THE HISTORY AND DEVELOPMENT OF THE ELECTRONIC COMPUTER PROJECT AT THE INSTITUTE FOR ADVANCED STUDY

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P-377

10 March 1953

The RAND Corporation
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Willis H. Ware

A talk presented before the Professional Group on Electronic Computers of the Institute for Radio Engineers, San Francisco, 28 January 1953.

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Willis H. Ware

Gentlemen:

It is a great pleasure to be here tonight and to present the paper which inaugurates the technical meetings of the future San Francisco chapter of the Professional Group on Electronic Computers. As you may know, about two years ago there was organized at Los Angeles under joint I.R.E.-A.C.M. sponsorship a group to meet monthly for technical papers on computers and related subjects. It was the activity of this group which helped stimulate the formation of the National Professional Group on Electronic Computers. Quite properly, the Los Angeles group became the first chapter of the P.G.E.C. and to date, remains the most active one, even more so than the first eastern chapter at Philadelphia. Your chapter here at San Francisco will become the second in the West, and I am quite certain that it will enjoy great success. I have had a chance today to meet your new officers and I have great confidence that their leadership will make your chapter one of the finest.

The field of which we are all a part is certainly one of the most recent and most rapidly growing of all those in electronics.

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*The work reported herein represents a cross section of the efforts of the entire group at Princeton. Much of it has never been published anywhere, and some of the ideas are the subject of patent action by the Institute for Advanced Study in behalf of the U. S. Government.

Details of the early days of the field are not generally known; and before launching into a discussion of the digital computer work at Princeton, I would like to indicate some of this early history of the electronic digital art, and to mention some of the personalities involved. It seems rather significant that a discussion of the Princeton work with its far reaching influence and its really basic contributions to the art should be the subject of the first technical paper before this new group. To the best of my knowledge, this is the way it happened.

As many of you already know, the grand-daddy of the large scale electronic digital machine is the ENIAC. In 1941 there had been some readjustment of the faculty at the Moore School of Electrical Engineering at the University of Pennsylvania. Knox McIlwain had left and joined the staff of the Hazeltine Electronics Corporation in New York; and Irven Travis had resigned to join the Ford Instrument Company in Long Island City. Subsequently Dr. Travis returned to active duty with the Navy and after the war, he entered the Burrough's organization where he is now guiding the digital work as Director of Research. To replace these two men, Dean Pender secured Dr. Arthur Burks who was a mathematical philosopher from the University of Michigan and Dr. John Mauchly, a physicist from Ursinus College and Johns Hopkins. Mauchly was a consultant for Aberdeen Proving Ground where he became cognizant of the enormous number of man-hours being consumed by the hand computation of firing and bombing tables. It occurred to him one day that it would be possible to do electronically what the desk calculator did mechanically. A memorandum to this effect was circulated among the Moore School faculty and after a considerable discussion, a formal proposal was drafted and submitted to Aberdeen. The machine described in this proposal was for the purpose of doing just one problem - namely the data reduction involved in preparing firing tables. There was no thought at that time of using the machine for general purpose scientific computations nor was it designed with this thought in mind.

The computation load at Aberdeen was sufficiently heavy at this time that the proposition looked like a good bet. There had always been exceptionally good relations between the Moore School and Aberdeen inasmuch as Knox McIlwain of the Moore School and then Colonel Leslie Simon of Ballistic Research Laboratory had worked together for a long time on certain statistical quality control problems. Accordingly a contract was let between the Ordnance Division of the U. S. Army and the Moore School for the development and construction of such a machine.

Stationed at that time at Aberdeen was Captain H. H. Goldstine, a mathematician on leave from the University of Chicago. He was sent to Philadelphia as liason officer to the computer development; his wife, Adele Goldstine, was also a mathematician and had had some prior experience with hand computation.

