Paper R-166-1

DIGITAL COMPUTERS
AS
INFORMATION-PROCESSING SYSTEMS

by

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June 1, 1949 Revised September 28, 1951

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INTRODUCTION

To most people the name "digital computer" implies a restricted activity in the area of scientific computation and the solution of engineering problems. Such a concept is much too narrow, and the modern digital computer might better be called an "information-processing system."

Digital computers used as information-processing systems represent a new branch of communications engineering and an extension of the concept of servomechanisms and automatic control. More broadly, the digital computer promises to mechanize many of the routine and clerical aspects of management.

This discussion will be presented in four parts:

1. Illustrations of information-processing systems.
2. A general description of a digital computer.
3. A few elementary principles of computer operation.
4. The coding or instructing of an automatic computer in some simple processes.

INFORMATION-PROCESSING SYSTEMS

Several examples of information-processing systems will first be described.

Fig. 1 illustrates information flow during engineering computation. It is used to illustrate one of many fields of application.

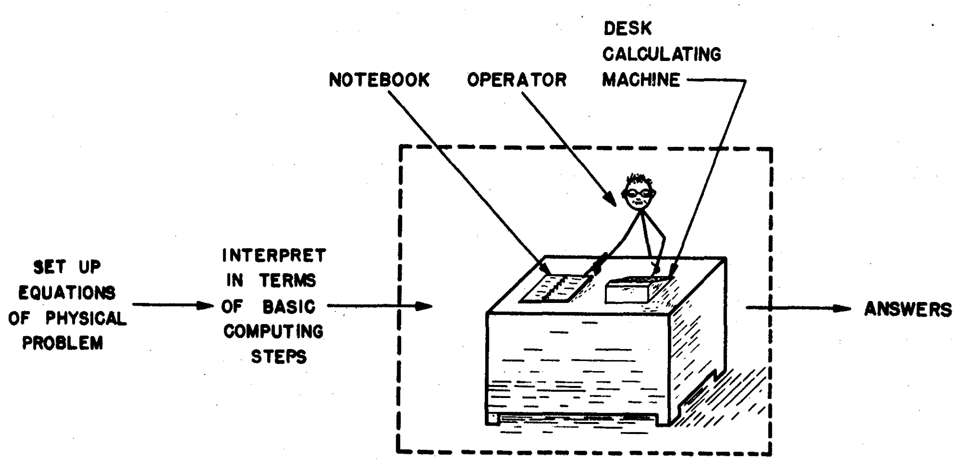

Fig. 1. Calculation

The first operation is the collection of information in the form of equations representing a physical problem. These equations are then interpreted in terms of basic numerical computing steps required for a solution. Finally, the problem may be given to the operator of a desk calculating machine, who will follow the instructions leading to the proper answers. Examining the contents of the dotted box in this and subsequent figures, we may pick out, by comparison, the essential features of an automatic digital computer. A digital computer must have mechanisms for storage, for arithmetic computation, and for central control. In the illustration, the notebook is equivalent to the function of storage in a digital computer. In the notebook or in computer storage will be placed the instructions for the computations to be executed, the initial data of the problem, and partial results during the process of computation. A desk calculating machine corresponds to the arithmetic element of a digital computer. The human operator and the central control of the machine perform similar functions. The operator (or the central control) examines the instructions in the notebook (or storage) and executes these operations one at a time using the calculating machine (or the arithmetic element). Partial results of the computation are kept in the notebook (or storage). We will return to these ideas later. One might here point out that the modern digital computer, like the human operator, does one operation at a time. Unlike the operator, the automatic computer may perform these operations at tremendous speeds, perhaps reaching 100,000 times the speed of the operator of a desk calculating machine. The ratio 1 to 100,000 is approximately the ratio of a minute to a normal work year.

Fig. 2 shows information-processing in an insurance company. Data on new policies is received, whereupon standard clauses are printed according

