Telephone Switching and the Early Bell Laboratories Computers

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This article summarizes the salient features of seven relay-type computers designed and built at Bell Telephone Laboratories. Emphasized are features derived from telephone technology and the role played by the Bell Laboratories designs in advancing the computer art.

I. INTRODUCTION

Various papers, some of them listed in the references, have presented material on two interrelated subjects: (1) automatic data processing as applied to machine switching in the Bell System, and (2) work on digital computation as it grew out of telephone technology and as it was applied to seven relay-type digital computers designed and built at Bell Telephone Laboratories between 1939 and 1950. Together, these papers tell an important story of Bell System contributions to the field of automatic digital computation. It has been felt for some time, however, that a single account of the pertinent facts and developments would be of interest and value. Thus, this paper makes no claims of presenting new material; rather, it is an attempt to bring together many diverse accomplishments and to show their relationships so that a single paper will be available for convenient reference.

II. THE PANEL SYSTEM

Bell Telephone Laboratories and its pre-1925 predecessors, the Western Electric Engineering Department and various American Telephone and Telegraph Company groups, have been engaged with problems of automatic data processing for almost 60 years. The basic reason, of course, is that any automatic telephone switching system must process digital data, beginning with the signals and dialed digits originated by a customer in placing a call.

In the period from about 1903 to 1916, several types of automatic dial systems were developed, built, and soon abandoned. Starting about 1914, however, two successful systems incorporating central control features were developed: the panel machine switching system[1] used in the United States and the power-driven rotary system used in several European countries. These systems were probably the first in which the familiar electromechanical relay assumed a dominant role in the design. More specifically, the relay opened new possibilities of automatic control. As a consequence, many of the principles of modern computer design were incorporated into telephone switching at a very early period.

The relay, for example, made possible the efficient conversion from one numbering system to another. This was important because it was realized early that the decimal system of notation was wasteful of equipment in the machine handling of numbers. One of these conversions was incorporated into the relay call indicator, subsequently known as the panel call indicator,[2] used in transmitting called numbers from panel offices and displaying them on lamps at a manual office. At the panel switching office, each decimal digit was converted to a four-pulse code, each pulse having one of two possible signal levels. At the manual office, this special panel call indicator code was converted back to decimal form for display to operators. In another conversion used in panel switching, the first two digits of a customer's telephone number were translated into three digits of an entirely different numbering base, namely 5, 4, 5. (That is, the first digit ranged from 0 to 4, the second from 0 to 3 and the third from 0 to 4.)

The relay also eased the problem of circuit logic. It became easier, for instance, to instrument a system to cope with the all-trunks-busy condition. In other words, upon receipt of an overflow signal, the panel system would automatically change its switching program. This kind of operation is popularly called conditional transfer in modern computers.

Panel switching also provided storage or memory facilities on both a high-speed and low-speed basis. Revertive pulses* were stored in high-speed relay registers; office-code routing information (two-digit codes) was wired in and made available by a slower-speed rotary selector. Both serial and parallel types of operation were employed: serial operation in such circuits as those for revertive pulse counting and call indication, and parallel operation, for example, in reading information on routing.

* In the revertive pulsing arrangement, a switch control sends a start signal to a distant selector, which then begins to advance blindly. Each time the selector advances to a new position, it sends back a pulse (hence the term revertive) to the switch control. When the selector reaches the desired position, the switch control sends a stop signal. A revertive pulse counting circuit was invented by E. C. Molina in 1911. This circuit was an improvement on an earlier counting circuit used in a rotary system developed by F. R. McBerty.

In the 1920's, the valuable bistable flip-flop circuit[3] came into use, called the "W and Z" relay combination in telephone switching. In addition, the decoder type of office-code translator[4] used the direct-access type of table look-up, replacing in some applications the earlier cyclic look-up operation. Also, Boolean algebra for optimizing logic circuitry was being studied, beginning in the late 1930's, by G. R. Stibitz, C. E. Shannon, W. Keister, and others.

In brief, then, many of the more important computer operations and concepts were, in the 1920's and 1930's, already incorporated into the panel switching system, and, as the value of the new circuits was recognized, into other systems as well. It might be asked, therefore, why automatic digital computers were not developed simultaneously. In the period from 1925, for example, this writer heard many of his colleagues say with firm conviction that relay circuit techniques could be used to carry out arithmetical operations commonly performed with desk-type adding machines. The reasons are the traditional ones of economics and failure to see a compelling need. But more importantly, no one had taken the initiative to make a thorough study of all aspects of such a project.