At the Moore School from about 1942 on, was a large number of wartime contracts. J. Presper Eckert, who was a classmate of mine at the Moore School, had worked on many of these projects and when the computer development came along, he was put in charge of the engineering. Burks and Mauchly were the principal figures in the logical design of the machine, although they each made contributions to the engineering phases.

Let us switch now to another thread of the story. A prominent name in almost any project in the country during the war was that of John von Neumann, the mathematician from Princeton. Particularly, he was associated with the Manhattan Project, where he came into contact with the scientific computation being done on IBM equipment at Los Alamos. Von Neumann was a consultant also to Aberdeen, and as the completion date of ENIAC approached in 1945, he suggested to Dr. Nicholas Metropolis and Dr. Stanley Frankel of the Manhattan Project's Los Alamos laboratory that they use the ENIAC in the solution of some of their problems. Accordingly, arrangements were made on the basis of which a Manhattan Project problem was selected to be a test problem of considerable proportion for ENIAC. Metropolis and Frankel were to do the coding and operating and to take part in debugging the machine, since this problem was to be its initial shake-down problem.

This brought together at Philadelphia an imposing team: Eckert, Mauchly and Burks of the Moore School; Goldstine of Aberdeen; von Neumann of Princeton; and Metropolis and Frankel of Los Alamos. It was a time of great stimulation to everyone. It had been apparent to the ENIAC people, even before the machine was finished, that there were obvious improvements; the need for a fast and large memory was admitted and preliminary work in fact was done on an acoustic memory. However, in the interest of getting the machine completed, these continuing improvements were sidetracked, and the design was frozen. It also became clear during the lengthy shakedown period that the ENIAC was difficult to use for general scientific calculations. Preparing ENIAC for a problem consisted of physically establishing a large number of connections by means of switches, patch cords, transmission lines and so on. This, however, is no reflection on the foresight of the designers since the machine was originally intended for the special and single purpose of calculating firing tables. Rather, it is a testimony to them that the ENIAC was so versatile on difficult, general scientific problems.

In the course of the many discussions among these several people, the concept of what we now know as the "stored program machine" evolved. It is probably true that the idea was reasonably obvious to those who worked with and on the design of ENIAC; to the best of my knowledge the idea is not traceable to any one person. The proposal for EDVAC which Eckert and Mauchly prepared almost before ENIAC was debugged described a machine which stored its own instructions, could operate on them as the course of the problem dictated, and had a large high speed acoustic memory.

Meanwhile John von Neumann saw in machines of this kind, not only an aid to computation for hitherto uncalculable problems, but also an aid to analysis and to pure, abstract mathematics. It was his feeling that a mathematician who was pursuing some new field of endeavor or trying to extend the scope of older fields, should be able to obtain clues for his guidance by using an electronic digital machine to consider large numbers of possible conclusions from a stated set of postulates and by using the machine to compute large numbers of numerical cases to try to establish some trend of behavior. It was, therefore, the most natural thing that von Neumann felt that he would like to have at his own disposal such a machine.

As a result of his interest, a contract was let between the Ordnance Department of the U. S. Army and the Institute for Advanced Study at Princeton for the design and construction of such a machine;* The Army was to receive only information and reports; the machine was to remain the property of the Institute. A group of six engineers – Julian Bigelow, James Pomerene, Ralph Slutz, Robert Shaw, John Davis and myself – were assembled together in June of 1946 and the Electronic Computer Project of the Institute for Advanced Study was under way. Of our group, two were from Hazeltine Electronics with background in the design of military equipment, two were from ENIAC, one was from an NDRC panel on bomb damage, and one from an M.I.T. laboratory working on prediction.

I would like to digress a moment here to indicate the nature of the Institute since it is somewhat different from the usual academic organization. It will also indicate in what kind of atmosphere the Princeton development was accomplished.

There has existed for a considerable time an Institute for Advanced Study at Dublin, Ireland; it is the purpose of this place to afford an opportunity for post-doctoral study on a subject and in a way of one's own choosing. Dr. Abraham Flexner knew of this Institute and became convinced that a similar place was desirable in this country. He persuaded two members of the Bamberger family,

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*U.S. Army contract W-36-034-ORD-7481 and later DA-36-034-ORD-19.

