CARNEGIE INSTITUTION OF WASHINGTON
1530 P STREET, NORTHWEST
WASHINGTON 5, D. C.

OFFICE OF THE PRESIDENT

August 6, 1948.

Mr. J. Ross Macdonald,
34 Westgate,
Cambridge, Massachusetts.

Dear Mr. Macdonald:

I had hoped to acknowledge your letter of April 6 with the statement that I had read your paper on "The Storage of Information—Its Evolution and Future," but my reading has necessarily been confined to other subjects in recent months, which accounts for my delay in writing. Nevertheless, I appreciate your sending me the paper, for my interest in the general subject continues, and I trust that I may have opportunity in the not distant future to examine your discussion with care.

Cordially yours,

V. Bush.

JOHN W. MAUCHLY KINGSLEY 5-4901 J. PRESPER ECKERT, JR.

ELECTRONIC CONTROL COMPANY
Control and Computing Equipment
1215 WALNUT STREET
PHILADELPHIA 7, PA.

February 15, 1947

Mr. James Ross MacDonald
Building 32
Massachusetts Institute of Technology
Cambridge, Mass.

Dear Mr. MacDonald:

The subject which you have chosen for your seminar paper has so many ramifications that it is difficult to know how to answer your question. You have probably seen the more or less popular account called "Machines without Men" which appeared in the November, 1946 issue of Fortune.

In our work we have not as yet had the opportunity to devote ourselves to any detailed elaboration of the ways in which memory devices can be employed in controlling industrial processes. We understand that Professor Samuel Caldwell of MIT has given some attention to this, and if you have not already done so, you should certainly confer with him.

An unlimited number of control applications are certainly possible. At the present stage of development, however, the applications which should be made first are naturally the ones in which the largest advantage can be taken of the high speed which is inherent to these electronic devices. This high speed may be useful either because the device which is to be controlled requires new control signals at very short intervals, or it may be useful because the number of intermediate operations which must go on within the control mechanism is large. As far as we are concerned, digital computation may form a necessary part of the cycle of operations required for control.

We shall appreciate it if you could send us a copy of your seminar paper, or if you have no extra copies available, at least loan us a copy when it is ready. This subject certainly deserves a great deal of attention, and we are glad to learn that you have become interested in it.

Sincerely yours,

John W. Mauchly

John W. Mauchly

JWM ds

THE STORAGE OF INFORMATION

- Its Evolution and Future

by

James Ross Macdonald

THE STORAGE OF INFORMATION — ITS EVOLUTION AND FUTURE

by

James Ross Macdonald

A Seminar Paper Submitted in Partial Fulfillment

of the Requirements for the Degree of

Master of Science

in

Electrical Engineering

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Cambridge, Massachusetts May 25, 1947

CONTENTS

ABSTRACT

Throughout the history of man, storage has been of great importance because it is indispensable to communication. Many mechanical devices have been developed to store information for future use through communication. Such relatively permanent devices have always been necessary to aid man's limited and short-lived memory. Today, compact storage is more than ever necessary for the great modern fund of general information and for computing machines.

Micro storage offers at least a partial solution to the problem of the storage of general information. Developed concomitantly with ordinary photography, it has only recently become economically practical for large-scale storage of record material. Through the use of microfilm techniques, an areal reduction ratio of about a thousand is at present possible, allowing large amounts of material to be stored in a small space.

Magnetic recording is another important storage method which has recently undergone extensive development. Invented by Valdemar Poulsen about 1898, the recording of sound on magnetic tape or wire enjoyed a short initial period of popularity but was practically forgotten thereafter until the 1930's. Since that time, and particularly during the war, there has been a rush to exploit its possibilities, leading to the development of several new magnetic media and recording methods. The chief advantages of magnetic recording are immediate playback and the compactness and permanency of the record.

Although large-scale digital computers have only been developed within the last ten years, numerous storage media are now used for computational storage. In a computer, storage is necessary both to introduce data into the machine and to store partial results of calculations. The speed of a computer determines the types of storage most applicable to it; because there are a number of computers of different speeds and storage capacities now operative or under development, various different storage methods are required.