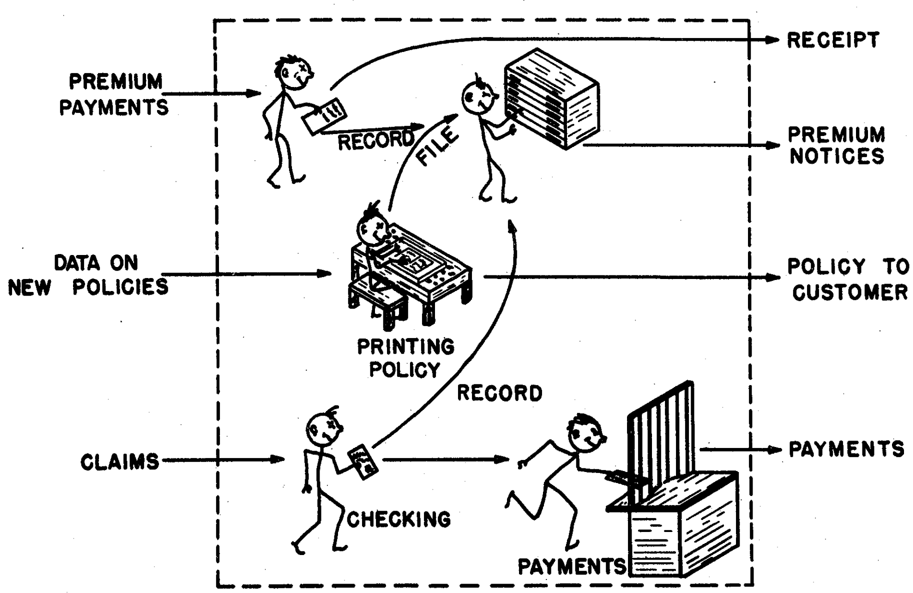

Fig. 2. Insurance

to this data, the policies mailed to the insured, and the information filed for future operations. Information from the file generates the sending of premium notices, and premium payment records are filed and receipts mailed. Claims, as they arrive, must be checked against the insurance policy files and payments sent out. As in the first example, we are dealing with the routine handling of information according to prescribed and predetermined instructions. In theory this flow of information can, like that in engineering calculation, be fully mechanized if suitably flexible equipment is available.

The flow of information for a military fire-control system is illustrated in Fig. 3. Information on a target is collected by search radar sets. A new

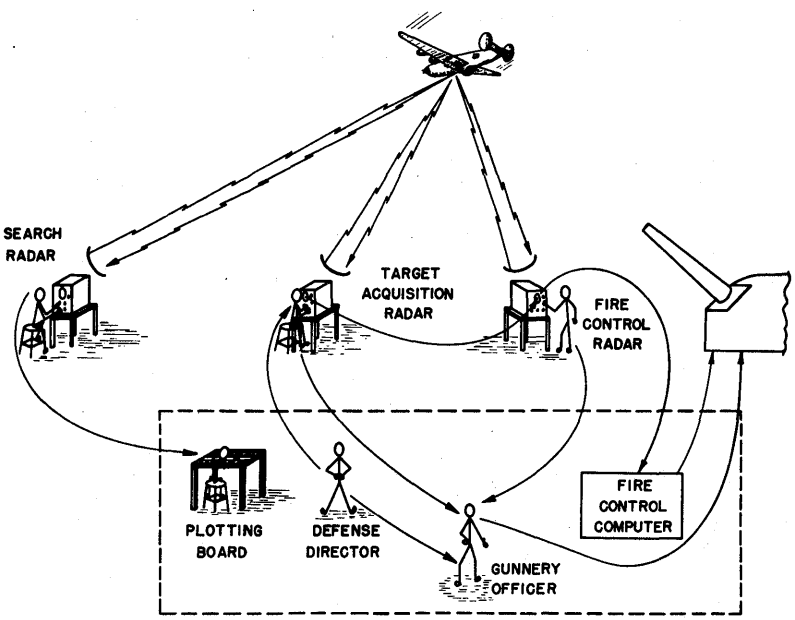

Fig. 3. Military fire control

target is identified, and the threat, if any, is evaluated. Aircraft locations are plotted until course and speed can be estimated, and using this information the defense director suitably disposes his defensive equipment. A target-acquisition radar may help to position a precision fire-control radar. Information from the latter is used by a fire-control computer for generating gun orders. Control of this system is under the gunnery officer. Here also, most decisions are routine according to standard procedures and doctrine, as established during training, and proper logical instructions to automatic equipment can produce similar results more accurately and at higher speeds.

The problems in logistics are primarily those of information-processing. Logistics is the military supply problem, which has identical counterparts in the civilian economy. Logistics embraces a tremendous range of subjects, from simple bookkeeping to a prediction of business cycles and industrial mobilization. Included are computations of the effect of governmental budgets on business conditions, calculation of the shipping space required to supply a given military operation, and questions like the following: if the Navy builds 100 destroyers, is there at the same time enough steel available for the Army to purchase 10,000 tanks? The answers to such questions are based on extensive sorting, bookkeeping, and computing procedures.

In Fig. 4 a simplified problem arising in logistics is illustrated, that of automatic inventory control. Several distribution centers for material are shown. As supplies are dispensed, stock withdrawal information is transmitted to a central accounting office where an inventory record is kept. Should supplies become low or the usage rate of a particular item unexpectedly increase at one distribution center, replacements must be provided. Replacement may be through reorder or, if a surplus exists elsewhere, through transshipment