Mr. Louis Bamberger and his sister, Mrs. Felix Fuld, to endow such an institution; and in the early 1930's there was established on the campus of Princeton University and within the building of its mathematics department, but financially and administratively distinct, the Institute for Advanced Study, of Princeton, New Jersey. Flexner became the first Director, a post which is filled today by J. Robert Oppenheimer. In 1937, the Institute moved to its own property and buildings on the western edge of Princeton although it remains closely connected, intellectually and academically with the University.

The purpose of the Institute is to provide facilities for research and study without the burden of formal courses and regimen. It has a small permanent faculty which includes, in the physical sciences, Albert Einstein, John von Neumann, Herman Weyl, Oswald Veblen and Robert Oppenheimer; this faculty neither lectures nor holds classes. Contact with the visiting members is through informal discussions and rump sessions, often during a walk in the fields or woods, or over a cup of tea or a game of Go or Kriegsspiel in the Commons Room. It is the intention of the Institute to maintain sufficiently small size that it is a true community within which ideas and thoughts are free to circulate among all its members. It contains a School of Mathematics which includes most of the physical sciences, and a School of Historical Studies which includes the social and historical sciences. Because of the large proportion of temporary members, and its limited funds, it had always operated without experimental facilities.

Fundamentally, then, the Institute is a place which works with blackboards, paper and pencil: not with physical instruments and experimental techniques. So the coming of six engineers with their assortment of oscilloscopes, soldering irons, and shop machinery was something of a shock, both academically and socially, to the Institute body.

The building which was to house the Computer Project was not complete when the staff first convened in the summer of 1946. Accordingly we took up residence in the boiler room in the second basement; our work benches surrounded the boilers and miscellaneous shop and laboratory equipment was stuffed in any available corner. With the coming of autumn, the situation warmed up quite considerably; so much so in fact that the group enjoyed an improvement in social status and moved to some unoccupied storerooms in the first basement. However, by Christmas of 1946, the permanent building was completed, and the staff of 6 engineers, 3 shop people, and 4 wiring technicians moved in. The size of this engineering staff has scarcely changed to this day although a planning-coding group, several computing machine operators, and a group interested in dynamic meteorology now share the building. Administratively, von Neumann was Project director; and Herman Goldstine, by now discharged from the Army, the associate director.

The basic philosophy of the Princeton machine had already been established by von Neumann, Goldstine, and Burks through a series of discussions which reflected their own feelings and the community ideas evolved at the Moore School. The results and conclusions of these discussions have been published in the now-famous "Planning and Coding" series of reports.*

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*See Bibliography

The engineering group, hence, had the outline of the machine given to them; it was their job to turn these pages of text and mathematics into vacuum tubes and physical hardware.

As originally conceived, the Princeton machine was to include the following features:

1. A 1,024 word asynchronous electrostatic memory
2. A memory register
3. A shifting register
4. An accumulator
5. An asynchronous logical control
6. Several auxiliary magnetic wire storage devices
7. Input and output equipment of Teletypewriters operating via magnetic wire units.

The machine was to be all parallel and to have a word length of 40 binary digits including sign; numbers were to be considered as less than 1 in magnitude; and negative numbers were to be handled as complements. Orders to the machine were to be 20 bits long and were to be stored in pairs in the 40 place memory. The machine was to be a stored program machine capable of operating on its own orders as the progress of the computation required. The original order list contained 22, including addition and subtraction with clear and hold, absolute value or number options; multiplication without round-off; division with round-off; shift right and left; conditional and unconditional transfer of control; partial substitution; and input-output.