One of the oldest storage media now used in computers is punched paper tape. Originally developed in the eighteenth century to control weaving patterns, paper tape was later used for automatic telegraphy, and, recently, as an external computational storage medium. Punched cards, which were first employed for the tabulation of large amounts of data by Hermann Hollerith in the 1880's, have since been applied to many problems in accounting and mathematics by the International Business Machines Corporation and are used in two modern computers for external storage. Although neither magnetic tape nor microfilm has yet been used in a computer, several machines now under construction will utilize these media to achieve a much faster speed of recording and reading information than is possible with punched tape or cards.

Rotating wheels have been employed for the storage of numbers since they were used in the first calculator, invented by Blaise Pascal in 1642. The earliest projected automatic-sequence-controlled computer, designed by Charles Babbage in the early part of the nineteenth century, was to have used several thousand rotating wheels with inscribed, circumferential digits for internal storage and punched cards for automatic control. Electrically set wheel counters were developed in response to the needs of automatic telephony by 1910 and have since been used in modern calculators and in the Harvard Automatic-Sequence-Controlled Computer, a modern counterpart of the original Babbage machine.

By far the largest part of the work on storage media for use in computers has been carried on for the development of high-speed internal storage devices. The Eccles-Jordan flip-flop circuit, invented in 1919, has been used to provide both binary and decimal storage, and relays have been employed by the Bell Telephone Laboratories to supply the entire internal storage necessary for a computer. A new type of transmission line, the acoustic delay line, developed during the war, has a large, relatively cheap storage capacity, and is to be used in at least two computers now under construction. There are considerable possibilities inherent in the storage of data on the circumferences of rotating magnetic or phosphor-coated disks or cylinders; this storage method is now under investigation at Harvard.

A consideration of the storage capacities and speeds of the different types of modern storage media indicates that those devices in which information is distributed over a two-dimensional continuum are the most efficient and allow information to be reached most quickly. Therefore, of the high-speed storage devices now in the developmental stage, perhaps the most important will be electrostatic storage tubes like the R.C.A. selectron and other tubes which similarly store information as discrete charge elements on a two-dimensional dielectric surface. And extrapolating, the computational storage device of the future would seem likely to be three-dimensional, with storage points arranged in a three-dimensional matrix.

Besides their usefulness in computers, many of the storage devices and techniques that have been developed for computational applications will be of great value in the future for other purposes. Computational selection and switching methods promise to be very useful in the rapid location of large amounts of information stored on microfilm. Dr. Vannevar Bush has even posited a generalized individual storage repository which will achieve associative linkage of information, as in the brain, through the use of high-speed selection and large microfilm reduction ratios. Finally, storage will be used in the future automatic factory to control the sequence of machine operations and thus to eliminate much of the mental repetitive work now necessary.

I

INTRODUCTION

A. THE IMPORTANCE AND NECESSITY OF STORAGE

The primary aim of this paper is to show how and why different means of informational storage have been developed and employed in modern times. The various reasons for the development of important storage methods will be evaluated in terms of the function and efficiency of each method. From a consideration of the new types and uses of storage, an extrapolation to its future uses will be made.

The storage of information is intimately connected with the communication of that information; hence, it is impossible to discuss one process without the other. It is obviously of no utility to store information that will never be used again. Storage is of importance because of its pragmatic relation to communication. Because man's memory is finite and forgetful, it has always been necessary to augment it by some mechanical or external means. All types of storage are thus means of preserving information in an unchanged and readily communicable form.

The history of stored information by no means begins with the invention of writing, much less with the invention of writing on paper, but, instead, may be traced back to the very beginnings of language. All of man's progress has been contingent upon his being able to communicate the results of experience to others so that they might make use of these results. Therefore, the history of storage is as old as the history of man.

Perhaps one of the earliest uses of storage was that of the cave man when he drew a mark on the ground or broke a tree branch to indicate to his fellows the direction he had taken. This use of sign language constituted a concrete way of storing information by association: an associative complex was set up in the mind of the cave man between the physical sign and the thing that it represented. Thus, the sign, whether it was a mark on the ground, a word, or a picture, became the symbol of some external, perceptual reality.

With the development of the ability to differentiate between a thing-in-itself and its symbolic representation, man made one of his most significant advances. In effect, he gained the ability to make abstractions. He represented a mastodon by the word for mastodon and remembered the word. This use of words as symbols representing perceptual realities effected an incalculable savings in time and effort; instead of being forced to point out the physical mastodon when he wished it considered, the cave man had only to use the word for mastodon.

