indispensable now. It is becoming increasingly vital at a startling rate.

Computing machines are themselves an engineering product. It is entirely likely that, in their ultimate development, the engineering profession itself will be the biggest user of that product.

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A Review of the Bell Laboratories' Digital Computer Developments

E. G. ANDREWS

THE Bell Telephone Laboratories have designed and built seven digital computers. They are all electro-mechanical types using telephone systems relays and teletype transmitting and recording devices as their principal apparatus elements.

This succession of developments had its origin in 1938 in the mind of Dr. George R. Stibitz, then a research mathematician with the Bell Laboratories Stibitz observed that in one laboratories' development area, a considerable portion of computing effort involved complex number arithmetic computations. Another development area was designing dial systems using relays and crossbar switches as the principal apparatus. Stibitz recognized that the design techniques employed by this latter group were directly applicable to a systems design which could also produce a computing system for the first group. He designed such a system. He called it a "complex number computer."

Mr. Samuel B. Williams, a telephone systems design engineer, supervised the engineering and manufacturing of this early computer. It is believed that he thus became the one who first produced an automatic digital computer for purely scientific computing.

Dr. Thornton C. Fry* publicized this creation before the Mathematical Society at Dartmouth in the fall of 1940.[1] Demonstration equipment consisting of a keyboard input device and a teletypewriter for recording answers was installed at the University. This equipment was connected by a telephone circuit with the computer in New York. Those attending the conference placed their own test problems on the keyboard at Hanover, N. H. The computer in New York made the computation and controlled the printing of the answer on the teletypewriter at Hanover. The complete operation required about 1 minute. This feat of remote control operation was not to be duplicated until a computer conference was held in Washington, D. C., 10 years later.

With this complex number computer as the pioneer and with the Model VI as its latest achievement, the Bell Laboratories computer development has spanned the pre-electronic computer development era. The seven computers now are known by Model numbers, with Model I being the designation of the complex number computer. Two Model V computers were built. Table I shows some statistical information about their size and use. The Models V and VI, although operating at electromechanical speed, offer several challenges to current electronic computers. While the same cannot be said of the Models I to IV, nevertheless, they have features of interest.

Model I

The Model I consisted of about 400 relays and ten crossbar switches. It was operated from any of three stations located in various parts of the Laboratories' 463 West Street building. The station equipment consisted of a number of push button keys for originating a problem and a teletypewriter for recording the answer. It is the only one of the seven computers to employ crossbar switches.

Fundamentally, the Model I could handle only two kinds of problems, multiplication and division of complex numbers. The results of successive such problems could be accumulated when the operator required it. This feature made it feasible to add and subtract complex numbers. By multiplying a number by +1 or −1 with the accumulator key operated, the number was added to, or subtracted from the previous accumulation.

This computer operated with binary coded decimal notation, with the decimal digits 0 to 9 being represented by the binary numbers 0011 to 1100. The input and output information consisted of eight place numbers, but the calculator carried operations out to ten places, the two extra places being used to improve accuracy when accumulating the results of several problems.

The Model I was in daily use until 1949 when it was removed from service due to obsolesence and to make way for its successor, the Model VI.

Model II

The Model II[2,3,4] was built for the National Defense Research Council and placed in operation in September 1943. It is truly a special purpose computer. Its purpose was to handle some specialized fire control computing for several months. But on the completion of this computing assignment, new problems arose. It is still in service.

It has about 440 relays It uses paper tape input and output. It has a flexible control provided by external

* Subsequent to the original publication of this paper, it has been brought to the attention of the author that the paper describing the computer was delivered at the meeting by G. R. Stibitz. The local arrangements for the remote control operation were supervised by T. C. Fry.

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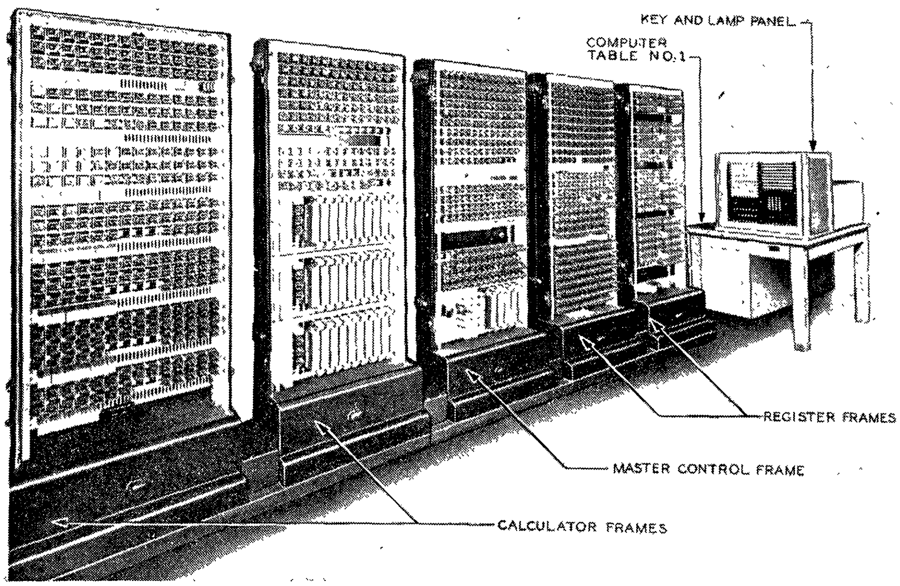

