part one

those were the machines

THE RELAY COMPUTERS AT BELL LABS

by GEORGE R. STIBITZ as told to MRS. EVELYN LOVEDAY

Sometimes these days when I am at one of the many teletypewriter stations of the sophisticated GE computer at Dartmouth College asking for, or putting in, a program related to my work of applying mathematics to biomedical problems, I feel like the old lady in the nursery rhyme who said, "Lawk a mercy on me, this can't be I!" For I can remember when.

At my somewhat advanced age (or what often feels like it), it seems only yesterday—but it was actually in 1937—that I liberated some relays from a scrap pile at Bell Telephone Laboratories where I then worked, and took them home to start what I thought of as a play project. I had observed the similarity between the circuit paths through relays and the binary notation for numbers and had an idea I wanted to work out.

That weekend I fastened two of the relays to a board, cut strips from a tobacco can and nailed them to the board for input; bought a dry cell and a few flashlight bulbs for output, and wired up a binary adder. I wired the relays to give the binary digits of the sum of two one-digit binary numbers, which were entered into the arithmetic unit by pressing switches made of the metal strips. The two-flashlight-bulb output lighted up to indicate a binary 1 and remained dark for binary 0.

I took my model into the labs to show to some of the boys, and we were all more amused than impressed with some visions of a binary computer industry. I have no head for history. I did not know I was picking up where Charles Babbage in England had to quit over a hundred years before. Nor did it occur to me that my work would turn out to be part of the beginning of what we now know as the computer age. So, unfortunately, there were no fireworks, no champagne.

Being a compulsive generalizer, I wondered what could be done with a large number of such adders. Further evenings at home were spent entertaining myself by sketching circuits for addition, multiplication and even division. The idea occurred to me that decimal digit adders could be set up in binary form, with each decimal digit expressed in binary form by multiple contacts on keys. I actually designed such decimal adders, but soon found that the "carry" circuit was complicated, and that the circuits for converting a number to its complement were rather complicated.

No mathematician can abide lack of symmetry, and so I looked around for a neat way of solving this difficulty. The tidiest kind I could think of was to shift the range of decimal digits to the middle of the list of 4-bit binary numbers. This shift was equivalent to adding 3 to the decimal digit so that decimal 0 was represented by binary 3

Dr. Stibitz is presently a research associate in physiology at Dartmouth Medical School, where he is involved with computer applications in biomedicine. Formerly with Bell Labs (1930-1941), he was later an independent consultant (1946-1964). In 1945, he received the Harry Goode Memorial Award for pioneering in edp; in 1966, he was honored with a D.Sc. from Denison Univ. He has an MS from Union College, and a Ph.D. from Cornell Univ.

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(0011), and so on. With this symmetric arrangement, the 9's complement of any decimal digit was found by changing each binary 1 to a binary 0, and conversely. The interchange was easy with relay (or any binary) circuits. All that was needed was a single two-pole contact leading to all the relays of the number to be inverted.

Unfortunately, when two excess-3 decimals are added, the sum is too large by six units, so it was necessary to think about some translating circuits to remove three units and get back to an excess-3 code. In compensation, there was the happy accident that, in the excess-6 code of the sum of two digits, all numbers greater than decimal 9 are 5-bit binary numbers. Hence, if the 5th binary digit was 1, it meant that a carry was called for and this was easy to accomplish.

Well, as I said, all this thinking was the kind of play project that I still indulge in very frequently in place of golf, or other constructive leisure time pursuits.

fortune and need

Soon, however, it had to become work in earnest, for Dr. T. C. Fry, chief of the mathematics group I was in, told me that the difficulties of handling complex numbers had come to his attention, and he asked whether my little relay calculator could do complex arithmetic. Could it! I had already thought out most of the components for a complex calculator, and so I soon had drawings sufficiently complete to be considered.

These were highly unusual, since I knew nothing of the language of symbols of the well-developed switching art, and my sketches must have amused the switching engineers. But—there was Sam Williams.

Now my calculator had had two pieces of good fortune. One was the coincidence of the binary adder and my circuit diagrams with Fry's expression of complex computing needs. The second was the assignment of Sam Williams to the evaluation of the calculator's feasibility to meet the needs.

Sam had been a switching engineer for many years and was thoroughly familiar with all properties of relays, but not with mathematics or number theory. He had to struggle, not only with my dismally unconventional drafting, but also with the ideas of binary notation and operations, and with my excess-3 coded decimal notation.

All the angels were with us. He not only made a thorough study of the calculator and reported it was feasible, but, from my knowledge, made many useful suggestions about control circuitry. In a few weeks we got the go-ahead signal; Sam was given the job of detail design and we were off to the races.

At this point there were some small complications about correcting 9's complements into 10's complements, but they were not serious. The adders were now designed and multiplication was not difficult. Rather than use multitudes of relays to perform this operation we decided to use some relatively new pieces of telephone equipment called crossbar switches, which were, in effect, compound relays with many contacts.