It is essential to note the dichotomy between the thing-in-itself and the symbol thereof. One is the real, the other, the ideal. This distinction becomes readily apparent when it is understood that while a real object has an infinite number of characteristics, the symbol of the object is defined primarily in terms of a finite number of its most obvious characteristics. Most symbols are not completely defined, since, if they were, they would, of necessity be the object which they symbolized. This state of affairs is actually the case with the cardinal numbers, which are completely defined symbols.

As man progressed, the order of abstraction that he was capable of making increased, and the next stage of storage developed: this is exemplified by the written word, which is essentially a symbol, or coded form of the spoken word. Gradually, man's thought and memory began to be more and more concerned with abstractions; but even today not all memory consists of abstractions. Those percepts concerned with the body itself, such as pleasure and pain, need not be expressed in terms of words to be felt or remembered by the individual. It is, nevertheless, usually necessary to employ words to express these emotions when they are to be communicated.

Just as words make up ordinary language, so numbers and mathematical operations form the language of mathematics. This language again consists of abstractions, often of a higher order than that represented by the written word. Numbers are symbols representing certain information; hence writing down a purely numerical solution to a mathematical problem is as much storing information as is writing down a description of a method of making cherry pie.

It is important to make clear the distinction between the terms "storage" and "memory" as they will be employed in this paper. Bergson defined memory as "... the intersection of mind and matter."* Although this is a rather romantic definition, it does indicate that memory is more than mechanistic. Thus, as a distinction is rightly made between the brain and its thought, a distinction should also be made

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*Bergson, Henri, Ref. 1, p. xii.

between the physical mechanism of memory and memory itself, the result of this mechanism. There is an essential dichotomy between the mechanism of memory and the thing remembered, which constitutes the memory. Unless one is a complete materialist, it is necessary to admit that although the former is materialistic, the latter is not. On the other hand, the case is altogether different for all types of external storage: the storage media, the process of storing, and the thing stored are all of the same kind. In Bergson's idiom, storage is the intersection of matter and matter.

It is also necessary to define two generic types of storage. The distinction between the two types is based on the controlling motivation behind the development and use of a specific kind of storage. To the first class of storage belong those storage methods which were developed or came to be used because of a direct need for storage, while the second class comprises storage methods which did not originate primarily from a need for storage and, consequently, are not usually thought of as being storage at all.

Common members of the first class are the book and the phonograph record. These devices were developed and are used to store information for later communication. This type of storage will be arbitrarily designated "explicit" storage. In contradistinction, members of the second class will be termed "implicit" storage. Representative members of this class are works of art and electronic circuits. It is undeniable that if these objects have meaning, they are concrete means of storing information. But neither type of object originated from an awareness of a need for storage on the part of its creator. The inventor of a circuit is concerned primarily with what it can do; it is only incidental that the physical connection of wires and circuit components represents a stored form of the inventor's idea. Likewise, the artist is more motivated by a desire to express his subjective perception of reality than a desire to explore the practical possibilities of his medium as a means of storage.

All physical things that have meaning store information. The transformation from implicit to explicit storage is effected when the physical object or method is adapted to serve the practical purposes of storage. This process is well illustrated by the transition from painting to photography. The distinction between implicit and explicit storage is a fine one, but it is fundamental and is very necessary in limiting the scope of the word <u>storage</u>. In the succeeding pages, only explicit storage methods will be considered.

The general storage of information is necessary to pass on knowledge from generation to generation. The bulk of accumulated knowledge in modern times is too great to be handed down orally from father to son. It is now impossible for any one individual to encompass the entire fund of information in even a very restricted field of specialization unless he has both a long life and the extensible cranial capacity of H.G. ~~[illegible]~~ Wells's Selenites.[4] Not the least important of the advantages of storage is that stored information is usually easily duplicated, and thus knowledge can be widely disseminated.

Recent years have seen the application of storage to automatic mathematical computers and other automatically controlled mechanisms.

In these devices, whose development gained considerable impetus from the needs of mechanized warfare, storage may serve two distinct purposes: first, to control the sequence of operations of the device, and second, in the case of a computing machine, to store intermediate results of the computations until needed in the further solution of the problem. Both functions of storage are often found in the same device. Thus, the computer also uses storage to direct the course of the problem being solved; and many machines, such as the projected "automatic factory," whose primary function is not computation, will, nevertheless, include a computing machine in addition to their controlling storage. The time that must be used up in getting information out of storage ("reading out" or "reading"), and the time necessary to place information in storage ("recording") are the chief factors which determine the speed at which a computer can operate, and so, the time to solve a given problem. Thus, it is of major importance to examine the various types of computational storage and to contrast their characteristics.

