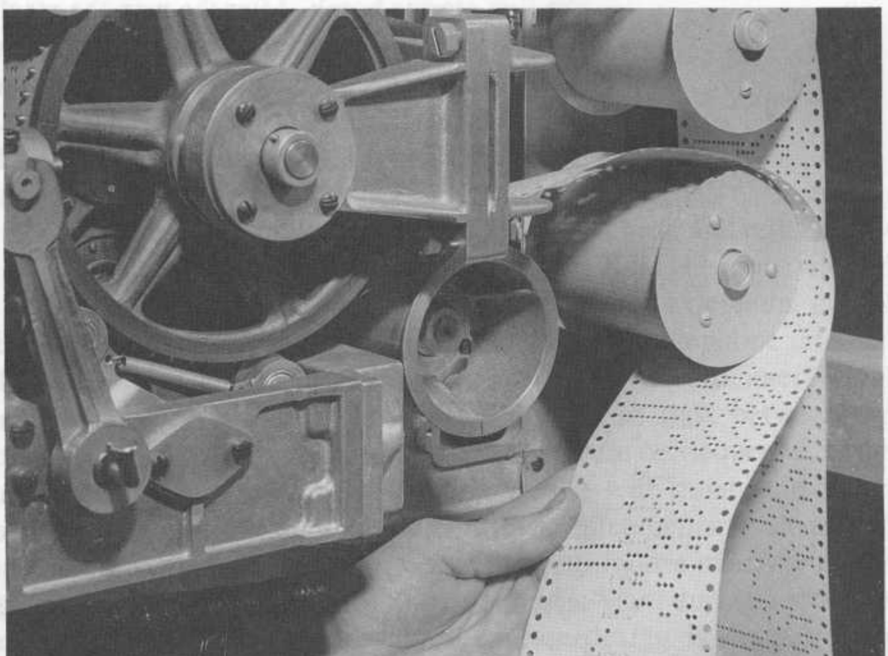

Figure 6.4. Twenty-four-column punched-paper tape for input of calculating sequence on the Automatic Sequence Controlled Calculator. Courtesy Cruft Laboratory, Harvard Univeristy.

mathematics at Vassar College to attend the Navy's Midshipmen's School. In 1943, the Navy ordered her to go to Harvard and join Aiken's staff. Very quickly she assumed the task of preparing codes for the ASCC to solve a variety of problems, and so began a long and productive career as one of America's pioneers in what is now known as computer "software."

Recall that from the telegraph and telephone industries came not just the electromagnetic relay but also the techniques of paper tape and plugboards, which calculator designers adopted for the control functions of their machines. Reflecting its hybrid ancestry, the ASCC used both: paper tape for input of its operation sequence, and plugboards for operations like the routing of results to the several output devices, or the formatting of typed output intended for publication.

Even before its public unveiling, the calculator was kept busy doing classified work for the United States Navy. At least one of the problems it worked on involved a calculation of the blast effects of the first atomic bomb. After the war, the machine settled into a more prosaic role of calculating and printing tables of Bessel and other related functions, the tables reproduced by photolithography directly from the machine's typewriters. Thus, Babbage's dream of computing and printing mathematical tables finally came true, even as the ASCC ushered in an age of computers that would transform the whole process of compiling and using tables, in some cases making tables themselves obsolete.

The ASCC was finally retired in 1959; a part of it may still be found in the foyer of the Harvard Computation Laboratory. Aiken went on to supervise the design of three more large-scale calculators; as these were completed they took on the names Mark II, III, and IV, and the ASCC became known as the Harvard Mark I. The Mark II (completed in 1947) was a calculator more in the spirit of the Bell Labs Model V, computing entirely with relays, not mechanical driveshafts or clutches. It was a big machine by any standards: it contained 13,000 relays and occupied a large room at the Navy's proving ground at Dahlgren, Virginia. Like the Mark I, it was controlled by a combination of sequence tapes and plugboards; like the Bell Labs Model V, it could be operated as two independent machines and work on two problems simultaneously.

By the time the Mark II was installed at Dahlgren, many were beginning to feel that vacuum tubes offered a number of advantages over relays for automatic calculator circuits. Aiken was leery of the what he perceived as the inherent unreliability of tubes, but for the Marks III and IV he did employ some tubes to gain higher speeds. In many respects these calculators were anachronisms, but the Mark III did pioneer the use of a high-speed magnetic drum for the storage of numbers and instructions. The drum became the most popular storage device for electronic computers of the "first generation," even though the architecture of those computers was far different from what Aiken developed. His influence on postwar computing was strong, not so much as a designer of machines, but as the director of the Harvard Computation Laboratory, which was one of the few places where what we now know as "computer science" was taught. Aiken's students were among the first to receive a thorough training in the fundamentals of computing, and after leaving Harvard many of them helped steer the direction of academic, commercial, and military computing for the next three decades. Aiken also frequently travelled to continental Europe, where he inspired and influenced many computer projects otherwise out of the Anglo-American mainstream.