After two years or so of experimental investigations, soul searching and meditation, the group agreed upon a set of basic postulates under which the machine was to be designed. We referred to them as "The New Look". The first set of these axioms had to to with the philosophical design:

1. All circuits, particularly those which occurred many-fold times, must be designed such that tube aging, resistor, and voltage drift, etc. should not affect performance.
2. The logical memory function which is required in shifting registers and in binary counters should not be provided by transient devices; as inductors, capacitors, or delay lines.
3. The asynchronous arithmetic unit should be independent of pulse width, pulse shape, and rate of rise — in general, independent of all characteristics of a pulse except amplitude.

Similarly, there was a set of statements for electrical and mechanical design procedures. For electrical:

1. Resistor dissipation limited to half of manufacturer's rating.
2. Tube plate dissipation limited to half of manufacturer's rating.
3. Maximum current drawn from a tube to be half the capabilities of a new tube.
4. Resistors to be allowed to drift 10 percent in the worst direction or combination of directions and not affect performance.
5. The internal impedance of tubes to be allowed to vary from half to double normal value and not affect performance.

6. Crystal diodes, if used, to be allowed to decrease to half back resistance and not affect performance.

Of these, the two restrictions on tubes need clarification (Figure 1). On the $e_p - i_p$ characteristics of the tube is plotted the curve of half rated plate dissipation: the product of $e_p i_p$ is equal to half the number of watts that the handbook allows. There is also plotted a curve whose ordinates are half the ordinates of the zero-bias curve. The cross-hatched region bounded by these two curves is the allowable design region. The so-called "notch point" falls, for a 6J6, at about 100 volts and 7 milliamperes.

The mechanical restrictions were:

1. The physical layout to be "3-dimensional" in order to keep stray capacitance minimized. (Figure 6).
2. Signal circuits to be on one side of the chassis; all heat dissipating elements, on the other.
3. Resistor leads not to be bent within 1/2" of the body; insofar as possible, leads to be kept straight.
4. All other tenets of good workmanship, including good soldering, cleanliness, and so on.

Remember that these decisions were reached in 1947-48; although many of them are commonplace and accepted today, at that time they represented radical departures from the customary commercial techniques and procedures. With each one of these items defining, as it were, a circle of convergence, we hoped that there would be a region common to all of them so that the machine could get built.

Eventually, the group arrived at the design of several standard components which were then assembled as logically required. The principle building block, the toggle, is illustrated in Figure 2 together with 3 ways of changing its state. The toggle itself is a grounded cathode 6J6 with resistor values and supply voltages as shown; quiescent plate voltages are 100 and about 30 volts; and quiescent grid levels, 0 and about -30 volts. The grid-cathode diode action holds the upper grid level very closely so that output from the toggle is taken, through a cathode follower if necessary, from the grid. This well-defined upper level of 0 volts is the level against which gating is performed, as illustrated by the right-hand gate circuit.

Most of the gating in the Princeton machine is of the double-triode or current-transfer kind. The gated signal on the left grid, either 0 or -30 volts, comes typically from another toggle. A gating signal going from +10 to -10 on the right hand grid of the double triode samples the state of the left grid. If the gated signal is -30 volts, the current remains in the right triode or the holding section; if, however, the gated signal is 0 volts, the current transfers to the left or gating section, and the plate of the toggle is pulled downward. Another, but little used way at Princeton, is to couple a negative signal through a diode to the grid. Clearing of a large number of toggles to a standard state is done by dipping the +150 volt supply to the appropriate side of the toggle. Notice that any of these gating schemes are positive acting in the sense that they place some element of the toggle at or near a voltage level which is consistent with the state to which the toggle is to be turned; there is no reliance on stray or explicit capacitance within the toggle circuit to provide memory of previous history. This kind of gating plus direct coupling throughout the entire machine achieved the desired freedom from all pulse characteristics except amplitude and also achieved the required asynchronous operation.