There are three separate topics which must be treated in any consideration of actual storage methods. The physical form of the storage medium, the method of recording, and the method of reading out information are all extremely important and not often independent. There are other factors which will be analyzed in this paper, such as the space required by a given storage unit, its cost and permanency; but these subjects are concerned with the problem of efficiency, whereas the form of the medium and recording and reading techniques are directly related to the possibility of using the medium for informational storage, and hence are the more fundamental. In the following pages, these considerations will be of primary concern, the questions of efficiency will deal chiefly with the final application of the given type of storage.

B. THE PROBLEM OF CLASSIFICATION

In both the general and the computational storage of information, it becomes imperative, as the bulk of stored material grows, to classify this information or data by means of some ordering procedure. The speed with which the information can be reached and returned is of great importance in both of the above types of storage, and it is through classification that the speed can be greatly increased.

The word storage, as applied to general information, may have several meanings. This multi-ordinality arises because storage is employed at several different levels. It has been shown that words, since they have an informational value, store information. But also the orderly arrangement of words in a book represents information which is stored in the book. Finally, books may be stored in a library. The function of classification is also multiple. Classification is used to order information according to some logical scheme, and it is also used to enable the information to be located when it is localized in a physical storage medium such as a book. The function depends upon the level of storage being employed. Thus, a classification system can be set up solely in terms of intangible subjects like Greek Philosophy and Keynesian Economics; when the system is employed to order the storage of books dealing with these subjects, however, a different function of classification is made use of. In practice, the two functions are seldom separated.

Our civilization is largely based on reading and writing; nevertheless, few people outside the library profession realize how swiftly written material accumulates in these days of technical efficiency, cheap duplication, and rapid transportation. Dr. Fremont Rider, Librarian of Wesleyan University, states that many large libraries have doubled their holdings every sixteen years in recent times, and he educes considerable data to support this thesis.[3,4] If this trend persists, Harvard University will have 8,000,000 volumes in 1962, 16,000,000 in 1978, and so on. This is a geometrical progression which is definitely alarming. By judicious disposal of some of its older holdings, a library might be able to stem this rising tide of books to some extent, but the trend could still not be adequately controlled by that method. Since the rate of increase is not likely to change appreciably in the near future, it is obviously necessary to find some means of storing information more compactly. It is also extremely desirable to evolve and employ selection methods of greater rapidity when bodies of material of these orders of magnitude or greater must be dealt with. Later in this paper possible methods of accomplishing these desiderata will be described and evaluated.

There are two generic types of classification: mnemonic or associative, and selective. The operation of associative classification is best understood by consideration of the human memory. Memory is associative, with one fact suggesting another because they are related in the mind in accordance with a complicated network of trails in the matrix of brain cells. This process is well illustrated by the following observation of Samuel Butler:*

> When asked to remember "something" indefinitely you cannot: you look around at once for something to suggest what you shall try and remember. For thought must be always about some "thing," which thing must either be a thing by courtesy, as an air of Handel's, or else a solid, tangible object, as a piano or an organ, but always the thing must be linked onto matter by a longer or shorter chain as the case may be. I was thinking of this once while walking by the side of the Serpentine, and, looking around, saw some ducks alighting on the water; their feet reminded me of the way sea-birds used to alight when I was going to New Zealand and I set to work recalling attendant facts. Without help from outside I should have remembered nothing.

Associative classification has recently been applied in a very interesting fashion in the projected "memex" of Vannevar Bush.[6] This device is to be an individual information repository which will use computational techniques to achieve the effect of associative grouping of information. The actual operation of the memex will be described in Chapter V.

The second type of classification is selective. Its operation and limitations for human use are explained by Vannevar Bush as follows:**

> The real heart of the matter of selection, however, goes deeper than a lag in the adoption of mechanisms by libraries, or a lack of development of devices for their use. Our ineptitude in getting at the record is largely caused by the artificiality of systems of indexing. When data of any sort are placed in storage, they are filed alphabetically or numerically, and information is found (when it is) by tracing it down from subclass to subclass. It can only be in one place, unless duplicates are used; one has to have rules as to which path will locate it, and the rules are cumbersome. Having found one item, more-over, one has to emerge from the system and re-enter on a new path.