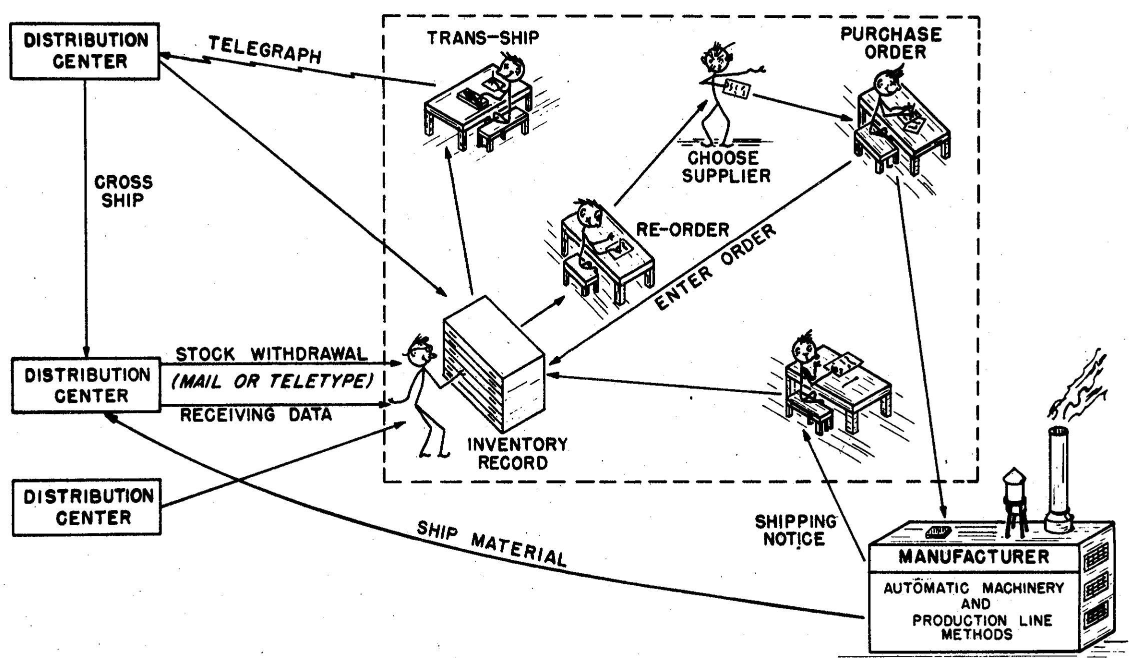

Fig. 4. Logistics: Inventory

from another center. Assuming a reorder, a supplier must be chosen, a purchase order executed, and necessary entries in the file made, with an estimate of the delivery time-lag and its effect on stocks. When manufacturing is complete, shipping notices must be filed, the supplies are received by the distribution center, and final receiving data are provided to the central accounting group.

Again in this example we have a highly routine clerical operation at the automatic inventory-control center. In many ways automatic inventory is basic to the other problems in logistics, where it is important to know usage rates, supplies on hand, and other information which as obtained by present methods may be seriously out of date. Automatic inventory control is of paramount importance because it treats the multitude of small items. Many million catalogue items are currently required by the Army, Navy, and Air Force. It may be easy to determine the number of B-29 aircraft available, but almost impossible to determine the supply of carburetor jets on hand for their engines without which the aircraft may be worthless. In the past, the uncertainties of this supply problem have often been solved by over-production, assuring enough of everything at all points but often resulting in great surpluses. In the future, industrial capacity to supply this surplus may not be available, so that more rapid, more efficient, and less costly accounting must narrow the margin between production and actual usage.

A final example of information processing is shown in Fig. 5. Congestion and delays in present and future civilian air traffic can be directly traced to inadequate information processing. In present-day air traffic control, aircraft locations may be obtained by radar; aircraft altitude, identification, and destination are available by radio; schedules and flight plans are transmitted by teletype; landing instructions and assignment of flight lanes and holding patterns are transmitted by radio. However, there is no high-speed automatic aid to the central information processing.

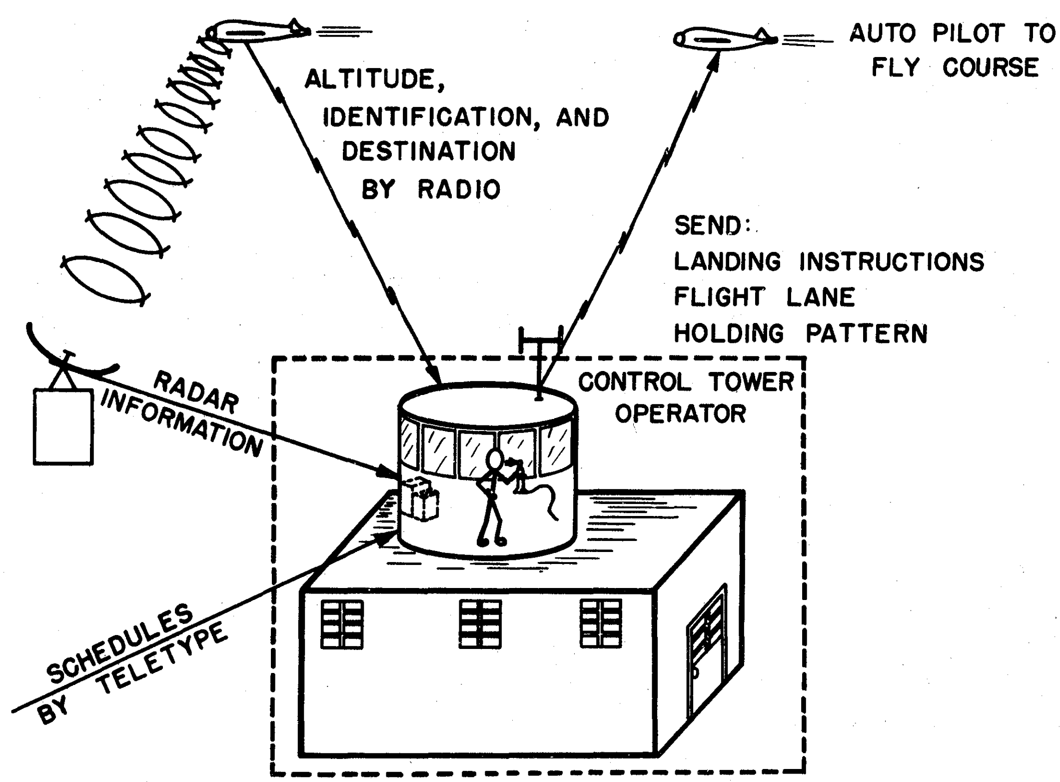

Fig. 5. Air traffic control

The reader now begins to see the common pattern in all these information systems.

