THE DIGITAL COMPUTER
WHERE DOES IT GO FROM HERE?

Willis H. Ware

P-608

5 October 1954

Presented before the Los Angeles Section of
The Institute of Radio Engineers

The **RAND** Corporation

1700 MAIN ST. • SANTA MONICA • CALIFORNIA

SUMMARY

The modern digital computing system can range from a 100 tube device the size of a desk to a many thousand tube device weighing several tons. Some machines may perform 10,000 operations per second; others, only a few hundred. In common, however, they all exhibit when compared to a competing system staffed by people, a phenomenal record for freedom from error plus some measure of increased rate of production.

This paper presents a short background of this new field of electronic computing machinery and briefly examines the characteristics of the modern machine, its applications, the difficulties of using it, and the limitations imposed on it by the present state of the electronic art. A forecast of probable future trends in application is given, together with a discussion of the expected advances in the technique and physical hardware and in the logical organization of such machines.

Ladies and gentlemen, I'd like to discuss with you tonight some of the salient aspects of that modern day wonder--the electronic digital computer. This vigorous new field has been advancing at a tremendous pace and from all indications, the rate of advance is likely to increase. One conjectures, in fact, that these digital computing devices may do for civilization's mental activity, what the Industrial Revolution did for civilization's muscular activity. However, before we can look toward the future, there is a certain amount of background that must be laid in order for my suggestions to appear reasonable and not just so much blue sky thinking.

A word about terminology. The presence of the word "digital" implies that these machines deal with numbers which represent or describe physical quantities. This is in contra-distinction to the analog computer, which deals directly with the physical quantities. A group of digits, that is, a group containing 0's, 1's, 2's and so on, need not represent some characteristic of a physical quantity; in fact this group need not be a number at all in the usual sense. In a suitable code, the digital group may represent any kind of information and hence, the digital machine has the power to deal with all kinds of information rather than with only numerical expressions.

One is then led to define a computer in the following way. A computer is a device which supplies output information derived from accepted input information by means of a process of logic. Further, a "process of logic" is defined as any systematic process of derivation which is demonstrably free from self-contradiction.

This is obviously a good definition, because it was written by a Definitions Committee of the IRE.

This is a very general statement but it implies the very broad and generalized kind of device with which we are dealing. If the "process of logic" uses the computational rules of ordinary arithmetic, then this computer is simply one for carrying out numerical calculations. Almost always, however, the "process of logic" includes much more than just the computational rules of arithmetic.

As the various specialized fields of electronic engineering go, that of the digital computer is a relative infant. Prior to 1945 a true all-electronic computing machine did not exist; there were a few relay computing machines constructed by the Bell Laboratories, and there was Harvard's Mark I. This latter was a joint effort of Harvard and the IBM Corporation and was constructed entirely of standard business accounting machine parts. There were also, of course, the various kinds of mechanical business accounting machines. Just as the war was closing, the ENIAC was completed at the Moore School of Electrical Engineering at the University of Pennsylvania. This machine whose name is derived from the initial letters of Electronic Numerical Integrator and Computer, became the granddaddy of the modern machines. This computer was an 18,000 tube giant, and it is certainly a measure of someone's audacity that such a thing was ever proposed and built. At that time devices of such complexity had never been built, and it was a great mystery how such a monster could be kept in operation for a few minutes, much less the days and weeks through

which it did successfully perform. Before ENIAC was completed, however, its designers saw certain rather fundamental organizational changes of the equipment which should be made to have a more versatile and powerful machine. The culmination of these ideas was the EDVAC machine and the commercially built Univac machine.

In the spring of 1946 a small group was organized at Princeton's Institute for Advanced Study for the purpose of constructing a machine after the ideas laid down by von Neumann and others. This machine represented a considerable advance over all previous ones, and in the course of its design and construction a number of very nasty engineering problems had to be overcome. This Princeton machine was to be the first to use all miniature tube types; it was to be the first to have a large parallel electrostatic memory. With the exception of about 120 tubes associated with the video amplifiers of the electrostatic memory, the balance of the machine's 3500 tubes was all completely direct coupled. Except for bypass purposes, there was not a capacitor to be found. Although having only 20% of the tubes of grandfather ENIAC, the Princeton machine was both much faster and more powerful.