Figure 1. Model III computer. Frame equipment with covers removed

problem programming. The program is perforated on a tape which is made into a loop. The control unit recognizes 31 instructions which include the addresses of the registers.

The calculator and registers employ the bi-quinary number representation with its self-checking features. The Model II has had no respite. It is still in operation at the Naval Research Laboratory and is operated under the supervision of Mr. B. L. Sarahan.

Model III

The Model III[5] was built for the National Defense Research Council and placed in service in June 1944 at Camp Davis, N. C. It was designed to handle several kinds of problems concerned with the testing of fire control equipment. In this sense, it is a special purpose computer. However, it is sometimes thought of as being a general purpose computer in a limited sense because it handles many types of problems very creditably.

Figure 1 shows the computer as originally delivered. It then had about 1,400 relays and used seven pieces of teletype equipment. The control equipment (not shown) was located in an adjoining building. It was subsequently expanded as will be described later. Many features, new in the computing art, made their initial appearance in this computer. The foremost of these is the 100 per cent self-checking of all operations. Our engineers believe that they have achieved a design in the Model III and its successors, which positively stops the machine on any kind of a single failure. Most combinations of two or more simultaneous failures also stop the machine. The merits of this feature will be discussed further in the summary.

A second feature worthy of special note is the calculator. Almost single handed, Mr. E. L. Vibbard, a dial systems telephone switching development engineer designed a calculator employing the bi-quinary notation and using the multiplication table principle for multiplication and division operations. Those who are familiar with the design details of the calculators in all seven of the computers generally agree that from the viewpoint of logic of design and ease of understanding its operation, this calculator is the Bell Laboratories' best.

Other noteworthy features of the Model III are: table hunting, double entry interpolation, subscript notation (to be described), storage tape operation, and unattended operation. One part of the principal problem handled on this machine requires that a cubic be fitted to four items of empirical data. The four items are functions of four values of time, T_{-1}, T_0, T_{+1} and T_{+2}. With the value T_0 calculated, the Model III readily obtains the data corresponding to the four subscript values. Only the Models III and IV have this feature.

When the Army Field Forces Board Number 4 moved from Camp Davis to Fort Bliss, Tex., they took the Model III with them. In 1949 extensive changes were made to increase its general usefulness by increasing the storage capacity and adding more flexibility to the programming provisions. This computer has been in constant use. It is being operated under the supervision of Mr. Nelson E. Sowers.

Model IV

The Model IV[6] computer was built for Naval Ordnance to do the same kind of computing as the Model III. In its general appearance, it differs little from the Model III, but some changes were necessary to enable the Model IV to cope with trigonometric functions of angles from -90 degrees to $+360$ degrees. In Naval circles, this computer is known as the MARK 22 computer. It was placed in service at the Naval Research Laboratory in March 1945 and has been in constant use. Like the Model II, it is operated under the supervision of Mr. B. L. Sarahan.

Model V

The Model V[7–11] is the Laboratories' most ambitious computer development from the viewpoint of size and general flexibility. Two have been built, one delivered in December 1946 to the National Advisory Committee on Aeronautics (NACA) at Langley Field, Va., and the other delivered in August 1947 to the Ballistic Research Laboratory at Aberdeen, Md. Each has approximately 9,000 relays and 55 pieces of teletype equipment.

The Model V embraces a system of computers which can be operated together or independently. The system permits six computers and ten problem positions. As one computer completes the problem on its associated problem position it automatically picks up a waiting problem position. This arrangement makes it possible to load new problems on idle problem positions thereby providing uninterrupted use of the computing equipment itself. Thus computer Number 3, for example, may complete its solution of a differential equation set up on problem position Number 5, and in a fraction of a second start a radically different problem set up on problem position Number 2. The two installations each have two computers with 3 and 4 problem positions. Figures 2 and 3 show the Aberdeen installation.