Conclusion

Relay technology seemed to hold the potential for building powerful computing machines that were cheap and reliable, yet it never really fulfilled that promise. Relays were indeed mechanically rugged and relatively cheap, but calculator circuit design imposed severe constraints not found in telephone circuits. Most critical was the fact that relays were prone to intermittent failures, usually caused by a piece of dirt or dust between the contacts.[3] In a telephone circuit this was of little consequence, as the telephone system can still function acceptably with some degradation of service. Indeed, the highest priority in a telephone system is to maintain service—any service—despite the failure of many of the system's components (this is especially important during a storm or flood). But the philosophy of calculator design is diametrically opposite: if there is any chance that the machine might deliver a wrong answer, say a misplaced sign or decimal point, it is better to shut the whole system down and fix the problem before continuing.

The result was that relay calculators needed elaborate checking circuits or redundancy, which made them costly and overly complex. Where there were no self-checking circuits, as on the Mark I, its operators had to periodically run portions of a problem through the machine twice, using different registers to ensure that everything was all right. By contrast, when a vacuum tube fails, it usually does so catastrophically, i.e., it burns out. That renders the whole circuit inoperative, so it is less likely to spew out wrong answers before the problem is noticed. So although it was true that tubes were less reliable than relays, they actually allowed one to build a total system that in the long run was more reliable when measured in terms of the average number of arithmetic operations between failures. These characteristics of tubes, coupled with their higher speeds, spelled the end of relay calculator development. The invention of the transistor by Bell Labs scientists in 1947 eventually allowed the construction of computing machines that combined the ruggedness of relays with the speed of tubes, and rendered the question moot.

During the immediate postwar years, a few relay machines were built to take advantage of lower initial costs and development time. Relay technology was especially appealing in Europe, where capital was hard to raise in the late 1940s. In West Germany, Zuse founded a commercial company, Zuse K. G., of Neukirchen, that produced several compact and reliable relay calculators in the 1950s. One of them, the Z11, sold well and continued to be used into the 1980s. But in 1955 he changed over to electronics—first with vacuum tube and later with transistorized computers. (In the mid-1960s his company was absorbed by the German electronics firm Siemens.) Some European groups adopted the relay design philosophy advocated by Aiken, who made several trips across the Atlantic at that time. Two such machines were the BARK and the ARRA, which introduced automatic computing to Sweden and the Netherlands in 1950 and 1952. At King's College in London, A. D. Booth built the ARC—a machine whose architecture reflected the latest ideas on internally stored programming from John von Neumann and other Americans, but which used relays to save costs.

In the United States, Engineering Research Associates designed a high-speed magnetic drum for the storage unit of an electronic computer, but before assembling the computer they built a relay processor to test the drum's powers. This combination (called the *Abel*) turned out to be so useful that the United States Office of Naval Research installed it in Washington, D.C. and continued to use it for many years for a wide range of problems, mainly logistics calculations. Modest relay devices were also built in Japan in the early 1950s.

These examples illustrate the place of the relay calculator in the history of computing: almost from the start they were eclipsed by the faster vacuum tube computers, but at the same time they played a vital role as the machines that introduced to the world the concept of automatic, sequential calculation. It was with relay technology that the first functional automatic calculators finally came into existence, after years of hope and promise.

Notes

1. Neither the Z4 nor the ASCC, described later in this chapter, had conditional branching at first, but the capability was retrofitted to both machines after the end of the war.

2. One reason AT&T did not then produce computers was that it was a regulated monopoly, whose main line of business was domestic telephone service; and it was prohibited by law from entering into a business such as computing, which was outside their main line of business.

3. In one famous instance, Grace Hopper found that a moth trapped between two relay contacts was causing the Mark II to malfunction; she removed the moth and taped it in the logbook, noting that she had found the "bug" that was causing the problem!

Further Reading

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Berkeley, Edmund. *Giant Brains, or Machines that Think.* New York: Wiley, 1949. A good survey of the automatic electromechanical and electronic calculating machines available in the years following the end of World War II.

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Dunsheath, Percy. *A History of Electrical Power Engineering.* Cambridge, Mass.: MIT Press, 1962. A general history of the principles and history of electrical engineering technologies that were the basis for the electromechanical calculators.

Harvard University, Computation Laboratory. *A Manual of Operation for the Automatic Sequence Controlled Calculator.* Harvard University Press, 1947. Reprinted by MIT Press, 1985. A detailed description of the ASSC (Harvard Mark I), written mainly by Grace Hopper under Howard Aiken's direction. The 1985 reprint edition contains a new foreword and introduction, which both provide valuable historical information about Aiken's work.

Stibitz, George. "Computer." In *The Origins of the Digital Computer*. Edited by Brian Randell, 247-52. An informal and easy-to-understand description by the inventor of the Bell Labs Model I calculator.