After the Princeton development had been in process for about 2 years, a number of government agencies felt the need of similar computing devices and so several machines patterned after the von Neumann machine were built. To the largest extent possible, these other machines utilized design techniques and details which had been evolved by the Princeton group. Beyond this, each of the offspring went its own way, and in fact some of the offspring reached completion before the parent did. Today there are 7 machines

of the Princeton family: There is the original still at the Institute for Advanced Study; there is one at Argonne National Laboratory and another at Oak Ridge National Laboratory. A fourth is at Los Alamos Scientific Laboratory, a fifth and sixth at Aberdeen Proving Grounds and at the University of Illinois; and the last at The RAND Corporation in Santa Monica.

In 1951 the business machine corporations finally decided this new kind of machine represented potential profit; within the next year or two, IBM announced its 701 machine; and Engineering Research Associates, its 1101 and 1103 machines. Subsequently, ERA was to become a division of the Remington Rand Corporation as was also the Eckert-Mauchly Corporation who designed and produced the Univac. During this same interval there were a number of smaller, equally powerful but slower machines in design. For the most part, these so-called "medium sized machines" were designed and constructed by small independents many of whom were later to become divisions of large business accounting machine companies. As the situation stands today, there exists and are in active operation the old faithful ENIAC and EDVAC, the 7 Princeton class machines, 18 of the IBM 701's, about 10 Univacs, about 6 of the 1101-1103 variety, UCLA's SWAC machine, 3 machines of the SEAC family which originated at the Bureau of Standards, for a total of nearly 50 big computers. In addition there are probably 25 or 30 smaller cousins in operation. With further production of some of these types plus the introduction of new types in the next year or two, there will probably be at least 200 and perhaps as many as 500 digital computers of various sizes in

operation by the 1956-57 period. These figures do not include the various specialized machines being built principally for the military.

The rapid growth of this field is evidenced also in the technical societies which serve it. Foremost among these is the Professional Group on Electronic Computers, which as you know is a part of the IRE. Although this PGEC was the 16th of the Professional Groups to form, it went rapidly to first place in size and today is the largest and strongest with a membership of 2600. It is satisfying to note that the impetus for the formation of this Group came from an independent organization which sprang up here in Los Angeles and which was initially sponsored jointly by the IRE and the Association for Computing Machinery. This nucleus group had already grown to such size that its meetings averaged 70 each month when it petitioned the IRE for the formation of a Professional Group on Electronic Computers. As the first chapter of the PGEC, the local organization has sponsored the computer sessions of the past two WESCON's, has played a prominent part in the first Western Joint Computer Conference of last February, and will again contribute greatly to the second such Joint Conference this coming March. Our local chapter has sponsored one independent Symposium and continues its very successful and well attended monthly meetings.

What is the nature of these devices which have grown so mightily in 10 years? Why do they play such an important part in science and business and what can be expected for their future?

The typical digital system consists block diagrammatically of a number of well defined sections. First there is the arithmetic section whose job is to perform any and all of the arithmetic operations which may be demanded of the system. It will probably also do other operations than simple arithmetic; for instance, the operations involved in formal logic. Note that I say arithmetic or logical operations and not mathematical operations; digital systems deal only in add, subtract, multiply, divide and so on; they are not integrators or differentiators. The mathematical operations must be reduced to an arithmetic process before the machine can handle them. Secondly, there is a memory or storage section whose function is to store initial data, intermediate results, final data, constants, and lastly, the list of instructions needed by the machine to do its job. Next, there is the control section which withdraws instructions from the memory, interprets them or decides what the machine is to do at that instant, and exercises influence over all other parts of the system to execute the desired operation. Last, there is the input and the output section whose job is to act as transducer between the digital machine and man, or other machines as the case may be. These input-output equipments are the means for putting a problem into the machine and of withdrawing the finished results. Arithmetic, memory, control and input-output; these are the four essentials of a digital system.

It follows from the previous remarks that the presentation of a problem to the machine consists of introducing through the input mechanism into the memory, two distinct sets of information; the initial data and constants of the problem, and the list of

instructions in such sequence and arrangement as to cause the machine to proceed through a prescribed arithmetical program. Typical instructions which might appear are add, multiply, subtract, divide, shift a number left, store a number in the memory, get a number from the memory, input a number, output a number, take the left half of this number and the right half of that number and put them together to form a new number, and so on. These basic operations are put into the machine at the time of its design and construction, and remain unchanged; each problem then uses this list of instructions in such assortment and quantities as to result in the solution of the problem at hand. It is the job of the user--usually a person with mathematical background--to concoct the proper mixture and arrangement of instructions to effect the required solution.