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*Butler, Samuel, Ref. 5, p. 65.
**Bush, Vannevar, Ref. 6, p. 106.

Library indexing uses the selective system. Although there are numerous methods.[7,8,9] all use a combination of letters, numbers, or letters and numbers to make up the classification code by which a given book is ordered in the hierarchy of class and subclass. Thus, the subject, The History of Italian Art, would be indicated as 709,45, W56, and N6911 in the Dewey Decimal, Cutter Expansive, and Library of Congress classification codes. Through use the above codes become partly mnemonic, and it is hence not always necessary to use a code book to decode a given combination. For instance, in the Dewey Decimal system 709 designates a subject in the class, history of art, and 0.45 always refers to Italy. Although parts of the selective system may become mnemonic, the actual use of the system to locate information is still time consuming because of the great spatial extension of a large number of books.

The above difficulties are not important in the case of information stored for computational use. This information usually consists of data in the form of a great number of superficially unrelated numbers, usually specified to ten decimal places or more. To each number is assigned a position code number. Each position code number corresponds to either a definite spatial position in the storage medium or a definite group of storage elements, depending upon the type of storage used. The position numbers form a monotonic sequence, and hence are the ordered part of the classification. Removing a stored number for use merely consists in using its position code to control a switch which selects the proper position in the storage medium or the proper storage group. The number is then removed electrically and can be transmitted where it is needed with extreme rapidity. If there were 10,000 numbers to be stored, a code number for each could be made up from four decimal digits, since these digits could be permuted in 10,000 different ways. In practice, decimal codes are seldom used, but the principle remains the same. It should be emphasized that these code numbers correspond exactly to the classes and subclasses mentioned by Bush and used in library indexing; each number designates one of the possible members of a certain class or subclass. Selective classification is well suited to machine storage because the speed of the selection switch and associated equipment can be made so great that their operation time is comparable to the time necessary to prepare the machine to use the stored information.

II

G E N E R A L   S T O R A G E   M E T H O D S

INTRODUCTION

In any treatment of the evolution of storage, some consideration must be given to the development of general storage methods before any discussion of computational storage can be logically undertaken. General storage is the basis upon which computational storage has been developed, and, apart from providing the foundation for this development, general storage is of great importance in its own right. Books, moving pictures, phonograph records are trademarks of our age; but, because general storage methods are so much a part of everyday life, their background is practically common knowledge. For this reason, this chapter will be limited to a discussion of two of the less well-known types of informational storage which have recently come into use, microcopy and magnetic wire and tape.

The storage methods to be considered have either already been adapted for computational use or have great possibilities for such applications. In order to gain proper perspective for an adequate understanding of the possibilities of this use of such methods, however, it is first necessary to consider their fields of usefulness for general storage, and to contrast their characteristics with those of more common, competing types of storage.

A. MICRO STORAGE TECHNIQUES

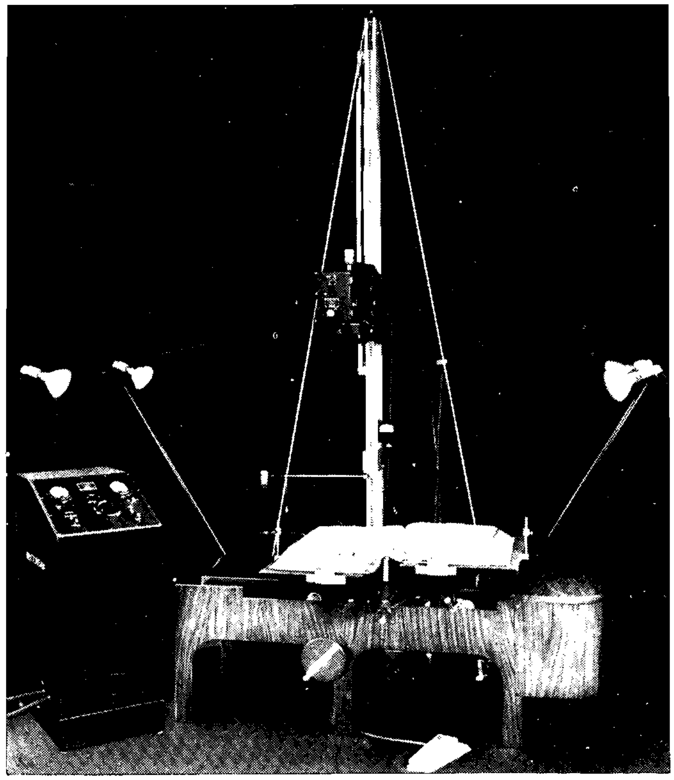
Only within the last century has bulk storage of the printed word become a problem. Ease of duplication and modern bureaucracy, which demands seven copies of every document, have combined to produce the familiar spectacle of whole buildings dedicated to the preservation of records. Today, more than ever before, a method of storing general information compactly is urgently necessary. The rising flood of paper must be checked not only before it inundates us all, but also before the very mass of the stored information begins to defeat the purpose of storage, and it becomes impossible to locate desired information.