Another part of the asynchronous operation has to do with providing the required logical memory function in a shifting register. Since we did not depend on any transient storage device, every register of the Princeton machine consists of two ranks of toggles with intercommunicating gates (Figure 3). One of these ranks is designated the "permanent rank" and the other, the "temporary rank". The arrows indicate how information may be transferred by suitable gates. A left shift in a register of this kind consists of a vertical transfer from the permanent rank at the bottom to the temporary rank at the top, followed by a diagonal left transfer back to the permanent rank. The significant point here is that in no case is information destroyed in the "sending" rank of toggles before it is firmly installed in the "receiving" rank. Since the gating is already direct coupled, the transfers may take place at an arbitrary pace, and the device is truly asynchronous: free to proceed at any speed from indefinitely slowly up to its ultimate capabilities as limited by stray capacitance.

A similar double rank arrangement is used in the binary counters (Figure 4). Here one set of intrastage gates transmits a "1" as a "1", but the other set transmits a "1" as a "0". Hence after information has progressed from the bottom toggle to the top and back to the bottom, it has changed state, which is the requirement of a primitive single stage binary counter. An "0" which is in the bottom toggle is transferred to the corresponding top toggle as a "1"; it is then returned to the bottom as a "1". Hence the "0" of the bottom toggle has become a "1" which is the desired action for a simple, single stage binary counter. The interstage gating connections essentially pass carry information from stage to stage.

This particular kind of counter has a great deal of logical flexibility and is capable of being arranged to do more than simple counting. Because a second rank of toggles has been used to provide the temporary memory function logically required in a counting circuit, and because the gating is direct coupled, there is complete freedom in the shape of the input signal. It need only attain a given minimum amplitude.

The adder is basically an analog device, operating by summing currents through a standard resistor (Figure 5). The two incident digits control standard current sources whereas the carry is introduced as a voltage step at the top of the summing resistor. The sum output then consists of four voltage levels separated by 50 volts; it is interpreted to the binary registers by a system of decision-gates, essentially an analog-digital converter, known as the "digit resolver"; when it wasn't working, it was called the "digit dissolver". Carry time down 40 stages of this adder is about 8 microseconds.

The logical control consists of the standard toggles, double triode gates, and a few diode gates. The principle point of interest here is the way in which timing is accomplished. No pulse generators as such exist. Whenever a given operation is performed in a register, a standard toggle in the control receives the signal as the toggles of the register. The inherent reaction time of this timing toggle then determines the length of the operation. For instance, consider clearing. Assume that somehow, the $+150$ volt clearing level has been depressed to about 30 volts; this same signal is applied to register and timing toggle alike. When the timing toggle has flipped, as recognized by a suitable observation of one of its grids, the clear signal of the register is terminated, and a suitable invitation signal is passed on to the next element in the sequence. Such an "invitation signal" is the "somehow" that initiated in the first place the clear signal in this example.

The memory of the Princeton machine was originally intended to be the Selectron tube. However, this development was not quite ready when memory construction had to be started, so that a Williams type memory has been built. The memory consists of 40 5CP1A cathode ray tubes storing 1,024 spots in a 32x32 raster. The regeneration cycle is about 20 microseconds, and the dot, double-dot technique is used. Four widths of beam turn-on pulse are available, according as it is necessary to perform a 0 over 0, 0 over 1, 1 over 0, or 1 over 1 restore or write operation. Each regeneration cycle is potentially an action cycle for reading or writing, if the synchronizing circuit between the memory and the arithmetic unit so requests.

There are a few miscellaneous facts of interest. For a long time, the power supply consisted of a 600 volt bank of lead cells grounded at the center. The battery bank was maintained by charging generators and was used either directly or as the prime mover for various voltage regulators. Recently, the machine has been switched to an all-electronic power supply system. The tube complement of about 1700 consists of all triodes - 6J6, 5670, 5687 - except for a scattering of 6AL5 diodes, the 120 pentodes used in the video amplifiers of the memory and the 40 cathode ray tubes. There are no crystal diodes because the germanium art was too shaky when we had to make many of our basic decisions in 1946-48.