A problem position has these facilities: one tape reader for problem input data, one to five tape readers for the program of instructions, and as many as six tape readers for tabular data. The five program tape readers allow considerable flexibility in introducing subroutines. The six table tape readers allow for extensive use of tabular data. These

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							
No. of built-in routines	2	0	0	0	0	4	200
Decimal point: fixed, or Fl.	Fix	Fix	Fix	Fix	Fix	Fl.	Fl.
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	No	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—auto. 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	425	440	1,400		1,425	9,000	4,600
Pieces of teletype equip.	4	5	7		7	55	16
No. of number registers	4	7	10	14	10	15	12
No. 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			1	1	1	0.8	0.8
No. of problem stations	3	1	1	1	1	3 & 4	2
Arranged for unattended oper.	No	No	Yes	Yes	Yes	Yes	Yes
Number notation with self-checking: bi-quinary	No	Yes	Yes	Yes	Yes	Yes	Yes
Number notation with self-checking: "2 out of 5"	No	No	Yes	Yes	Yes	No	No
Number notation with self-checking: "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.

readers are not used for tables of logarithms (base 10), antilogarithms, sines, cosines, and antitangents because these functions are wired into the machine on a permanent basis.

The calculator has these features: floating decimal point, multiplication by "short-cut" addition, automatic round off (but subject to cancellation), and indeterminate arithmetic operations. Other new features in the Model V are: special facilities for trigonometric and logarithmic calculations, rather elaborate discriminatory controls, and special auxiliary equipment for processing of various paper tapes.

The out-of-service time for the Model V computer is very low. Recent reports from the NACA installation show that their computer is turning out better than 22 hours of computing per day. It is operated around the clock; 16 hours on an attended basis and 8 hours unattended. It is operated under the supervision of Mr. Thomas B. Andrews.

Model VI

The Model VI[12,13] shown in Figure 4 was built for the Laboratories' own use. Extensive test usage on actual problems began in 1949. Incident to this, details of the final design were evolved. The computer was finally placed in regular service in November 1950. It resembles the Model V in many respects but it is somewhat simpler in design in these respects: one computer (instead of two or more) constitutes the installation, less elaborate discriminatory controls, and less elaborate problem positions. However, it has features not found in its predecessors. It has three storage tapes, one of which may have either or both numbers and instructions. Also, it has a system of several hundred semipermanent subroutines which has brought about a marked reduction in programming effort. Its value is best shown by the fact that only one set of programming instructions is required for a particular type of a problem, such as a problem of determining the frequency response for a communications system network. No further programming is required even though one problem of the type may have only six or eight parameters in simple impedance configurations while the next one may have over a hundred parameters in complex impedance configurations. In each case the internal subroutine control adjusts itself to the particular problem at hand. More detailed information about this feature has been covered in other papers.

Another feature, also contributing to a reduction of programming effort, is what has been called the "end of numbers" check signal. It is easiest explained by showing its application in a matrix problem. The problem data, in this case, includes this check signal after the last term of each line of coefficients of the matrix. The program is made applicable to a matrix of any order. Furthermore, the program is made to recognize the check signal as an indication that there are