Microfilm and associated micro-techniques of storage furnish the logical solution to this problem. By utilizing these methods, a filing space saving of more than 99 percent can be effected. In many instances it is possible to set up a retention schedule whereby documents are kept for a certain length of time, then destroyed; yet, at present, the total amount of stored material is increasing rapidly in spite of such procedures. By preserving all future material in the form of microcopy, it should be possible to keep the total space required for a given storage program almost constant.

The essential principles of microphotography are very simple. The material to be reproduced in microfilm is photographed in a reducing camera very similar to modern miniature cameras. Thus, the area of an image on the film is much smaller than the area of the original image. Sixteen millimeter film of the motion picture type is most commonly used in microphotography. For normal reading of the microfilm, a positive print is made which is read by means of an enlarging projector. Figure 1 shows modern types of recording camera and reading projectors. Both camera and reader have convenient controls for adjusting the reduction and magnification of the image.

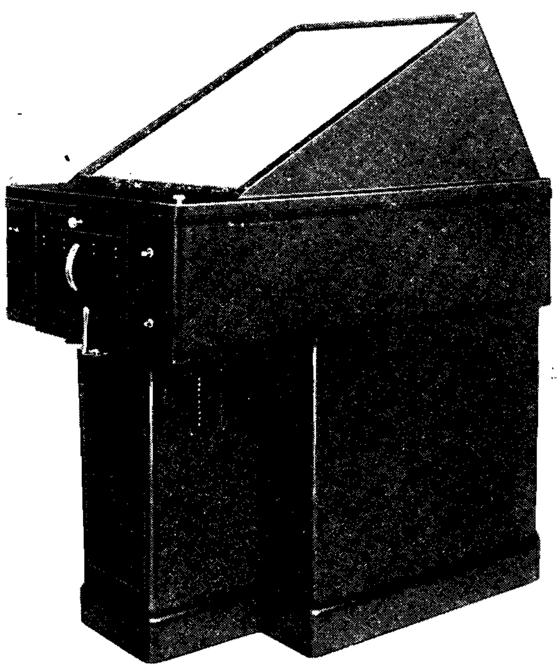
Although the basic idea of microphotography is almost as old as photography itself, it was not until 1940 that the 76th Congress ruled that government records preserved on microfilm were legal. It is to be noted that such microfilming is thus made optional but not mandatory. Yet as early as [illegible], John W. F. Herschel, an English mathematician, who was also one of the early workers in photography, proposed the preservation of public records in microfilm form.[10] The first microphotographs were produced about 1840, and by 1865 the technique of microphotography had been developed to a high degree of perfection in France and England. One of the most romantic early uses of microphotography was the "Pigeon Post" which operated during the ~~seige~~ siege of Paris in 1870. In this communication system, which used pigeons to carry microfilm messages to and from the ~~beseiged~~ besieged city, V-mail had a direct precedent. The Germans also employed microphotographic techniques in the last war to produce the "microdot."[11] Entire secret messages were reduced to the size of dots and glued on top of the periods in ordinary letters.

It was not until quite recent times, however, that the mass production of excellent lenses and photographic film made it economi-



Recordak Corporation

Micro-file Recordak Model C Camera photographing a huge bound volume.



Microstat Corporation

Microfilm Reader by Microstat, Type R-1, for engineers and executives is electrically controlled.