At the present time, the Princeton machine is in full operation. The input-output equipment has been changed from Teletypewriter to punched card with the result that the memory may be loaded or emptied in about 50 seconds. The machine has done a large number of problems - some number theoretical problems, a few astronomical, and so on; but is spending a large part of the time calculating sets of non-linear partial differential equations for the meteoroligists interested in numerical weather forecasting.

There are a number of offspring of the Princeton machine, not all of them closely resembling the parent. This occurred because many government agencies in 1948 needed machines which could not be bought; it was felt that by making exact copies of the von Neumann machine the desired computing facilities would be obtained most expeditiously. From about 1949 on, engineering personnel visited us rather steadily and took away designs and drawings for duplicate machines. As was inevitable, all groups quickly caught up with us, and most of them went off on their own tack to independently finish their machines.

The AVIDAC built at Argonne National Laboratory is nearly identical in all respects with the Princeton machine; however, Argonne's machine for Oak Ridge, the ORACLE, copies Princeton philosophy but departs radically in detail. It uses cathode-coupled or Schmidt toggle circuits together with appropriate gating circuits; a logical adder instead of an analog adder, and a Williams memory which has two cathode ray tubes in parallel at each station. Two machines were built at the University of Illinois: the ORDVAC which is now at Aberdeen, and the ILLIAC, at Urbana. These machines have an arithmetic unit nearly identical to Princeton's, a control which differs in detail, and a Williams memory using 3" cathode ray tubes, and paper tape input—output. Los Alamos has built the MANIAC computer which again has an arithmetic unit nearly identical to Princeton's, but a control which differs in philosophy and in detail, a Williams memory which uses 2" tubes, Teletypewriter output and photocell tape reader input. RAND is building its JOHNNIAC machine which has an arithmetic unit again similar to the parent but contains extra sets of gates for drum communication and is different mechanically; its control is similar in philosophy but different in detail and in logic, its memory will be Selectron tubes, and the input—output will be punched cards. There have been indications that other people intend to build machines patterned after the von Neumann machine; in particular a company in Los Angeles has proposed a machine which is essentially an ORDVAC plus some of the input—output features of the RAND machine.

I would like to pay tribute here to the people from these other organizations — Chuan Chu of Argonne, Bill Gunning of RAND, Nick Metropolis of Los Alamos, and Ralph Meagher of Illinois — who without exception have themselves made significant contributions to the art. Their machines which are either completed or under way are a credit to the common ancestor.

To bring this story down to the present, I think it would be interesting to see what has happened to those people of the Moore School group and of Princeton which were mentioned in the earlier part of this paper. Of the Moore School people: Herman Goldstine now holds a permanent appointment to the Institute for Advanced Study and is associate director of the computer project there; von Neumann is still at the Institute; Nick Metropolis supervises the MANIAC project at Los Alamos; Stan Frankel is at Cal Tech building a machine with a minimal number of germanium diodes and vacuum tubes. Eckert and Mauchly, as is well known, organized their own company; and with their UNIVAC have become part of Remington Rand. Art Burks has returned to the philosophy department at the University of Michigan and has done some consulting work on digital machines. At Princeton, Julian Bigelow, who was chief engineer of the original group, now holds a permanent appointment to the Institute and acts in a consulting capacity to the computer project; Jim Pomerene, one of the original staff, has remained at Princeton and is now in charge of the engineering. Willis Ware, another of the original staff, is now at RAND, and is here tonight, relating this chronicle. Another original, Ralph Slutz, has been with the Bureau of Standards for several years, and had a large responsibility for the SEAC machine. John Davis is out of the field and Bob Shaw is with the Computer Division of Underwood. A later engineer at Princeton, Dick Snyder, was chief engineer for EDVAC and ENIAC at Aberdeen for a while, and is now independently working on magnetic disc memories. Another later engineer, Morris Rubinoff, is now at the Moore School and has recently proposed a DINA computer.