III. THE COMPLEX NUMBER COMPUTER (MODEL I)

In 1937 G. R. Stibitz, who had been employed at Bell Laboratories as a research mathematician since 1930, started to make some significant observations. He noted that Bell Laboratories employed a staff of girls using hand-operated calculating machines for solving the many types of filter network design problems resulting from the introduction of major improvements in voice transmission systems. He found upon closer examination that the bulk of the computing involved addition, subtraction, multiplication and division of complex numbers. Stibitz thereby established one of the prerequisites for a new computer development, namely, he saw a need for it.

Stibitiz also knew that another area at Bell Laboratories had for many years been working on dial switching systems as described above. He noted that many of the design techniques therein employed were directly applicable to the design of an automatic computer. He also noted that, for computation, decimal codes would be even less desirable than for switching. Thus, he initially decided in favor of the true binary code for representing numbers. This was a new and revolutionary idea in the computing field, even though small numbers had previously been used in binary form in the panel system decoder and in some European systems. Having made this fundamental decision, he then proceeded to design a relay-type computer. Stibitz thereby satisfied another prerequisite for a new computer development, namely, he demonstrated that it was a feasible undertaking.

Briefly, in the original paper design this computer was pictured as having a control board which accepted information from a bank of keys and which displayed output information — that is, the answers — on a bank of switchboard-type lamps. It handled seven-digit decimal numbers with the decimal point at any desired position. The arithmetic unit used an ingenious scheme for making the decimal-to-binary and binary-to-decimal conversions. The devices used were primarily telephone-type relays and slightly modified Strowger-type step-by-step switches.

Stibitz's design was a convincing demonstration that the development of such a computer should be undertaken and that it was an economically feasible project. It was decided that the scope of this computer should initially be limited to handling the four complex number computing operations. This limitation had the two-fold advantage of testing out the principles of an automatic computer on a small but adequate scale and of providing a machine that would perform useful services for the Laboratories. From this time, the computer gradually assumed the name of the "Complex Number Computer," generally shortened to "Complex Computer."

Stibitz studied his design intently. He incorporated many improvements, two of which led to marked simplification. One of these was that he abandoned the provision for a variably located decimal point. All real numbers, therefore, were converted by the human operator to numbers between $+1$ and -1. It would therefore be necessary for the operators to keep in mind the various scale factors and apply the proper resulting scale factor to the answer. The other major simplification was directed toward reducing the complexity of the necessary binary and decimal conversion facilities. The solution was a hybrid type of code for number representation now commonly used in modern computers and called the "plus-three binary-coded decimal" or BCD. Each decimal 0 to 9 was represented by binary numbers 0011 to 1100. This code provided most of the calculating simplicity of the pure binary code and at the same time preserved the decimal form, so that the thousands, hundreds, etc. digits were always recognizable. Furthermore, the code facilitated the inter-decimal digit carry operations, the complementing operation, and the algebraic sign determination. The plus-three system significantly lowered the cost of the arithmetic unit.

In November, 1938, the responsibility for development of the Complex Computer was placed in the hands of Samuel B. Williams, whose career had for many years been on the front lines of new telephone systems developments. As a consequence of his study of the project, Williams showed that improved operating conditions could be obtained by using push-button keys for the input and commercially available teletypewriter equipment for the output. The wisdom of this choice was to become apparent later. In the interest of simplifying the circuitry, Williams also chose to use the new crossbar switch instead of the step-by-step switch. The Complex Computer was the only one of the seven relay computers built at Bell Laboratories to employ crossbar switches.

Of course, there were numerous smaller changes in design arrived at as a result of frequent exchanges of ideas between Stibitz and Williams. Perhaps the most important of these was the decision to use two identical calculator units, one for handling the real terms of the complex numbers, and the other for handling the imaginary terms. This arrangement halved the over-all computing time with little extra development effort.

By March, 1939, the equipment design, under the direction of C. E. Boman, was well under way, and in the following month construction was started under the direction of A. J. Bendernagel. Construction was completed by October, 1939. The test period which followed indicated the need of the usual minor changes; these were soon completed, and the computer was moved to its permanent location at the New York City Bell Laboratories location at 463 West Street. The dreams of Stibitz and Williams had now been realized. The Complex Computer was placed in routine operation on January 8, 1940.