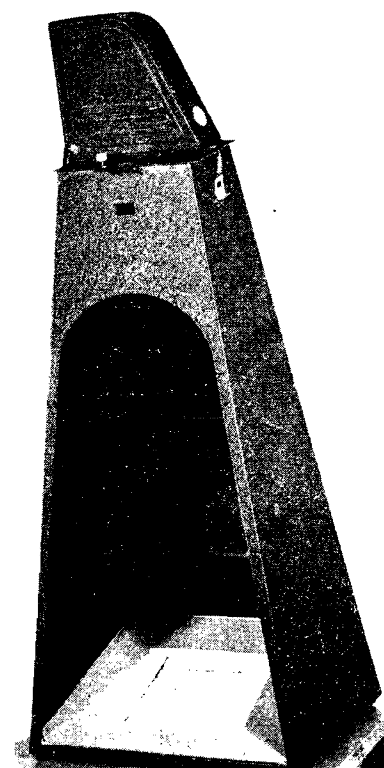


FIG. 2.—Students Microfilm Reader, Film at Placement I or III

cally practicable to achieve the large reduction ratios necessary for the large-scale storage of information on microfilm. It is obvious that the larger the effective reduction ratio can be made, the more savings in area, and hence in storage space, will be effected. Film resolution, as determined by grain size, is not at present the most serious difficulty in increasing reduction ratios. Large reductions require a camera whose objective lens will give a sharply defined image over an adequate field, and considerable work on cameras is needed to increase the linear reduction ratio much over the present practical maximum of about 30.

Microprint is another micro storing device that has recently begun to be exploited commercially. Like that of microfilm, the idea of microprinting is not new. Duncan C. Dallas, a London engraver, was the first to develop microprinting techniques. About 1866, he produced a miniature reference Bible on pages reduced to 1 9/16 inches wide by 2 3/8 inches long. This decrease in size corresponds to a linear reduction of about five. The pages were produced on a printing press, but the actual processes involved were kept secret by Mr. Dallas and seem never to have been disclosed.[12]

Albert Boni, a New York publisher, has been instrumental in developing microprint commercially in recent times. The Readex Microprint Corporation was formed about 1939 in New York under his direction. This company produces reading machines, and is carrying out a fairly extensive microprint publishing program. The process involved in the Readex method of producing microprint on paper is altogether different from that used by Dallas. The normal-sized printed material to be reproduced in microprint is first microphotographed. The resulting negative is then used to make a positive contact print on diazo paper. The printing is carried out under intense light and development occurs upon exposure to ammonia gas. The final microletters appear as dye images on the paper rather than as the silver bromide images of ordinary photography.[15] Diazo paper is considerably cheaper than ordinary photographic paper and wears much better than film. The Readex Corporation is also producing microprint by a secret offset-type technique which allows the use of ordinary paper and printing ink. A sample of Readex microprint is shown in Figure 2. One hundred ordinary pages are compressed on one side of a 6x9 inch sheet and both sides may be used. Each page of the original is reduced by a linear factor of about 15.

In contradistinction to the ordinary type of microfilm readers, which use light transmitted through the film to form the enlarged image, the Readex reading machine utilizes the technique of reflection projection from the opaque paper surface. The final image is projected onto a ground glass or plastic screen similar to those used in most microfilm readers. Selection of pages is very easily accomplished with the Readex machine. Two knobs are manipulated to set the tens and the units parts of the desired page number, the light is turned on, and the page appears on the screen.

There are several factors which must be considered in determining the efficiency of micro storing devices. The most important considerations are: space reduction, permanency of the medium, cost and ease of duplication, and ease of reading. A linear reduction of

Wilder, Thornton
The Bridge of San Luis Rey

pp. 100—199

Readex Microprint **SAMPLE** New York 1940

30 corresponds to an areal reduction of 900, which is about the present practical limit for microphotography. Linear reduction ratios of almost 100 have been experimentally attained, however, by the use of microscopic objectives and restriction of the field of view to within a few degrees of the axis.[14] Thus, given adequate optical equipment, the final limitation on the amount of reduction possible is set by the grain size, or resolving power, of the developed emulsion relative to the microletter size.