1. Information is collected.
2. Information is transmitted to a central point for processing.
3. At the processing center information is sorted, compared, revised, and combined into a form suitable for final use.
4. Information is transmitted in its new form from the processing center to the point of end use.
5. Information is used for the control of automatic machinery, aircraft, production schedules, etc.

In all parts of the information system, except that of information processing, a high degree of automatic electronic high-speed facilities have been developed. Radar, photography, television, thermostats, photocells, gages, and detectors are available for information collection. To transmit this information we have teletype, radio, and airmail. To use this information there have been developed servomechanisms, automatic pilots, production-line manufacturing, and automatic machinery. Only in the central information-processing has little change yet occurred. In the above examples the central information processing represents a system weakness and bottleneck. More information is collected and more can be effectively used than can be handled through the processing center. To the engineer this represents a poorly balanced and inefficiently engineered system. The inability to process information properly is responsible for confusion, errors, and high cost. In many areas information handling can now be likened to a 10,000-kilowatt generator feeding a 2,000-kilowatt motor over a 500-kilowatt line.

As pointed out by Professor Wiener in his recent book "Cybernetics," this electronic mechanization of the routine clerical functions of management may reach the proportions of a second industrial revolution. The social implications, while tremendous, need hardly be debated here since the trend is in process and its continuation inevitable.

DESCRIPTION OF A DIGITAL COMPUTER

A digital computer is essentially a device for executing arithmetic operations and for making choices or selections. The latter function, that of choice, is fully as important as the arithmetic operations and is essential to any of the information-processing operations already described. These functions will be illustrated in what follows.

Fig. 6 is a simplified block diagram of a digital computer showing the major subdivisions: the arithmetic element, the central control, and storage.

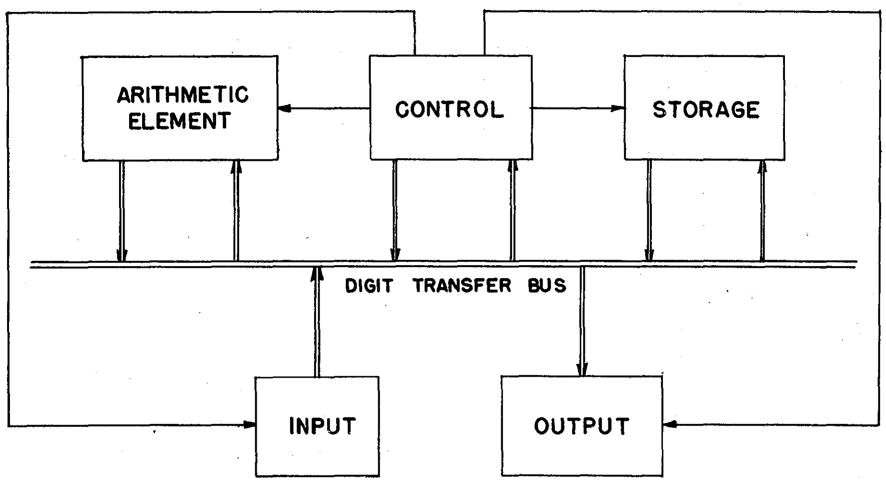

Fig. 6. Digital computer - simplified block diagram

To provide communication with the outside world, input and output devices are required. Storage in the digital computer consists of physical equipment capable of retaining, that is "remembering," coded information representing the instructions which the machine is to follow, as well as any initial data required for the information-handling process, and the partial results required during operation. The arithmetic element is the high-speed electronic equivalent of a desk calculating machine. It carries out the simple functions of addition, subtraction, multiplication, and division and minor variations of these. The central control is essentially an electronic switching system which takes coded instructions from storage and executes these instructions with the indicated numerical data.

Returning to a point already made, Fig. 7 again illustrates the similarity between the basic theory of a digital computer and the routine clerical