Let's tie this back to our definition. A computer is a device which provides output information--via the output equipment--derived--by the control and the arithmetic and memory sections--from accepted input data--obtained via the input equipment--by a process of logic--the list of instructions stored in the memory. Bear this last point in mind; the process of logic by which the machine works is the list of instructions stored in the memory. The infinite flexibility of this list of instructions--or program as it is called--and hence of the logical process is the reason a digital machine is adaptable to such a huge variety of problems.

The obvious application of a machine system able to solve lengthy and involved computational and logical schedules is to the problems of science and engineering. ENIAC was initially under-

taken for the sole purpose of computing firing tables for various weapons; however, it never got full time to this problem because it was diverted to general scientific problems first. Indeed, the acceptance test for ENIAC was a very nasty partial differential equation growing out of nuclear research. This was a type of problem the machine had not been intended for, but it none-the-less performed well. Computing machines have handled the whole gamut of scientific and engineering problems: differential equations of all kinds--ordinary, partial, non-linear; sets of linear algebraic equations; matrix inversions; experimental mathematics; linear programming; statistical problems and so on down the list. These particular mathematical techniques may have been used to compute shock wave behavior; or the design of a fractionating tower for an oil refinery; or the statistical behavior of a manufacturing process; or the behavior of a complex star system; or the behavior of an economy subjected to certain stresses; and on down an almost endless list. Such were the applications until the last year or two; a shift of emphasis and really a broadening of the horizons for such machine systems is indicated by recent trends in classifying machines. Less and less the digital system is called a computer; more and more prominent is the name "Data handling machine", or the "Data processing machine", or the "Information processing machine".

It is clear of course that digital machines can deal with numbers; further, one of the biggest sources of numbers today is the business world and its problems: inventory control, stock control, accounting procedures, scheduling of personnel

or manufacturing processes, payroll, sales statistics and trends, and all the rest. While the requirement of the business problem is to manipulate alphabetic data as well as numeric data, this presents no problem to the digital machine; and so one finds that machines can prepare and print out sales summaries in proper format and complete with column headings and other written material; or one finds that the digital system can take over a complete inventory and stock control system, preparing on each transaction any required shipping documents, any required purchasing documents, plus other required information; or one finds the digital machine computing a huge payroll and keeping track of personnel statistics at the same time. These examples are typical of the kind of common business problems that machines are beginning to assume.

There are other more subtle problems which in the past could not be handled adequately or completely because of the limitations of time. One by one these are yielding to machine solutions. For instance, consider the scheduling of aircraft equipment-- what particular airplane should be assigned to what flight for how many days and when? This would be easy except for certain built-in constraints and emergency conditions. For instance, every 1000 hours every airplane must be subject to a certain level of overhaul. Further, this overhaul can only be done at certain geographical locations. The problem is to have the airplane fly 1000 hours but finish up at the prescribed overhaul base; under 1000 hours represents financial waste to the company; over 1000 hours leads toward CAA action. Add to this the

emergency situation in which an airplane becomes unavailable for a scheduled run and hence there results a last minute reshuffling of assignments; and it can be seen that there exists a first rate problem. This kind of thing is typical of a class of problems in which it is desired to optimize some factor or set of factors subject to a set of constraints. There is a branch of mathematics for dealing with such a problem--linear programming; and such techniques are growing in importance and application.

These few applications of practically limitless ones may sound very wonderful and impressive and indeed they are; but to some imaginative people there is an element of behavior suggested which is really not present. It's an easy thing to call a large machine system a "giant brain" and to erroneously conclude that it is indulging in creative thinking processes. This proposition has received widespread publicity, unfortunately, by laymen and professional men alike; and it is worth a moment to scotch this idea. It would be nice to have a machine to which one could say, "Machine, here is a problem; I've written it out in longhand for you and I'm sure that although you have never done this problem nor anything like it before, you can figure out a way to do it. Call me at home when you're through." It would be nice indeed to have this machine. But we don't, and it is not likely that we ever will. The machine of today does not have learning processes nor does it have creative reasoning ability. It is possible that someday we may have a machine with certain learning ability, although the difficulty of providing sufficient equipment for such a device appears formidable. However I, for one,

am not worried that there will arise a race of intelligent machines which will warp the economy in their behalf and relegate me and the rest of mankind to servitude or to zoos.