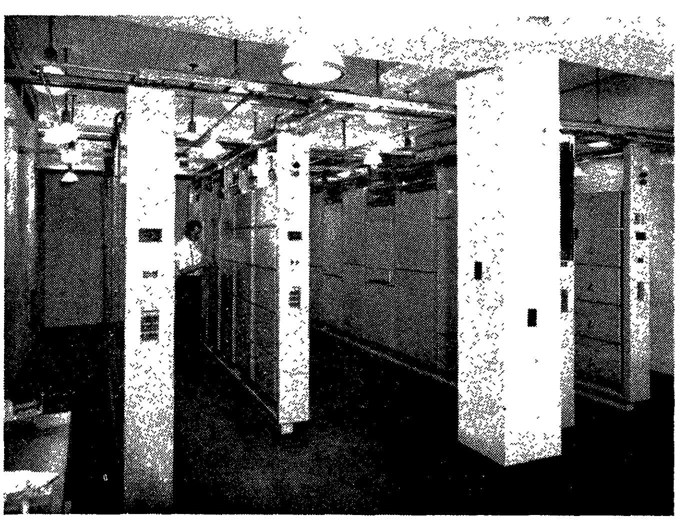

Figure 2. Model V computer. Frame equipment at Aberdeen installation

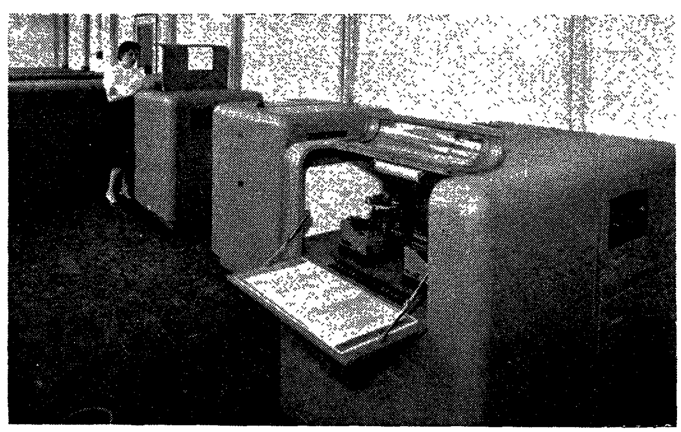

Figure 3. Model V computer. Operating room equipment at Aberdeen installation

no more coefficients for the line being processed. Heretofore, it has been necessary either to program for a matrix of a specific size or to include in the program a set of instructions for counting off a prescribed number of coefficients.

The Model VI has an automatic second trial feature which is operative under most machine trouble conditions. This feature functions only during unattended hours and obviously results in an improvement in unattended operation. This computer is operated under the supervision of Mr. D. T. Bell.

Summary

The Bell Laboratories' computers divide easily into two groups, the first including the Models I to IV, and the second including the Models V and VI. From the viewpoint of the current state of the design art, the first group belongs to an era that is past, and the second group to the era which bridges the past with the introduction of successful electronic computers. It is therefore to be expected that the Models V and VI would represent a highly satisfactory state of the development using electromagnetic apparatus. Similarly, it would be expected that they cannot be compared favorably with respect to speed or with the large amount of high speed storage capacity of the electronic type. But there are other figures of merit for gauging the satisfactoriness of a computer, and the Models V and VI possess many of them. Five of these will be discussed.

Dependability

The basic design of the control components has the heritage of the extensive experience derived from the design of telephone switching systems. Only timeproved dependable apparatus is employed, notably, the heavy duty *U* type relay. Relay contact design and detailed consideration of contact protection against electrical erosion have brought about excellent results in relay operation performance.

Ease of Maintenance

There are several factors which contribute to this feature. Generous use of indicating signals at a control panel assist in the analyzing of machine stoppages. Almost all machine failures stop the computer at once. This together with the helpful indicating signals indirectly prescribe the qualifications of the maintenance personnel. Engineering talent is not required. In fact all of the machines are being maintained by craftsmen having the same kind of training and skills that telephone systems switchmen possess.

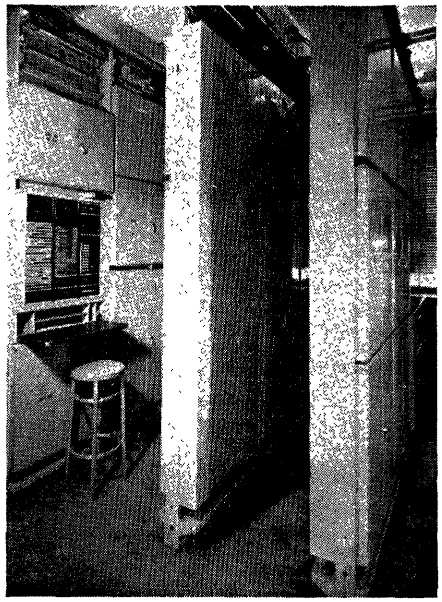

Figure 4. Model VI computer. Frame equipment

Ease of Operation

This is manifested when loading the machine with a new problem, when handling machine stoppages, when operating on an unattended basis, and when handling the transfer from one problem to another. No more than 5 minutes is required to load the most complex problem on the Model V. Even less time is required for the Model VI unless changes and additions are required in the internal routines. The Model V, if directed in the program, checks that all of the various tapes are loaded in the proper tape readers.

Because machine failures usually stop the computer at the instant of failure and because of the extensive use of indicating signals as referred to above, the amount of "down time" due to faulty machine operation is very low. Report from the two Model V installations indicate that on the average, only 15 to 20 minutes is required to locate the cause of a trouble and to take the necessary corrective action. There are two special features that are operative during unattended hours. One of these is the automatic second trial of the Model VI mentioned previously. The other is an automatic recycle when faulty operation is detected. This feature, which appears in all computers starting with the Model III, causes the control to abandon the problem at hand and to advance to a waiting problem. This feature has made unattended operation highly profitable. As stated above, the Model V at the NACA laboratories is attended on two of the three shifts. All other machines are attended on only one shif but they are all operated on a 24-hour-a day basis.