There were many serious discussions about 10-key vs. bank-type keyboards for input. The bank keyboard would have saved some memory equipment in the computer, but it was soon decided that the simplicity of the 10-key arrangement made it worth the extra cost. Operators' strips of 10 keys were adapted, and a second strip was modified for the operational symbols, +, −, ×, +i, −i, ÷ and =.

We thought very briefly of using binary notation for input and output, but the prospect of teaching binary notation to a crew of girls was appalling, and so the idea was abandoned pronto.

In complex operations it was handier to put the divisor into the machine first. We had to have a special type symbol in which the slash for division was turned backwards for this purpose. By putting the divisor in first, the arithmetic unit could start squaring the real and imaginary parts as soon as the slash appeared.

Since relays operate at about 10 milliseconds, the squaring operation (which was carried on when the slash appeared) took an average of 40 addition times, or some half-second with no allowance made for sub-normal relays. As I recall, for safety's sake we allowed a couple of seconds for this operation.

The capacity of the machine was to be eight decimal places with two extra digits provided in the arithmetic unit to compensate for excessive round-off errors when accumulating many subtabulations.

The machine was a parallel one, with two units which handled respectively the real and the imaginary parts of the calculations. A standard whimsey of sightseers when shown the imaginary unit was that it *looked* real. Somehow that remark lost its freshness after a score of repetitions. The two units operated in parallel, during multiplication, for example, when the real and imaginary parts of the multiplicand were multiplied by digits of the real part of the multiplier simultaneously.

success

Construction of the machine was completed in 1939, and debugging began, using diagnostic problems devised by Williams. Many of the relay operations were dependent on timing, with slow and fast operate and release relays determining the sequence of circuit openings and closures. When one relay in a register failed to come up to specs in speed of operation the whole calculation came out wrong. Slower relays, to initiate the next step of computation, cured the trouble but slowed the machine. All of this created some troublesome and often profane moments.

Even so, the final successful speed was nearly that contemplated in the original design. As I recall, the addition time was about 0.1 seconds.

In 1938 we had "known" on paper just what the computer should do, and the Bell Labs experience indicated that the relays would do what the paper design said they would, but nevertheless it was a spine-tingling experience when the wiring and design bugs began to give way, and true answers began to flow from the computer, just as we had envisioned they would.

The binary computing elements were so very different

A published poet, Mrs. Loveday is a member of a surfacing group of creative writers who have tiptoed into the computer field. She is now a freelance technical writer for Sperry-Rand patent attorneys, IBM, and the Colleges of Medicine at the Universities of Vermont and Dartmouth.

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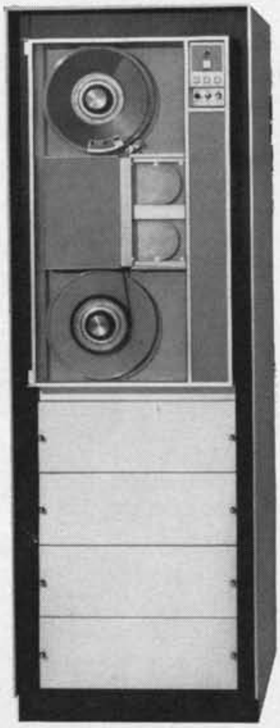

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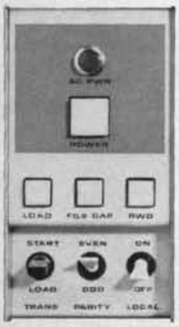

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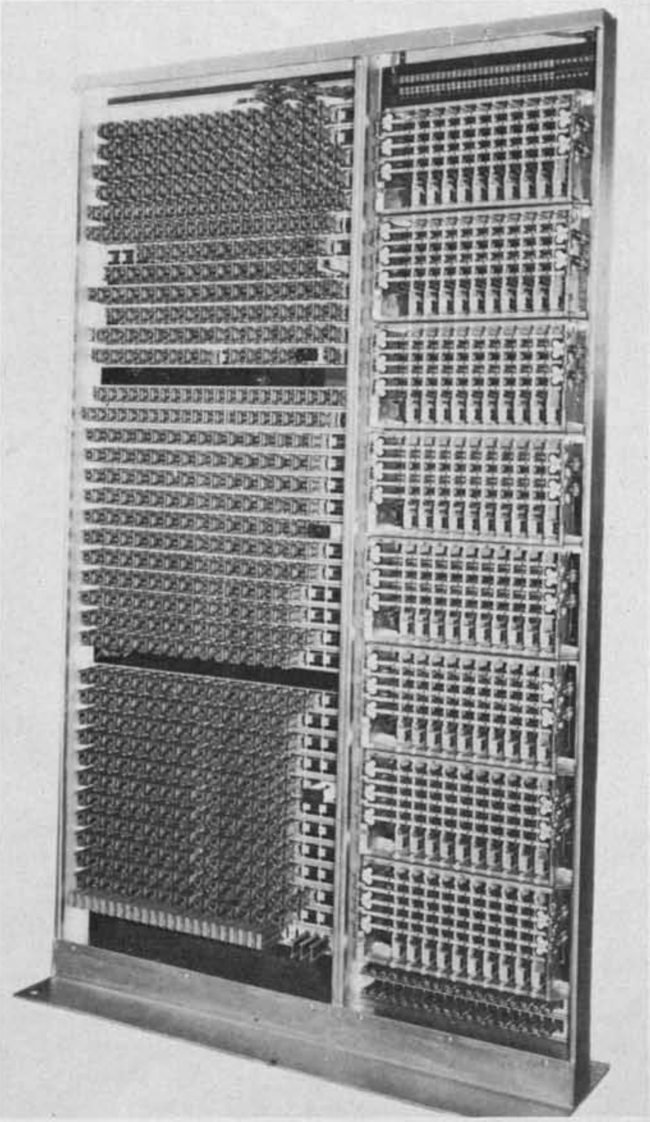
from the rotating gears of the conventional desk calculator, that it had been hard for many to believe they could do a more complex job and do it with incredible speed. Remember, this was in 1939.