The Complex Computer as finally built is illustrated in the two accompanying photographs. Fig. 1 shows one of the three operator stations. These were located in three separated areas in the West Street building. Thus, the first Bell Laboratories relay computer included a feature that is desirable in many modern installations: multiple input positions with the lockout facilities required for this type of operation.

Fig. 2 shows the computing equipment. The computer was an eight-place decimal machine with two extra digits provided in the arithmetic unit to compensate for excessive round-off errors when accumulating many subtabulations. While this Complex Computer was specifically designed to handle the four complex number arithmetic operations, the users soon found that, with certain special variations, the computer could be used advantageously for other types of problems.

IV. THE HANOVER DEMONSTRATION

But Stibitz and Williams had still more planning and designing to do. It had been decided to demonstrate the principles of the computer to the

Fig. 1 — One of the three operator stations of the Complex Computer.

public. Due to the nature of the device, it was further decided that the demonstration would be most effective if carried out before a mathematically minded audience. The scene chosen, therefore, was Hanover, New Hampshire, on the occasion of the fall, 1940, meeting of the American Mathematical Society. Williams designed new equipment to provide a station at Hanover and new facilities for operating the computing equipment remotely over a teletypewriter circuit.[5] The demonstration was held at the meeting of September 11, 1940. Stibitz read a paper describing the machine, after which he and T. C. Fry showed how problems could be introduced at the scene of the conference and transmitted to the Complex Computer in New York. They were then able to point to the teletypewriter, which typed out the answer within a minute.[6] Those interested were invited to introduce their own problems and check the results. The demonstration was also significant because, in employing a

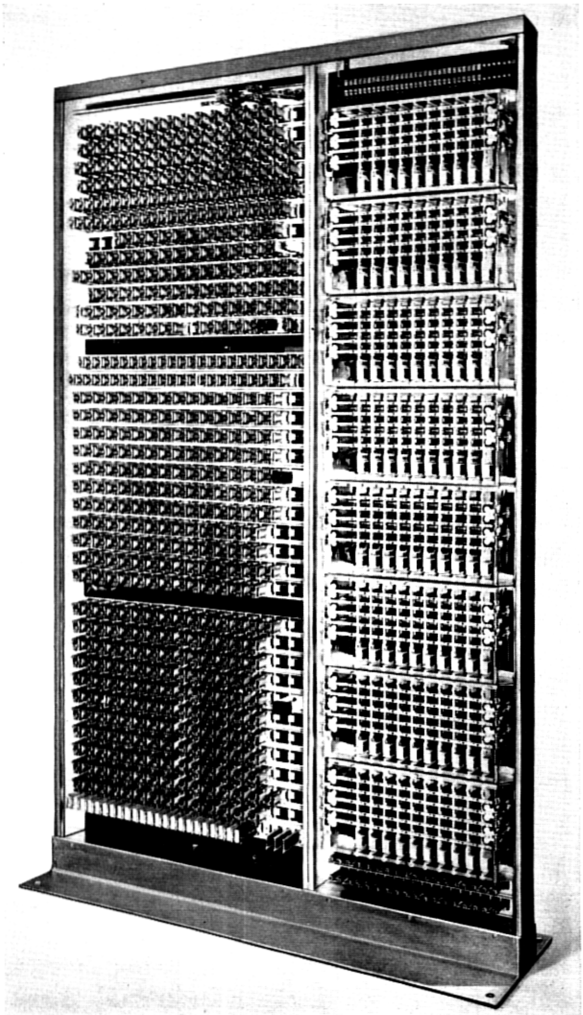

Fig. 2 — The computing equipment of the Complex Computer.

data link between Hanover and New York, it foreshadowed the present growth of data transmission services. During this demonstration, Williams monitored the computing equipment in New York, but it was wasted effort. The system worked flawlessly.

With the advent of World War II, demands on the Complex Computer increased, and many military projects moved a little faster toward completion because of its contribution. As other computers were built, the Complex Computer came to be called Model I. It was in daily use at Bell Laboratories until 1949.

Table I lists many of the logical and physical design features of Model I and of the five later models of computers. Two units of Model V were built, so that a total of seven relay-type computers were built at Bell Laboratories. Also, Model V could be expanded to a system of six computers and ten problem positions, although the two units were built with only two computers each and with either three or four problem positions.