There are, of course, many details, engineering, logical and mechanical, which I have not discussed. If there is interest in any points that I have skimmed over or in any that I have not touched, please feel free to bring them up in the question period. Particularly, I have not discussed the Selectron tube which your meeting announcement said I would. If someone would like, we can have a short discussion of it.

May I say again that it has been a great pleasure to present this paper here tonight; and may I again wish you every success with your new chapter. Thank you.

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2) Planning and Coding of Problems for an Electronic Computing Instrument; von Neumann and Goldstine (3 volumes)

3) Semiannual Progress Reports; Staff of the Electronic Computer Project, Institute for Advanced Study

All of these items were published by the Institute and some of them are no longer available. They all have, however, received wide distribution through government channels.

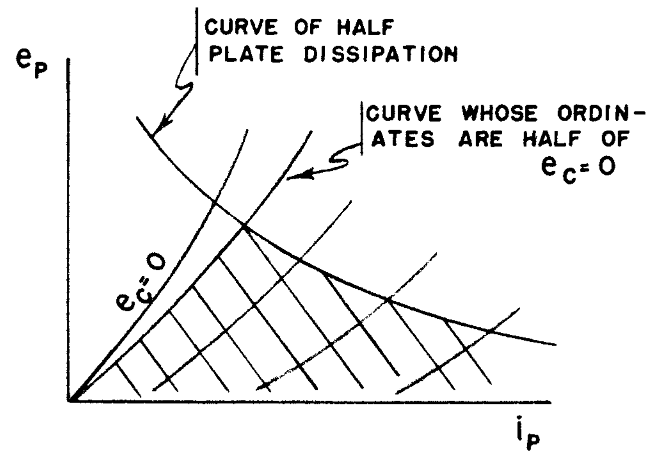

FIGURE 1

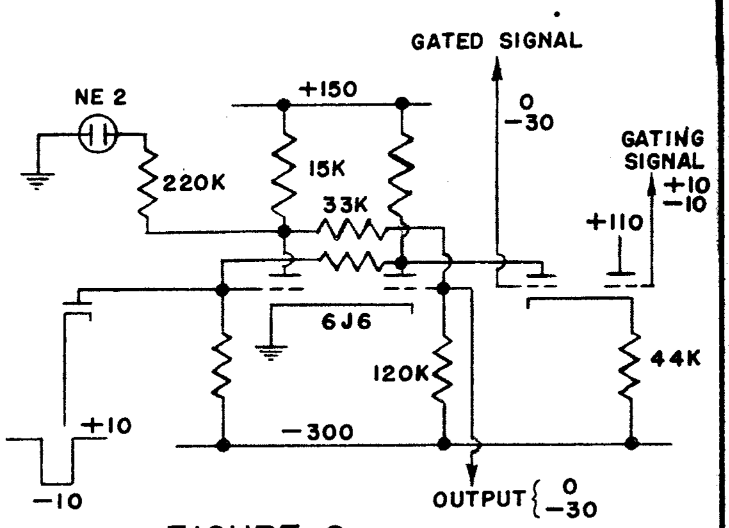

FIGURE 2

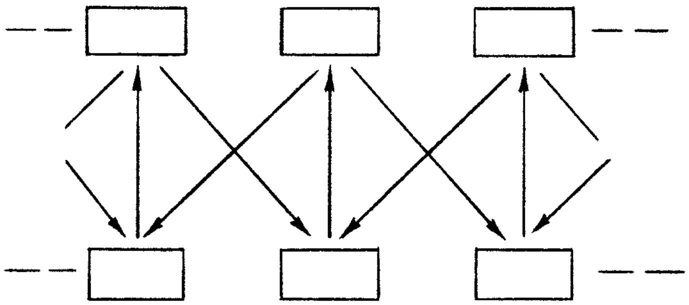

FIGURE 3

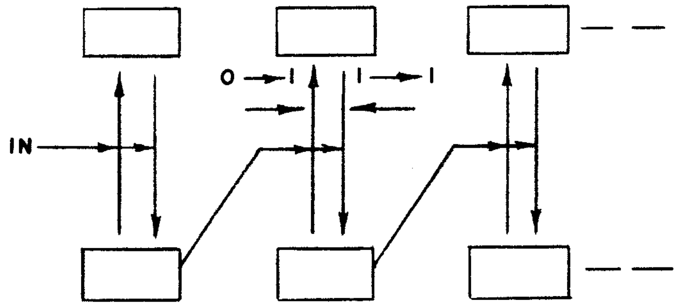

FIGURE 4

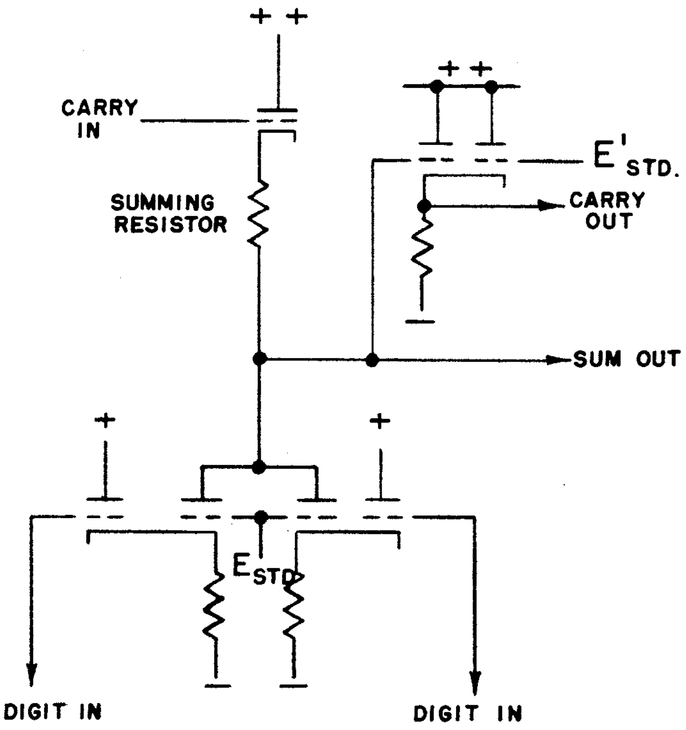

FIGURE 5

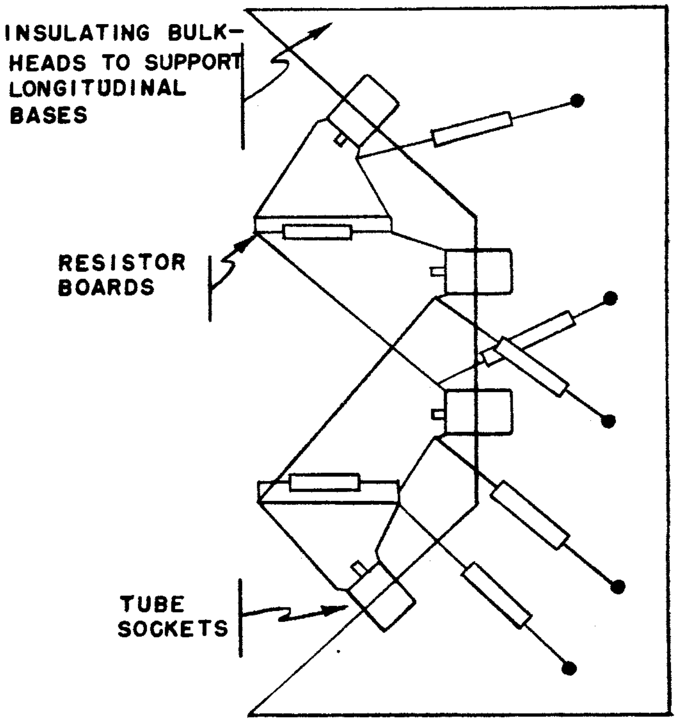

FIGURE 6