It is believed that this relay computer was the first (at least in this country) to employ binary components. Succeeding Bell relay computers were binary also, as, of course, are all modern high-speed computers.

At last, in January of 1940, after some months of debugging and testing, the Complex Calculator (as it was now called) was set up in the Bell Laboratories building at 463 West St., New York City, and turned over to the calculations people in the mathematics department. The girls were entertained when a small new bug cropped up causing the teletype to print out BOO several times. Witchcraft?

Originally it had been thought that only complex multiplication and division were complicated enough to be worthy of the new machine, but it was soon found that complex additions and subtractions were so mingled with the difficult operations that there were many interruptions. A few relays were added, and then we had sub-

Mainframe of the Complex Calculator (Model I)



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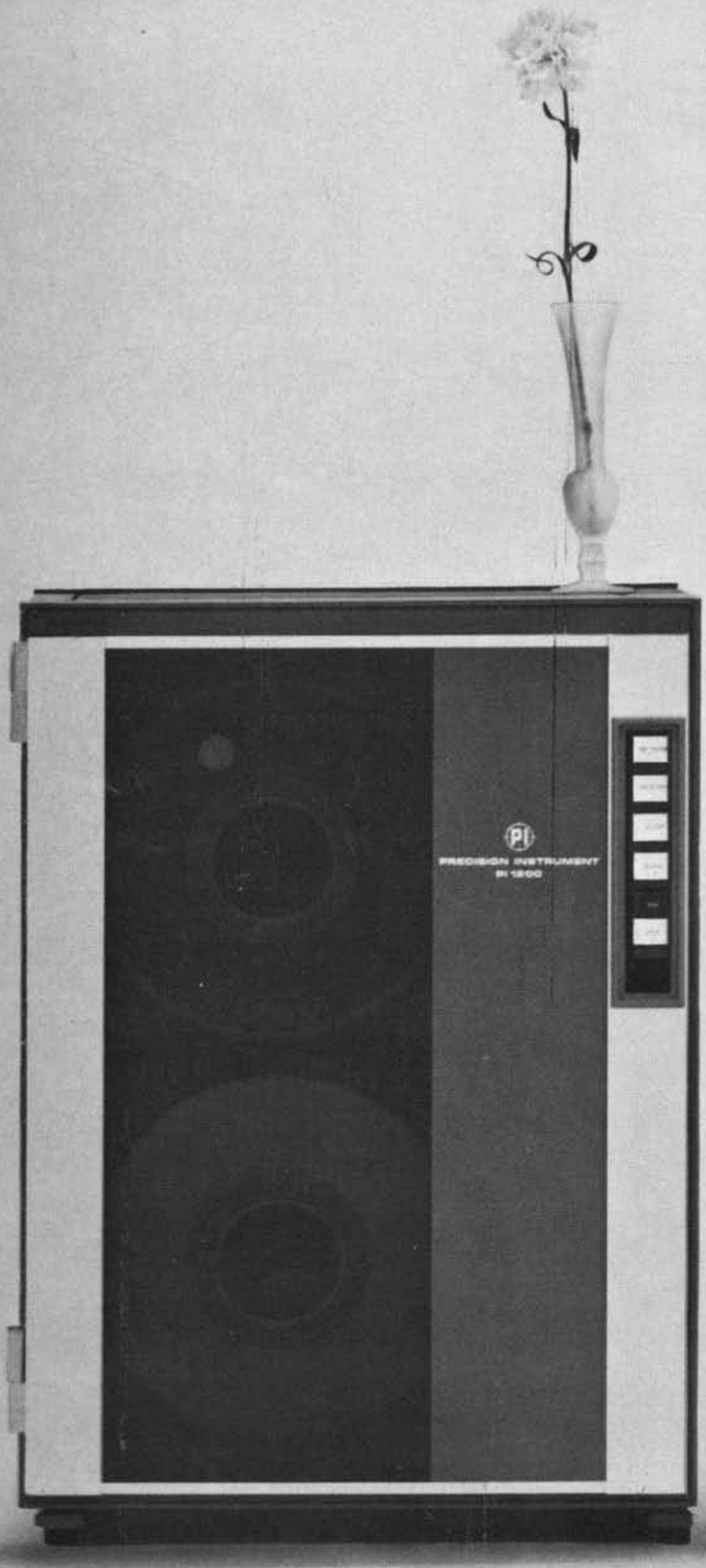