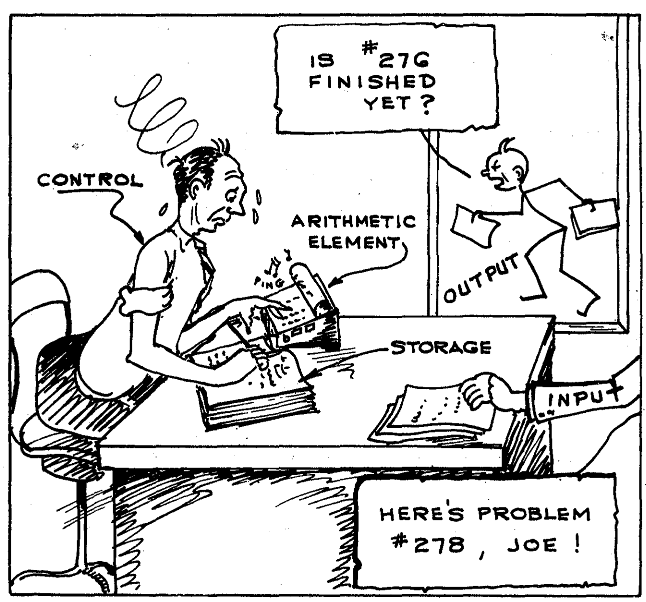

Fig. 7. Desk machine calculation - basic elements

operation of a desk calculating machine. Storage may be a notebook, a filing system, or any other method of retaining information. Just as a human operator can be instructed to recognize and follow different alternatives as the occasions arise, so can a digital computer be instructed to follow a calculating or control sequence which depends on the circumstances which are encountered. For example, in an air traffic control system an automatic computer would need to recognize when an aircraft is flying at too low an altitude or on the wrong course and react accordingly in some predetermined manner. In the processes of sorting and filing, choices are necessary in order to find the desired entries of information.

A digital computer is not a "mechanical brain." It can be set up to execute routine operations quickly and automatically which now occupy many man-hours. However, the digital computer is no more the equivalent of the brain than a radar set is equivalent to the human eye. The radar set has certain properties not possessed by the eye. It may be used in the dark and it may have greater range, but it does not distinguish colors and without additional information it cannot distinguish one airplane from another. As another example, one might consider the relationship of a bulldozer to the human hand. The bulldozer may be valuable in the building of a highway or an airfield, but is of no help in repairing a watch.

Likewise, a digital computer has its advantages and its limitations. In many operations its speed is vastly greater than that of the human being in making routine decisions and in the handling of information. Although the external storage available to a computer in the form of photographic film or magnetic wire may be practically unlimited, its internal storage by presently foreseeable techniques is very restricted. Internal storage of most presently-proposed digital computers is the equivalent of only a few pages of typewritten information. In other words, while the operating speed for certain functions in the digital computer may be 100,000 times that of the human being, it is entirely possible that the memory of the ordinary human being may be 100,000 to 100,000,000 times greater in capacity than the high-speed internal storage of proposed digital computers. This tremendous difference in balance between speed and storage capacity places important restrictions on digital computers which must be taken into account when discussing and planning information-processing systems.

COMPUTER OPERATION

This section contains a few comments on the physical operation of a digital computer. They are not necessary for understanding a discussion of applications or for the logical planning of how to use such a machine in an information system. They do, however, lend some plausibility to the proposed techniques.

For engineering convenience most modern digital computers use some form of the binary system of notation. The binary system employs the two digits zero and one instead of the 10 digits zero through nine found in the decimal system. This numbering system is a convenience because most physical components available to computer designers are most suitable for operation in one of two stable states. For example, a relay may be open or closed, representing digits zero or one. An electrostatic charge in a storage tube may be plus or minus, representing storage of a digit zero or one. Vacuum tubes are most reliable and have the greatest safety factors if operated fully conducting or completely cut off, again representing digits zero and one.

The binary system is illustrated in Fig. 8, which shows the relation between decimal and binary numbers. A carry of one digit into a new binary column occurs for each power of 2 instead of occurring at each power of 10 as in the decimal system. To represent the same numerical quantity, approximately 3-1/2 times as many binary places are required as decimal places.

DECIMAL	BINARY
0	0
1	1
2	10
3	11
4	100
8	1000
9	1001

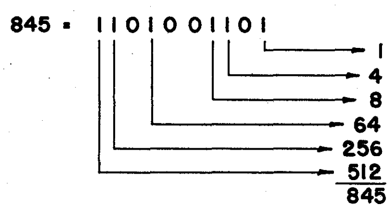

Fig. 8. Binary notation

Fig. 9 illustrates the multiplication and addition tables in the binary system. In contrast to the decimal multiplication tables taught in elementary school, the binary multiplication table has only three entries.

REPRESENTS POWERS OF 2

MULTIPLICATION TABLE:

1 × 1 = 1
1 × 0 = 0
0 × 0 = 0

ADDITION:

1 + 1 = 10
1 + 0 = 1
0 + 0 = 0

BINARY COLUMNS ≈ $3\frac{1}{3}$ × DECIMAL COLUMNS

ONLY DIGITS 1 AND 0 REQUIRED IN EQUIPMENT

Fig. 9. Tables for binary arithmetic

Mechanization of the binary multiplication table is illustrated in Fig. 10. Here a gate tube having two control grids is employed. For the tube to produce an output signal, both grids must receive an input signal. This condition corresponds to the operation 1 x 1 = 1. All other combinations are shown to result in zero output. A vacuum-tube circuit is therefore taught the binary multiplication table through properly wired connections much more quickly than the usual student learns the decimal multiplication table.