Why is a device which can do arithmetic and logic and remember, but which is really sub-moronic, of such value? Part of the answer lies in a property of the machines which unless carefully understood contributes fuel to the "giant brain" notion. The modern machine possesses a very elementary form of judgment in that it can decide for itself which of several paths of computation to follow; or it can even decide to make alterations in some of its own instructions, thereby altering its future course of progress. The usual thing is to make the machine inspect the algebraic sign of some number and to do either of two things according as the sign is positive or negative; another possibility is to decide according as a number is zero or not. By using these two decision choices plus a certain amount of arithmetic manipulation, it is possible to effect a decision criterion which is rather sophisticated and involved. The payoff is that the machine assumes some of the burden of handling the detailed structure of the problem. But the significant point is, that the machine cannot make a decision or choice unless every factor entering into the choice is carefully mapped out in terms of arithmetic or logical operations. In effect, the machine is only finding a solution of a problem in formal logic; it cannot make use of intuition, hunches, feelings and such. And it is exactly here that the careful distinction must be made. The modern machines do exercise rudimentary judgment but they do not think in any sense of the

word. Especially they do not learn, nor do they imitate the creative reasoning abilities of a person. Although one is sometimes tempted to be anthropomorphic toward a digital machine and ascribe to it a mental age, it doesn't do at all well. In this respect, the biggest and best of the modern machines can't compete with the youngest infant.

None-the-less, what the digital machine does do, it does with tremendous speed. The smallest members of the breed may do 50-100 operations per second; larger members will push this to 10,000 operations per second; and with some effort, it can be raised to 100,000 operations per second. This is admittedly fast, and this speed opens the way to solving a whole host of problems which have never been attempted because of the long time required to arrive at a solution by manual methods.

There is one further payoff from the modern machine, and this is its relative freedom from error. The average person in clerical or arithmetic operations will make an error perhaps once in a hundred or so times, whereas any machine worth its salt will err perhaps once in a million or ten million times. This is easy to see. If a machine goes at 10,000 operations per second, and makes a mistake every 100,000 operations, it will effectively break down every 10 seconds. No one--but no one, will stand for a machine this poor. Typical performance figures of the most recent types of machines now just completed or nearing completion are an error every 15 or 20 hours. The longest error-free interval with which I have had personal contact is 80 hours; this is for a complete machine. Sections of

some machines have gone much longer without error; a memory of one machine went 40 days without errors of any kind. Such performance implies an error rate of one in many tens of millions of operations.

This, then, is the present day machine. It may be a 100 tube device or it may be a many thousand tube device. It may be the size of a desk or it may fill a big room. It may do 100 operations per second or it may do 100,000. But whatever it is, it has an arithmetic section, a memory, a control and an input-output section. It has the power of making rudimentary decisions and can alter its own future course of computation. It has a basic set of operations which it can perform at prodigious rates and with unexcelled freedom from error. And lastly, it is ready to handle just about any problem of science, engineering, or business which comes its way.

We can see now what might sell a machine for a given application. It could be economics; the machine is cheaper than a manual system which it replaces. It could be the freedom from error so that the results are more reliable and decisions based on such results are worth more. It could be the high speeds enabling the machine to do more than a manual system, or to finish sooner or to complete a job a manual system couldn't handle.

What can we see for these devices in the future? At the present time, it is not uncommon to find that the time required to prepare a problem for a digital machine may exceed manyfold the time required to actually run the problem on the machine. This is one of the principal difficulties today of using these devices.

One large machine doing general scientific work can easily keep 30 mathematicians busy preparing problems. Here is one place in which improvement must be made; the difficulty of coding problems for machines must be minimized, but the direction of effort is not obvious nor is the solution likely to be easy. A limitation of the present art also appears in dealing with this problem and with the problem of making faster and more comprehensive machines. It is only by using the most conservative design techniques and by the most careful testing and selection of components that a system of many thousand tubes can be made to perform reliably with the desired error rates. To do something about the difficulty of coding or to build more expansive machines undoubtedly requires more equipment; with the present traditional techniques this is not a reasonable thing to do, either from an economic or practical viewpoint.