Before discussing Models II through VI, however, it is well to gain some perspective of the course of computer design at Bell Laboratories. Model I was a real advance in applying electromagnetic techniques to machine calculation, but of course by today's standards it would seem to be little more than an elaborate desk calculator. Model II was improved in many respects, but was essentially designed to perform only one type of calculation. Models III and IV represented more significant advances in that they were the first Bell Laboratories machines that in today's sense could be called programmable, but only for restricted classes of problems. Models V and VI, by contrast, were truly modern computers. Although slower than the more recent electronic computers, they were organized much like present machines. All five models, however, steadily advanced the computer art and anticipated many features that even today are just beginning to be widely used.

V. MODELS II–IV

Model II[7,8,9] was built for the National Defense Research Council, and was placed in operation in September, 1943. A truly special-purpose computer, Model II was designed to handle certain fire-control problems that took only a few months to solve. Afterwards, however, many other tasks were found for it. Model II used the bi-quinary type of number representation with its self-checking features. It used a paper tape input and output; the program was perforated on a tape formed into a loop. The control unit recognized 31 instructions, which included the addresses of the registers. Model II was retired from service by the U. S. Naval Research Laboratory in early 1961.

Model III,[10] the basic development of which was completed in June, 1944, was another computer built for the National Defense Research Council and used for military fire-control problems. However, it handled many types of problems creditably, and was to some extent a general-purpose machine. Many features of Model III were new, of chief im-

TABLE I — STATISTICAL INFORMATION ABOUT BELL LABORATORIES COMPUTERS, MODELS I TO VI

	Model I	Model II	Model III	Model III°	Model IV	Model V	Model VI
LOGICAL DESIGN FEATURES							
Number of built-in routines	2	0	0	0	0	4	200
Decimal point	Fixed	Fixed	Fixed	Fixed	Fixed	Floating	Floating
Discriminating action	None	Note 1	Note 1	Note 1	Note 1	Exten.	Yes
Multiplication	Yes	Note 2	Yes	Yes	Yes	Yes	Yes
Division	Yes	No	Yes	Yes	Yes	Yes	Yes
Square Root	Yes	No	No	No	No	Yes	Yes
Indeterminate arithmetic	No	No	No	No	No	Yes	Yes
Special trigonometric features	No	No	Note 1	Note 1	Note 1	Yes	No
Special logarithmic features	No	No	No	No	No	Yes	No
Round off — automatic or program	No	Pro.	Pro.	Pro.	Pro.	Auto.	Auto.
Subscript knowledge	No	No	Yes	Yes	Yes	No	No
Number of addresses in code		1	1 or 2	1 or 2	1 or 2	3	3
Self checking	No	90%	100%	99%	100%	100%	100%
PHYSICAL DESIGN FEATURES							
Number of relays	450	440	1,400	≈1750	1,425	9,000	4,600
Pieces of teletypewriter equipment	4	5	7	≈10	7	55	16
Number of number registers	4	7	10	14	10	15	12
Number of digits per number	8	2 to 5	1 to 6	1 to 6	1 to 6	1 to 7	3, 6, 10
Multiplication time in sec. per 5 digit number		≈4.3	1	1	1	0.8	0.8
Number of problem stations	3	1	1	1	1	3 and 4	2
Arranged for unattended operation	No	No	Yes	Yes	Yes	Yes	Yes
Number notation with self-checking bi-quinary	No	Yes	Yes	Yes	Yes	Yes	Yes
"2 out of 5"	No	No	Yes	Yes	Yes	No	No
"3 out of 5"	No	Yes	Yes	Yes	Yes	Yes	Yes

° This column applies to the Model III after its modification in 1949.
Note 1. Very limited application.
Note 2. With multiplier specified in program.

portance being its 100 per cent self-checking of all operations. The machine stopped positively on any kind of single failure and on most combinations of two or more simultaneous failures.

A second and very significant feature of Model III was its calculator, designed by E. L. Vibbard. This unit multiplied and divided by the principle of finding partial products in a multiplication table. Other noteworthy features were table-hunting, double-entry interpolation, and unattended operation. Also included was the feature now commonly called indexing. In the Model III it was termed subscript notation, although it did not have the full flexibility of modern computer indexers. In all, Model III was possibly the most interesting of the Bell Laboratories computers from the point of view of its design logic and of the ease of understanding its operations. In 1944 Model III was moved to Fort Bliss, Texas, and was in use until 1958.

Model IV[11] looked like Model III and did the same kind of computing. However, changes were included enabling Model IV to handle trigonometric functions from $-90°$ to $+360°$. It was built for Naval Ordnance and its basic development was completed in March 1945. In Naval circles it was known as the Mark 22, and was in service until early 1961.