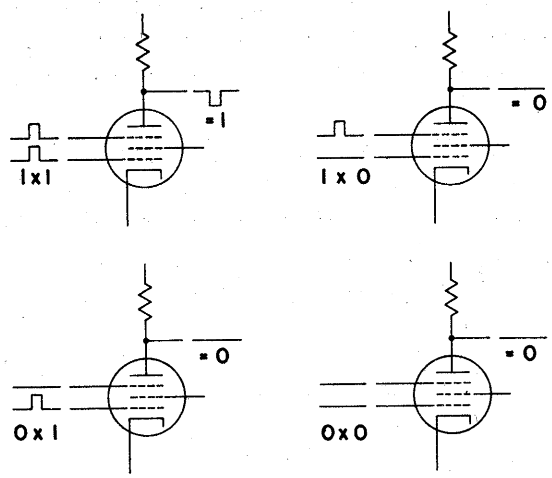

Fig. 10. Electronic binary multiplication

Several forms of information storage are available for digital computers. One such, the electrostatic storage tube, is shown in Fig. 11. Here a cathode-ray beam can be deflected to choose one of several hundred points on a storage surface. By proper pulsing of tube electrodes, the electrostatic charge at the selected point may be made either positive or negative. Either of these

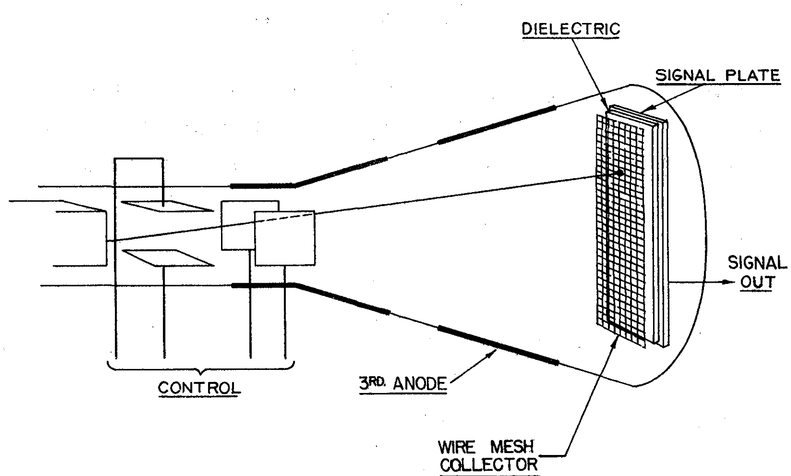

Fig. 11. Electrostatic storage tube

conditions is stable and is maintained indefinitely by an additional electron source in the tube which can replenish leakage from the charged areas. The information is "read out" by returning the beam to the storage location.

DIGITAL COMPUTER CODING

Some preliminary details of the operation of a digital computer will now be discussed. A digital computer follows, one at a time, the instructions which it takes from storage. Codes and instructions will be discussed in later paragraphs. The simplest, the so-called single-address, instruction code will be used here as an example. The storage in a digital computer is a sequence of pigeon holes or "registers" in which either numbers or control orders may be stored. These registers are identified by numbers as in Fig. 12.

A control order which may be placed in a storage register usually consists of two parts: the first describes an operation such as addition; the second identifies the number which is to be added. The latter number is identified by the location of its storage register. A control order might be written thus:

ad 746

In the computer the alphabetical characters and numerals would be represented by a suitable pulse code. This order would be interpreted to add into the arithmetic element the contents of storage register 746. It is important to note that "746" is an "address." It tells where to find the desired number; it is not itself the desired number. Other examples follow:

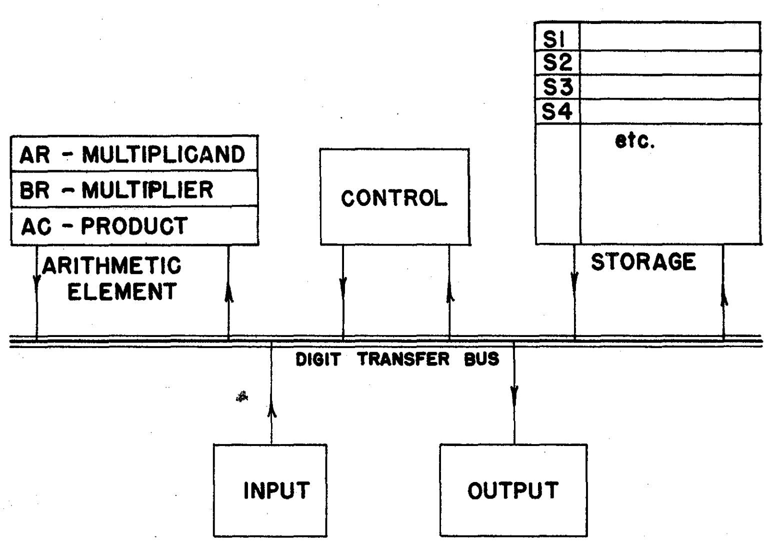

Fig. 12. Computer use in multiplication

Operation	Address	Name	Function
ca	931	Clear and Add	Clear all numbers from the arithmetic element and add the contents of storage register 931.
ad	213	Add	Add to the present contents of the arithmetic element the contents of storage register 213.
mr	1425	Multiply	Multiply the present contents of the arithmetic element by the number in storage register 1425.
ts	280	Transfer to Storage	Transfer the contents of the arithmetic element to storage register 280.