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traction and addition too. This easy alteration, in so complicated a machine, pointed up its flexibility as contrasted with mechanical machines.

Another group outside the mathematics department did a large volume of complex computations, so not long after the original installation it was decided to add a second teletype in another part of the building for the convenience of this other group. A third was added later in another location. Any of the three teletypes could be used on a first-come basis, and thus this first Bell relay computer included a feature only now appearing in some of the larger computers: multiple input positions with the lockout facilities required for this type of operation. Even in 1940, in a crude way, we had a time-sharing system.

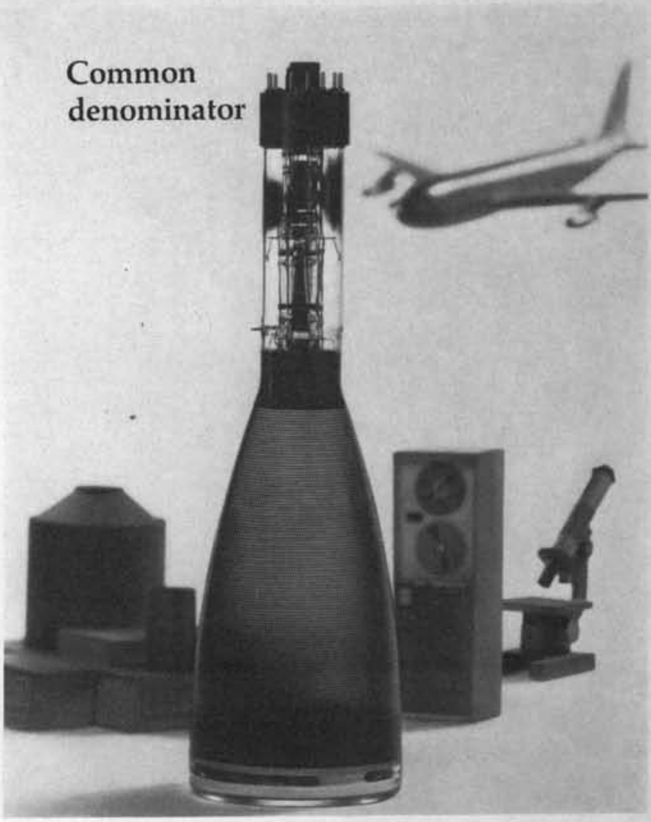
Further, while the computer had been specifically designed to handle the four complex number operations, users soon found that with certain special variations the computer could be used advantageously for other types of problems.

About the time the Complex Calculator was set up and operating well, Sam and I washed our hands and settled down to our customary work, pausing occasionally to go and peek at our baby, to make sure it was eating, sleeping and operating well. Soon we learned that it was to show off its tricks in public.

the public debut

Through Dr. Fry came a request for a paper on the computer to be presented at the September 1940 meeting of the American Mathematical Society at Dartmouth College. Originally it was planned to present the paper with

First demonstration of remote use of computer occurred at Dartmouth College in September , 1940. Teletype was linked to processor in New York City.



slides showing the equipment, teletype output and so on, and Dr. Fry suggested dictating problems for the computer over a phone link from Hanover to a teletype operator at Bell Labs in New York City.

With my usual genius for making things more difficult for myself and others, I suggested direct telegraph operation from Hanover, and this was decided upon. In July, Sam Williams designed some transceiving panels which were constructed and ready in late August.

The week before the Society meeting was a frantic one. We watched wiremen install the panels in McNutt Hall: arrangements were made for a circuit to New York City, to be protected against interruption, and finally, the day before the meeting, successful remote operation was accomplished. There was little time for a shakedown, but fortunately all went well, and I went to bed hoping the baby would perform well the next day too.

At the meeting I read my paper describing the machine, then Dr. Fry showed how problems could be introduced at the scene of the conference and transmitted to the computer in New York. We were then able to point to the teletypewriter which typed out the answers within a minute. It is believed that this was the first public demonstration of remote operation of an automatic computer, and foreshadowed the present growth of data transmission services.

Members of the audience were invited to submit problems to the computer, and I recall that Norbert Wiener was one who tried to stump it, unsuccessfully. This was Wiener's first introduction to the computer concept. Sam Williams was in New York monitoring the computing equipment, but it was wasted effort. The system worked flawlessly.