VI. MODELS V AND VI

As mentioned above, Models I through IV can be regarded as belonging to an era of the past. Models V and VI, however, bridged the gap between the beginnings of the art and the modern era of electronic computers.

In size and flexibility, Model V[12-16] was Bell Laboratories' most ambitious project in computer development up to that time. Two were built. One was delivered (1946) to the National Advisory Committee on Aeronautics, and the second was built (1947) for the Ballistics Research Laboratory at Aberdeen, Maryland.

As mentioned earlier, Model V was a system having a maximum of six computers and ten problem positions. Such arrangement permitted the computers to function continuously. Problems were loaded into idle problem positions, and a computer on completion of one problem automatically picked up another. A problem position had one tape reader for input data, up to five readers for the program of instructions, which allowed considerable flexibility in introducing sub-routines, and up to six readers for tabular data. Tables of logarithms, antilogarithms, sines, cosines and antitangents were permanently wired into the machine.

The calculator of Model V included: floating decimal point, multiplication by "short-cut" addition, automatic roundoff (but subject to cancellation), the ability to recognize most indeterminate arithmetic operations, special facilities for trigonometric and logarithmic calculations, and special auxiliary equipment for processing of various paper tapes. Model V also included rather elaborate discriminatory controls. These controls, as in the panel switching system application mentioned earlier, are now referred to as conditional transfers. Model V operated around the clock, and had an excellent record for low out-of-service time.

In recent years, the two Model V computers have had an interesting history. The unit at Aberdeen was transferred to Fort Bliss and later was given to the University of Arizona for educational and research programs. The unit built for the National Advisory Committee on Aeronautics was given to Texas Technological College in early 1958. Unfortunately, however, it was severely damaged in transit and was of no further use except for spare parts for the University of Arizona machine.

Model VI,[17,18] after an extensive test period, was placed in regular service in 1950. It was built for Bell Laboratories' own use in solving a wide variety of research and development problems. In essence, Model VI was a simplified version of Model V, having only one computer and less elaborate discriminatory controls and problem positions. In other respects, however, Model VI incorporated many improvements. It had three storage tapes, one of which could have either numbers or instructions. It had a system of several hundred semipermanent subroutines, each of which could be used for problems of the same type with differing numbers of variables. The internal subroutine control adjusted itself to the particular problem at hand. Model VI also had what is called the "end of numbers" check signal, which eased such problems as determining the end of a line of coefficients in a matrix-type problem. Also, Model VI had an automatic "second trial" feature that functioned during unattended operation, thus improving reliability in the presence of a trouble condition. After several years of service at Bell Laboratories, Model VI was given to the Polytechnic Institute of Brooklyn. In 1960, Brooklyn Poly retired this computer and gave it to the Bihar Institute of Technology in Bihar, India.

VII. CONCLUSION

With this background of Bell Laboratories work in the computer field, and of the telephone technology that prompted the developments, it is possible to make a few comments concerning the extent of the total contribution. Aside from their specifically mathematical aspects, these contributions are chiefly in the areas of machine accuracy and dependability, and ease of programming, operation and maintenance.

On the score of accuracy, through 1951 only two errors were reported as resulting from machine faults in Models III through VI. This enviable record reflects the corresponding accuracy of telephone switching systems and resulted partly from such telephone-derived features as self-checking and second-trial functions. The dependability of the computers also derived in large measure from the extensive heritage of experience in designing switching systems. In particular, notice must be taken of the U-type relay and its associated circuits. After many years of careful design, the U-type relay had become a symbol of the reliability of telephone systems, and it was used to great advantage in all the Bell Laboratories relay computers.

Model V compared favorably with other contemporary computers in ease of programming, and Model VI brought about an even greater reduction of effort. With problems using repetitive subroutines, programming effort with Model VI was near the minimum. In terms of operating ease, no more than five minutes was required to load Model V with the most complex problem it could handle, and even less time was required with Model VI. Generous use of indicating signals aided in analyzing machine stoppages, so that maintenance was thereby facilitated. For both operation and routine maintenance, highly trained personnel were not required.

These are the same factors stressed in telephone systems design, so the above summary could be an apt description of almost any switching system developed at Bell Laboratories. The similarity again stresses the way in which telephone research and development have had an important influence on computers.

VIII. ACKNOWLEDGMENTS

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