From these we can write the machine control orders for some simple arithmetic operations. In practice these would be written on a keyboard recording on punched tape, or magnetic tape. The numbers, orders, and their assigned positions in storage would be recorded. The information would then be read by the input unit of the computer and transferred to computer storage. Assume we are to write the control orders for

$$X = 27 + 53.$$

The original data must first be assigned to storage-registers; the following arbitrary choices will be made.

Register Identification Number	Contents of the Register
1275	27
463	53
936	X

The control orders from the above list will be

```
ca 1275
ad  463
ts  936
```

In other words, the first order will clear the arithmetic element of previous results and add the contents of register No. 1275; the contents of 1275 is the number 27 of our problem. The second order will add the contents of register 463 to the number already in the arithmetic element; that is, 53 will be added to 27 and the sum is in the arithmetic element. We next must dispose of the result. The third order when interpreted by the central control will take the number in the arithmetic element and store it in register 936. The operation is therefore complete with the result in the desired place.

Since the control orders used by the machine are from storage, they too must be assigned to storage registers. The entire coding might then be the following, assuming the control instructions are to be located beginning at register 728.

Register Identification Number	Register Contents
463	53
728	ca 1275
729	ad 463
730	ts 936
936	X
1275	27

We here assume that the computer starts with order 728 without now considering how this might arise. It should be noted that the computer takes instructions from storage registers in sequence until an appropriate order intervenes to change this sequence, as will appear in a later example.

Consider another example,

$$Y = (837)(2346) + 9285.$$

Storage register assignments and control orders might be as follows:

Register	Contents
11	ca 85
12	mr 91
13	ad 28
14	ts 47
28	9285
47	Y
85	837
91	2346

It is suggested that the reader enter on a sheet of paper the contents of the arithmetic element and the transfers of numbers for each order after the manner of Fig. 13.

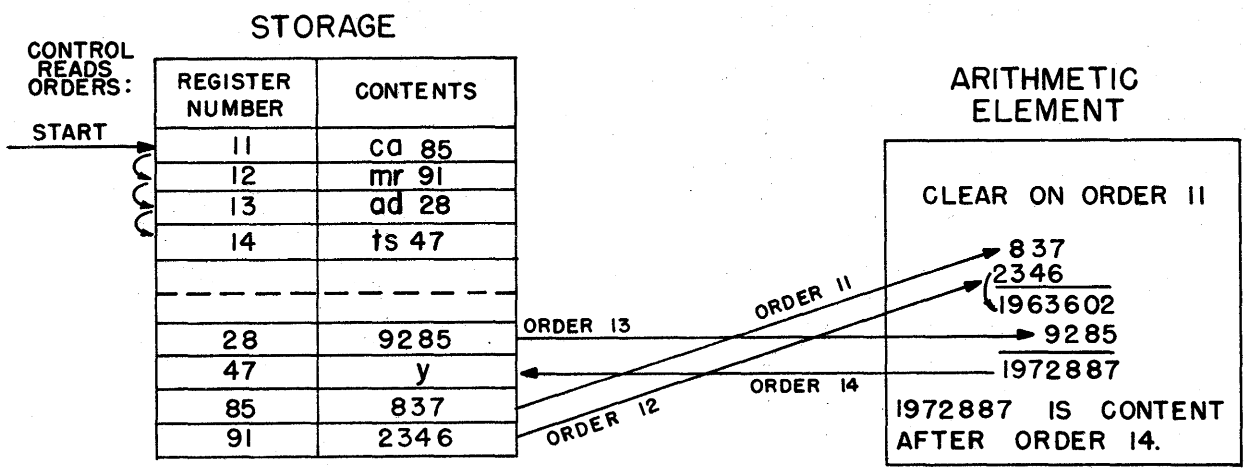

Fig. 13. Computer operations - specific example

Order 11 clears the arithmetic element and transfers into it the contents of register 85. The number 837 is thus placed in the arithmetic element analogously to the way a person would enter it on the keyboard of a desk calculating machine. Order 12 multiplies by the content of register 91, which is the number 2346. The product 1,963,602 is now in the arithmetic element. Order 13 adds to this the content of register 28, which is the number 9285, and our answer is now complete. The final order 14 transfers this answer to the desired register 47.

Several comments should be made on the preceding examples:

1. A clear distinction must be kept in mind between the identification of a storage register which is used in the order code and the number stored in that register which is used in the computation. The order specifies the pigeon-hole from which the number is to come; the number itself may have any numerical value.

2. No attempt has been made to describe how the computer accomplishes the operations indicated by the orders. If the definitions and uses of control orders such as in the above examples are understood, it is actually unnecessary for the person doing problem coding to know the physical nature of the equipment.

3. Examples are shown with alphabetical letters and decimal numbers. Most computers will operate in binary notation, but the persons using them will continue with the familiar decimal and alphabetical notation and the conversions will be automatic in the equipment.

The examples thus far have shown instructions for a digital computer to perform arithmetic operations. Although usually referred to as a machine for doing arithmetic, a function which is fully as important in a digital computer is the ability to make choices or routine decisions. To illustrate, we will set down the computer instruction code to permit finding the largest number in a miscellaneous group of numbers. Similar sequences are important in sorting, filing, finding the highest or lowest airplane over an airport, etc.