The pauses during which the computer solved each problem were as impressive as the operating period. The speed of computation was phenomenal for that time: only 30 seconds or so for a complex division comprising three multiplications and addition, and two divisions in eight-place real numbers.

A few newspaper reporters, in writing about this demonstration, toyed with the idea that some day kids would do their homework on a computer. My crystal ball was dusty and I put this thinking down to the usual journalistic extravagance. I must admit that I never at that time conceived of the computer as the teaching aid that it has become in very recent times.

However, the typical habits of the mathematician were making me try all kinds of generalizations of the relay computer idea. In 1939 and early 1940, I had made some specific proposals for improvements on what we already had, and I was anxious to implement them.

Unfortunately, the Complex Calculator had been so expensive that Bell Laboratories felt it impossible to invest money in further developments. The Calculator development, design, drafting, equipment, construction and debugging had cost $20,000—an astronomical sum in those days.

Then came World War II, and suddenly we were all plunged into unusual work and expenditures. In the second half of this article I will tell more about the life and times of the relay computers, the succeeding models of which we designed at Bell Laboratories for various military purposes. ■

(Next month the concluding article will reflect on the developments during the war, and describe the last models in the series.)

part two
those were the machines

THE RELAY COMPUTERS AT BELL LABS

by GEORGE R. STIBITZ as told to MRS. EVELYN LOVEDAY

As I said in the first half of this article, once we had the Complex Calculator going well at Bell Laboratories in 1940 and 1941, it was deemed economically unwise by the Powers Upstairs to build any more.

I had made several proposals in 1939 and 1940 to improve the relay computer. One of these was that in order to save the user the exasperation of having numbers overflow the computer I suggested a floating decimal point scheme (which was, in fact, finally used in a later computer about 1945).

Further, I had thought that the difficulty of troubleshooting a computer and timing its relays might be solved by a self-checking or error-detecting code. I called this the bi-quinary code, which was, in fact, more severe than the parity check used later, but was similar in concept.

In this code, each decimal digit was represented by two groups of binary (off-on) elements in each of which one and only one was ON when a digit was correctly represented. In use, a number of such paired groups would control check circuits. Before a number was stored or added, all of the elements were OFF and a check circuit determined this fact. Then, when one and only one element in the group turned ON, a check circuit verified the fact and permitted the next computational step to occur.

And so I fiddled on with these and other ideas, itching to try them out. The very ill wind of World War II blew me some good in this area, for I was loaned by Bell Laboratories to the National Defense Research Committee, (NDRC), which had the stimulating and brilliant Dr. Warren Weaver as its chairman.

I had designed a dynamic tester for anti-aircraft controls which was actuated by a punched-paper tape with digital information and which provided outputs simulating arbitrary motions of a target.

It was agreed by NDRC that a computer to produce the tape would be worthwhile and I designed a small "Interpolator" with taped program, teletype or punched tape output, and punched tape input. This computer needed only to add, though it could multiply by a constant in the program. Now I had a chance to use the bi-quinary self-checking code, and the control unit recognized 31 instructions, which included the addresses of the registers.

model ii

The detailed design of the Relay Interpolator (or Model II as it was soon to be called) was put into the hands of E. G. Andrews and his group at Bell Laboratories. Andy, like Sam Williams, was later a leading figure in the Association for Computing Machinery, and was always most competent in his work.

Model II was built on two relay racks. It contained some six registers for storing numbers and performed a linear iterative operation on data provided by punched tape. A few problems in harmonic analysis, calculation of roots of polynomials, and solution of differential equations were run, but Model II was too busy with routine data interpolation and smoothing to spend much time on fancy problems.

The program tapes were punched in machine language which included five-hole codes for "transfer from register B to adder," "read data," "punch," and so on. The tape was then looped with the ends glued together, and added to the program library.

Model II was installed in the West Street Laboratory in September, 1943.

It was exciting and a bit weird to watch this interpolator go about its work *sans* human boss: days, nights, Sundays and holidays. This was a year before Mark I was formally demonstrated, and the use of teletype tapes and readers, under the control of an impersonal bank of relays, was new. At that time it seemed to us we had a highly intelligent machine—this first programmable computer. It could call for the next program step from one tape and the next data from another at exactly the right instant, and detect any extra holes worn in the tape by repeated runs. Those