When a computer has completed a prob lem, it automatically advances to pic up any waiting problem. This, toc makes unattended operation feasible.

Besides these advantages in operatio ease, another has been developed bu it has not yet been incorporated into an computer as far as is known. This the self-correcting code for numerical data. Dr. R. W. Hamming devised this principle of coding.[14] A computer with this feature would show an unattended operation performance superior to anything we know today.

Ease of Programming

The Model V compares very favorably with other computers with respect to ease of programming. However, the Model VI has programming features which have brought about a marked reduction of effort compared with the Model V. The above description of the Model VI mentions the ease of programming a network problem. In such a case the programming of another network problem consists of two steps; first, prescribe the formula number, such as *A14*, for the network problem, and second, set down the parameters of the problem in accordance with the general framework of the program that was established for the first network problem. In setting down the parameters for any one of the several branches of a network, an identifying number accompanies the numerical values. For example, suppose that a branch has nine elements, consisting of three parallel circuits of a resistor, capacitor, and inductor in series. An identifying number, such as *C31*, would indicate to the control that the nine numbers which follow on the tape apply to the parallel-series configuration just described. The number *C32* might denote some other kind of a branch having nine elements, and *C33* might denote a branch having only four elements.

Similarly formula number *A15* might denote the internal program for solving a polynomial of any order up to 20. *A16* might denote the program for inverting a matrix of any order up to 12.

This feature is of prime value when there are problems having some repetitive subroutines. In these cases, the Model VI programming effort is near the minimum.

Machine Accuracy

This means 100 per cent self checking. The users of the Bell Laboratories' machines have reported only two occurrences of machine faults that resulted in machine errors. These were both reported by the NACA laboratory. No details have been received about these two cases, and as yet, no analysis is being made of them. Rather than try to disprove the claims for these two errors, it may be better to let them stay on the performance record. Perhaps more credence is accorded to our claims for self checking with two errors on the record rather than none. Because of this fine performance, the scientist uses the results obtained from these Bell Laboratories' computers with complete assurance because he confidently believes that his computer has not deceived him.

To acknowledge the names of all of those who have participated in this computer development would make a long list. It is sufficient to say that at various times, 20 engineers in the telephone switching development department have taken part in the development and construction programs. In the planning stages, mathematicians and scientists in the research department joined in the numerous discussions on fundamentals and objectives.

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The Transistor as a Digital Computer Component

J. H. FELKER

DIGITAL computers have been defined as machines that use a language explicitly and one may think of them as carrying on interior dialogues. This concept helps to illustrate one difference between the modern computer and other electronic machinery. The principal function of most electronic apparatus is to take low level signals and raise them to a power level sufficient to drive some device such as a loud speaker, servo motor, relay, or perhaps a cathode-ray tube. In a digital computer, however, there may be a thousand active elements that merely converse with one another. There may be a million alterations of state before an output device has to be energized. These internal operations need not be carried out at any particular power level. It is only necessary for one device to talk loud enough for the next device to recognize what was said. Devices are needed which have stable states that can be changed by very low input signal power. As the computer art advances, one hopes it will move towards the use of devices that listen intently rather than speak loudly. It is in this direction that the transistor can make its earliest contribution to the digital computer field.

Computer Functions

As is well known, computer operations can be divided into the two classes, memory and logic. Memory can be defined as a representation in space of a function of time. The logic operations can be defined as the recognition of spatial distributions of voltages and currents. These logic operations can be performed with passive nonlinearities, that is, a 3-terminal *and* circuit and other such logic circuits can be built with crystal diodes without the use of active elements.[1] It is necessary to use active elements only as amplifiers to make up for loss in these logic circuits and in delay lines. When the work described herein was started, it seemed that transistors could be got into digital computers at the earliest date if the transistors were asked to provide only gain and all the logic functions were performed in diode circuits while the memory functions were performed by use of delay line storage cells. This, of course, is the philosophy that was followed earlier by the SEAC group[2] with the exception that they used a vacuum-tube amplifier rather than a transistor amplifier. Since the transistor itself has voltage and current relationships quite similar to a germanium diode, it is expected that the germanium diode in a transistor computer will operate in a more natural environment than in a vacuum-tube computer and will respond to such favorable conditions by exhibiting longer life and more reliable operation than it has sometimes done in the past.

Reliability

Many earnest seekers have attempted to find out what kind of reliability can be

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