The procedure of finding the largest number in a group of numbers will be coded to follow the same procedure a person would use if given a pack of cards bearing miscellaneous numbers. The first number would be remembered until a larger one is found while turning through the pack; the latter would then be remembered until a still larger one is found, etc.

Assume that the numbers through which we are to search are located in storage registers beginning with register 81. The control orders will arbitrarily be placed in registers 8 through 17 as in the following table. Register 76 is used for the temporary storage of numbers; 77 holds the numerical value 1; and 78 will store the largest number found up to any point in the search. Register 78 will originally hold a zero.

Three new orders which have been introduced will be explained:

```
su 78
sp  8
cp 16
```

The first order is "subtract." It specifies that the number in register 78 is to be subtracted from the contents of the arithmetic element.

The next two orders are very powerful. They give the digital computer its flexibility to handle any form of information processing. We have seen that the computer normally extracts its instructions from storage in sequence. However, the "subprogram" order <u>sp 8</u> will alter this sequence and the next computer instruction will be taken from the indicated register. In this example the next order will be taken from register 8. This is a "start-over" or "go-someplace-else" order.

The "conditional subprogram" or "comparison" order, <u>cp 16</u>, is the order which permits a digital computer to make a choice - in other words, a decision. The conditional subprogram order behaves like a plain subprogram order on the condition that the arithmetic element holds a negative number. That is, if the arithmetic element has in it a negative number, the next machine order will be taken from the indicated register. On the other hand, if the arithmetic element holds a number which is positive, the conditional subprogram order will be ignored and the next order will be taken in sequence.

	Storage Register	Contents
	8	ca 11
	9	ad 77
	10	ts 11
Start	11	ca 81
	12	ts 76
	13	su 78
	14	cp 8
	15	ca 76
	16	ts 78
	17	sp 8
	76	temporary
	77	1
	78	Largest number, zero to start.
	81	27
	82	35
	83	21
	84	17
	85	39
	,	
	,	
	,	
	,	

The program for finding the largest number in a set will now be explained.

As suggested in the previous example, the reader should follow on a separate sheet of paper the contents of the arithmetic element and of storage registers 11, 76, and 78.

The starting point of this program is at order 11.

Order	Description
11.	Order 11 clears the arithmetic element (abbreviated AE) and adds the contents of register 81. AE now contains 27.
12.	The number 27 is transferred to register 76 and also remains in AE.
13.	The contents of register 78 (initially zero) is subtracted from 27 in AE. The result is 27, which is positive, indicating that 27 is greater than the number (zero) in register 78.

Order	Description
14.	The conditional subprogram order indicates that the next order will come from register 8 if the number in AE is negative (which it is not).
15.	AE is cleared; the number stored temporarily in 76 (this time a 27) is added in.
16.	27 is transferred to register 78 as the largest number found thus far.
17.	This subprogram order indicates that the next instruction is to come from register 8.
8.	This order and the next two should be watched carefully. They constitute the sleight-of-hand that permits the process to be self-sustaining. In these three orders a computation is done on the control orders themselves. In other words, the computer is altering its own control instructions. In this order AE is cleared and the contents of register 11 placed in it. The instruction "ca 81" is now in AE.
9.	The content (1) of register 77 is added.

```
ca 81
    1
-----
ca 82
```

The AE now contains "ca 82".

10.	The contents of AE is transferred to register 11, from which the next order is to be taken.
11.	Clear AE and add 35 from register 82.
12.	Transfer 35 to register 76.
13.	Subtract 27 in register 78, leaving +8 in AE.
14.	Because AE is positive, take next order from register 15. We now know the content of register 82 (and 76) is larger than that of register 78.
15.	Clear and add 35 from register 76.
16.	Transfer 35 to register 78.
17.	Take next order from register 8.
8.	Clear AE and add "ca 82" from register 11.
9.	Add 1, obtaining "ca 83."
10.	Transfer "ca 83" to register 11 to become the next order.
11.	Clear AE and add 21 from register 83.
12.	Transfer 21 to register 76.
13.	Subtract 35, obtained from register 78. The result is -14, which is negative, showing that the content of register 83 was not larger than the largest number (35) previously obtained.

Order	Description
14.	Because the AE holds a negative number, the next order is to be taken from register 8. The reader will note that orders 15, 16, and 17 are skipped because the number in register 83 is not to be remembered in register 78.
8.	Clear AE and add "ca 83."
9.	Add 1, giving "ca 84."
10.	Transfer to register 11.
11.	Clear AE and add 17 from register 84.

This cycle can be repeated as many times as desired. The two cases have been illustrated where the new number either is or is not larger than the largest previous number.

The powerful use of "decision" and the use of a computer to generate its own controlling program have been shown.

In an actual program, orders would be added to the above sequence to stop the cycle after all registers containing the miscellaneous numbers had been searched.

A computer capable of executing 10,000 of these single-address orders per second would scan and make decisions on about 1,000 of the above numbers per second.

References for a more detailed discussion of the comparisons of the computing machine with the human mind:

Dr. Warren S. McCulloch, "The Brain as a Computing Machine," Electrical Engineering, Vol. 68, No. 6, June 1949, pp 492-497.

Norbert Wiener, "Cybernetics," John Wiley Co.