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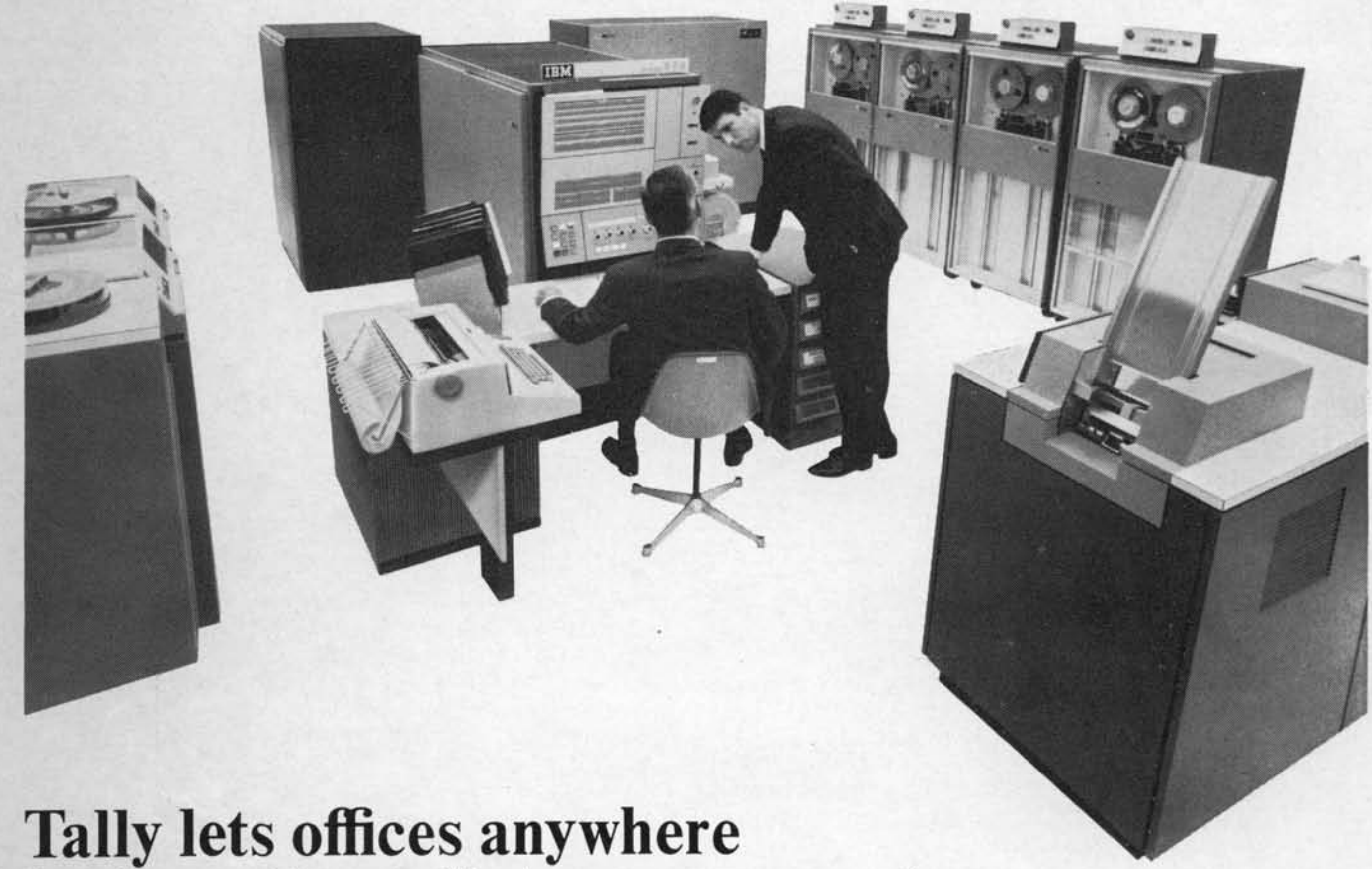

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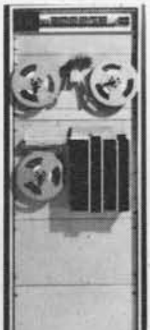

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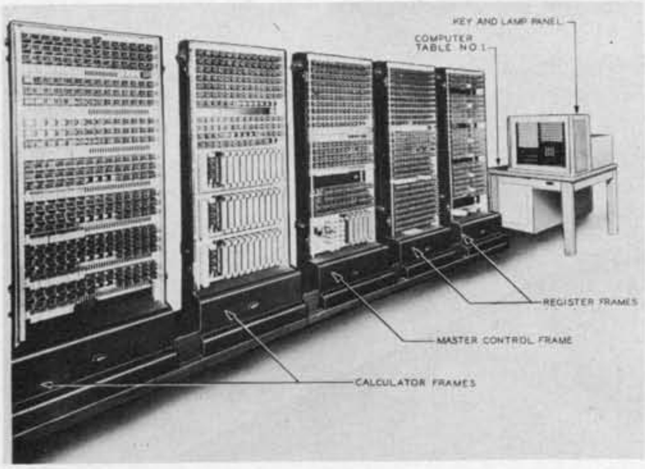
tapes took a pounding, and things were not perfect in this imperfect world. Sometimes we would come in on a Monday morning expecting to find hundreds of feet of tape ready for the dynamic tester, only to find that sometime during the weekend a tape had worn or torn through, leaving the computer without instructions.

But our room was well decorated in somewhat *avant garde* style. We kept spare tapes, glued into loops, hanging on pegs near the computer. Somewhere along the line we had failed to instruct the computer to reach out and take a new one off the peg when needed.