What can be seen in the crystal ball for future applications? Parts of the picture are rather cloudy; others are quite clear; but with this background and buildup, I think you can see the trend. What I'm about to say may be true by 1960; it will probably be true by 1965 and I'm inclined to guarantee it to be true by 1970. The solid state devices will have taken over in digital systems. The vacuum tube will have yielded to the transistor, the solid-state diode, the magnetic core, and the ferro-electric element. As a result the mathematically largest and most comprehensive machines will be housed in two or three boxes the size of desks. There will be practically no heat to dissipate,

and the reliability and performance will far exceed present achievements. The smaller and slower machines will be carried around like portable typewriters to do on-the-spot computing in the field.

As a result of the new solid-state electronic art, there will be no premium on minimizing equipment. As a result the fastest machines will be multipled in certain sections to provide operation rates exceeding a million per second. There will have been significant advances in the logical organization of machines and the basic philosophy of machine design which has not changed appreciably from 1945 to 1954 will have been modified considerably. Again as a result of the small, reliable and heatless components, these advanced design techniques will have produced mechanisms of great complexity and of great sophistication.

Machines will be everywhere. Entire production processes and factories will be machine controlled. As a result, production processes will be designed to go more rapidly because the machines can maintain sufficiently fast control. Banking will be mechanized, including check sorting and clearing, as well as the accounting procedures. All aircraft in flight will be constantly controlled and monitored by machines which ingest flight plans and position reports and keep a running track of all plane positions. Overdue planes will be promptly spotted and all courses will be checked for collision possibilities. Likewise, ground traffic flow in large cities will be controlled and expedited through machine control of traffic signals. Businesses will have expanded tremendously as a result of the economies resulting from the general

use of data handling machines in the inventory and accounting procedures. Although prices will be down, profits will be maintained as a result of the efficiencies arising from the machine processing of sales and purchasing information. Data supplied by the machines will be current to the minute, complete and accurate. This will be of inestimable value in the seasonal peak loads. Business efficiencies will be further increased as a result of the widespread use of linear programming techniques solved with machine methods. All business scheduling problems will have been optimized in this way. Government will make extensive use of machines to handle routine paper work; other systems will assimilate current economic reports and prepare condensed digests for high executives. There will be significant advances in the theoretical sciences as a result of new and extensive calculations performed by the biggest and fastest machines. Weather forecasting will be done by numerical methods leading to accurate and prompt weather reports. Medical diagnosis will be more certain as a result of machine assistance. A doctor need no longer remember the symptoms of every conceivable disease. His personal computer can do it for him, printing a list of all diseases fitting a stated set of symptoms. The ability of a data handling system to process enormous volumes of information and to systematically search this data for correlations and trends, will provide tremendous advances to the behavioral sciences. There will be machines large enough and fast enough to simulate with complete realism large segments of an economy or an entire business. Personnel training may well become a process of essentially playing

a game with a machine. It should be no trick at all to have the simulation so real that a fledgling executive cannot distinguish it from the actual business world. The advantage is obvious; no company funds or contracts are risked, should the trainee fail; and further, by suitable manipulation of the machine, the trainee can be presented with more strange situations than he'll see in a whole lifetime. Translation from one language to another will be mechanized. Most libraries will maintain reference files in a data processor so that a multitude of references and cross references on a stated subject are instantly available.

There will be many more new applications. The list will be limited only by the imagination of forward looking people and by the number of people who can be found to dream in these directions. Today many feasible applications are being passed by because of manpower shortage. As with most technical fields, we do not have enough trained technical persons to go around. If anything, the situation is more acute in the digital field because the kind of training our people need is just beginning to appear in college curricula. Especially is training lacking for applications people who have to be part engineer, part mathematician, part business man, and always a salesman.

Well, this is it. This is a once-over-lightly introduction to the fascinating young field of the electronic digital computer. This device with its arithmetic and logical capabilities has already entered widely into science and engineering and has begun its invasion of the business world. It is clear that machines will gradually relieve man of a great burden of routine clerical

drudgery and simpler mental tasks. In so doing there will be made available large amounts of time for intellectual activity and thought. This can result in either of two things: this time is squandered in useless and unproductive directions, or this time is devoted to a more rapid advance of the sciences and the humanities. We who are technically trained and hence appreciate this coming "mental revolution" most completely have, I think, a heavy obligation to see to it that machines do not lull us into a period of technical stagnation and that we do indeed make fullest use of the time dividend given us by these information handling machine systems.