An occasional visitor saw the machine (as did the revered John von Neumann), and a favorite show for company was to start a computation, then allow the visitor to stick a toothpick in any relay. When that inhibited relay was needed the computer would stop, only to proceed correctly as if nothing had happened when the toothpick was removed.

The Relay Interpolator, soon dubbed Model II, was used at Bell Labs, later at the Naval Research Labs. Model III, the Ballistic Computer (shown), was developed at the National Defense Research Committee in the early 1940's, had a 10-msec high-speed storage.



Model II was useful for a long while, and late in the war was moved to the Naval Research Laboratories. It was not retired from service until 1961.

hunting circuits and the next machine

The testing of anti-aircraft equipment demanded enormous amounts of computation and qualified people were scarce. Before Model II was set up and working, I proposed in 1942 to NDRC a relay computer along the lines of my earlier suggestion for an automatic computer. Luckily Warren Weaver was with me all the way. The scope of this Ballistic Computer (Model III) was discussed and it was decided to go all out to make it a large and versatile machine. That it was, for 1942.

We decided to have nearly a dozen registers, with program tapes, a couple of subroutines, two or three "tables" on punched tape, several teletype outputs and input punches, 100% self-checking circuits in the bi-quinary code, and many other features. Also, we modified the standard teletype reader to move tape in either direction. Table data were entered in blocks, and each block was assigned an address.

Andrews' group designed "hunting" circuits that directed the forward or backward motion of the tape and searched for any address demanded by the main computer. This search could proceed independently of the computations going on the main computer and these hunting circuits performed with extreme reliability. E. L. Vibbard designed the calculator which was a true multiplication table—a rare item—as both earlier and later computers used repeated-addition multiplication.

The table-hunting circuits would read addresses specified for calculating a second or third higher order interpolated value.

Storage space was expensive and slow. In this model, the high-speed random access storage (10 milliseconds) had a capacity of one or two dozen words as I recall. Low-speed storage was almost unlimited, but was read sequentially at about 15 characters per second.

It was necessary, or at least customary, to prepare the table tapes beforehand. This scheme was useful, but provided still another *avant garde* room decoration. Yards upon yards of punched tape, waiting to be used, were strewn about the floor. Screams of anguish could be heard from the programmers when any visitor unwittingly stepped on any of the tapes, and it made for some rather lively conversation.

To be crass about it, the Model III Ballistic Computer was a real show piece, though it did its work well. Table-hunting in a computer would not appear elsewhere for several years and it was fascinating to watch. The tape reader would run through the table tape in one direction, stop to read an address, click its relays in annoyance and rush off in the opposite direction, reading addresses as it went, until the proper one was found.

This computer operated seven days and nights a week, and did the work of an estimated 25-40 girls. Nights were not always fun for Sgt. Stoddard, who was learning the ropes on the machine, for he had an alarm bell by his bed which rang when the baby wanted attention.

In all, Model III was possibly the most interesting of the Bell Computers from the point of view of its design logic and of the ease of understanding its operations. In 1944 it was moved to Fort Bliss, Texas, and was in use until 1958.

Model IV looked like Model III and did the same kind of computing. However, some changes were included, enabling Model IV to handle trigonometric functions from −90° to +360°. Built for Naval Ordnance, its basic development was completed in 1945. In Naval circles it was known as Error Detector Mark 22, and it was in service until early 1961.

Models I through IV can be regarded as belonging to an era of the past, I think, and it was Models V and VI which bridged the gap between the beginnings of the art and the modern era of electronic computers.

model v: the floating decimal point

In size and flexibility, Model V was our most ambitious project in computer development up to that time. Two units were built. One was delivered in 1946 to the National Advisory Committee on Aeronautics (NACA) Laboratory at Langley Field, Virginia, and the other was delivered in 1947 (after months of activity at Bell Labs) to the Ballistics Research Laboratory at Aberdeen, Maryland.

This model was a system of six arithmetic units and 10 problem positions, an arrangement permitting the arithmetic units to function continuously. Problems were loaded into idle positions, and a computer on completion of one problem automatically picked up another.

Each problem position had one tape reader for input

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data, up to five readers for the instruction programs which allowed us flexibility in introducing subroutines, and up to six readers for tabular data. Tables of logarithms, antilogarithms, sines, cosines and antitangents were permanently wired into the machine.

Now at last, we had a chance to use my idea of the floating decimal point proposed in 1939. The concepts of zero and infinity gave us many headaches. I think we decided on 10^{-64} as zero, and 10^{64} as infinity, but I am not sure of these figures now. All the aspirin I took for those headaches did not improve my memory.

Besides the floating decimal point, the calculator of Model V included 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. There were also some rather elaborate discriminatory controls, which are now referred to as conditional transfers.

Model V could do the work of about 225 girls with desk calculators and even after electronics were available, these computers did a lot of work. This model worked around the clock and had an excellent record for low out-of-service time. I know that one week the computer worked 167 hours out of a possible 168, and most of the time was unattended.

In recent years the two Model V computers have had a rather 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 the Texas Technological College in early 1958. Unfortunately, however, it was severely damaged in transit—the truck tipped over—and the computer was of no further use except for spare parts for the University of Arizona machine.

the last of the line

About the time that the designs for Model V were completed I resigned from Bell Labs to go into independent consulting work. However, I kept in touch with my old colleagues at Bell, and knew something about Model VI, the last relay computer built there. It was built for the Laboratories' own use in solving a wide variety of research and developmental problems, and was placed in regular service there in 1950.

In essence, it was a simplified version of Model V, having only one computer, less elaborate discriminatory controls and fewer problem positions. I knew that this model had an "end of numbers" check signal, which eased such problems as determining the end of a line of coefficients in a matrix-type problem. Also, it had an automatic "second trial" feature that functioned during unattended operation, thus improving reliability in the presence of a trouble condition.

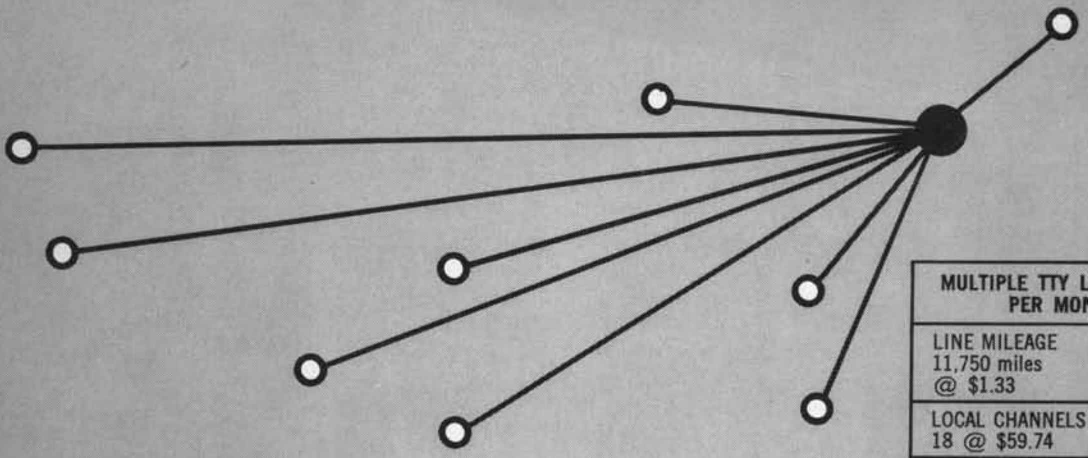
After several years of service at Bell Labs, Model VI was given to the Polytechnic Institute in Brooklyn, N.Y. In 1960, Brooklyn Poly retired this computer and gave it to the Bihar Institute of Technology in Bihar, India.

And so, with Model VI, an era was ended. By 1950 the excitement of electronic potentialities was sweeping the country, and our blessedly reliable old relays were slow by comparison.

Now we live in a true computer age, when for even the smallest business to admit it is not using a computer is as unlikely as for a teenage girl not to have a Beatles record.

But—as I said at the beginning—I can remember when!

Caught in the Dollar Squeeze of Multiple TTY Line Charges?



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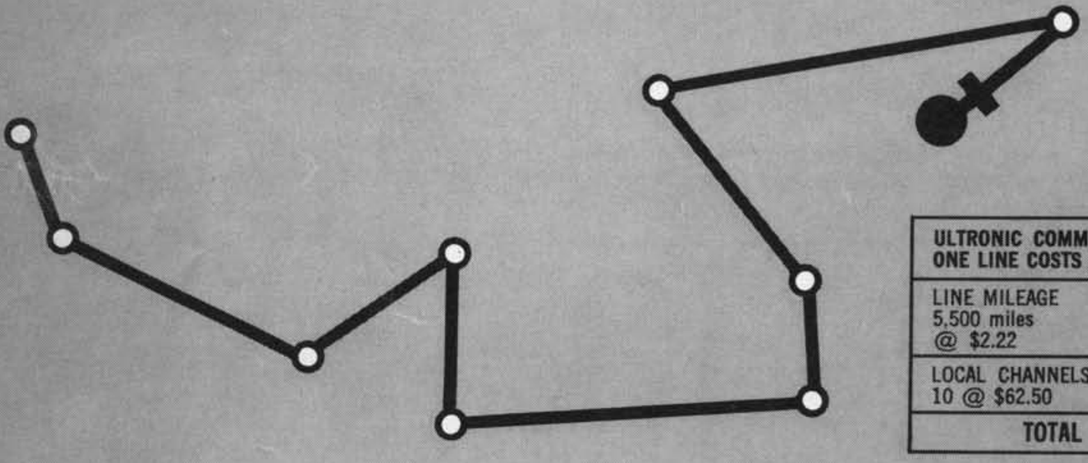

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