The following figures furnish dramatic examples of the space-reducing powers of microfilm. A 24,000-page, 4000-cubic-inch, 100-pound encyclopedia can be reproduced on 1½ pounds of microfilm, occupying 75 cubic inches; 750 cubic feet of material, printed on both sides, can be reduced to 1½ cubic feet of microfilm; the contents of 120 ordinary four-drawer files, when microphotographed, occupy only one four-drawer file.[15]

In the matter of permanency, microfilm and microprint are quite evenly matched. The Bureau of Standards has made measurements that indicate that the diazo dye will not fade within fifty years.[16] Microprint on regular paper, however, will last as long as the paper itself, or a thousand years or more for good rag stock. Most ordinary film is made with a cellulose nitrate base, which has an average life of between five and twenty years. Also, cellulose nitrate is very inflammable. Both of these disadvantages may be obviated, however, by substituting a more brittle, cellulose acetate base. Film made with an acetate base, when stored under the proper conditions of temperature and humidity (50–60 degrees, 50 percent humidity), will last as long as rag paper.[14] Nevertheless, the added care which must be taken when handling film and the special storage conditions necessary make microfilm inferior to microprint and ordinary printing in this respect.

An interesting extension of the permanency of microfilm has been made possible by the development of techniques for producing microfilm on metal plates or ribbons. The idea first seems to have occurred to T.K. Peters about 1912. After some experimentation, he dropped the idea but revived it in the 1930's and produced many metal microfilms for the "Crypt of Civilization" of Oglethorpe University in Atlanta, Ga.[15] Robert W. Carter claims that he produced the first microfilm on metal in Canada in 1929.[16] Since that time, he has perfected his process, which uses a rust-proof aluminum alloy, and developed reading machines of the reflection variety. He claims that the metal ribbon that he employs is no heavier than cellulose acetate film and that the performance of the ribbon is at least the equal of that of film. The advantages of metal as far as permanency is concerned are obvious, but the process has not as yet been developed commercially.

The microprint process is well adapted to large editions, since the cost of an edition decreases in proportion to its size and to the reduction in size of the individual units of the edition. Duplication of microprinted material, after the original negatives or plates have been destroyed or when they are not available, is relatively difficult. Microfilm represents the opposite extreme; it is well suited to small editions and duplication at any future time is easy and very fast.

If, for instance, it is desired to duplicate a vast amount of printed material on microfilm, the material is merely photographed, and the text stored on the microfilm has the advantage of photographic accuracy. Positive and negative prints of the original microfilm negative can be made by ordinary dark-room procedures. De Sola* cites the following example: the duplication of 400,000 3x5 inch forms, which would take a large crew of typists several months, can be completed with two microfilming machines and two operators in about a week.

There are two subdivisions under ease of reading: selection of material, and actual reading technique. At present, microprint has a definite advantage over microfilm in the ease with which a specific part of a given text can be selected. The classification of microfilm and the rapid selection of material on microfilm are difficult problems. Because so much material can be put on a reel of microfilm, it is often necessary, for economy, to put material dealing with several different subjects on one roll. And it is obviously much more difficult to search through a roll of microfilm to find desired information than it is to place a sheet of microprint in the reading machine and set two knobs. This difficulty can be eliminated by making microfilm in the form of sheets or cards, and reading them like microprint sheets by specular light.[17] This application of microfilm will be discussed in greater detail in Chapter V.

Reading machines for microprint and for microfilm give quite analogous results as far as reading ease is concerned. However,

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*De Sola, R., Ref. 10, p. 44.

reading machines of the type shown at the bottom right of Figure 1 do not tire the eyes as much as those shown at bottom left, because the observer is not looking directly at the source of light. It is generally conceded that reading with a machine is not as pleasant as the direct reading of a book, because of convenience, external light, loss of definition in the photographic and projection processes, and so on. Nevertheless, the use of a reading machine is not actively unpleasant and eye strain is not greatly increased.[18]

Micro techniques of storage will probably never replace ordinary books and magazines completely. Yet, in their field of applicability, they are extremely important. They possess the valuable and unique advantages of great space reduction and quick and cheap reproduction.

B. MAGNETIC STORAGE TECHNIQUES

In the field of general storage, magnetic media of various types are used to store sound. For magnetic storage, sound is converted to electric impulses which are applied to an electro-magnetic recording head. The recording head converts the impulses into audio-frequency variations in a magnetic field, which, in turn, magnetizes a recording medium in juxtaposition with the head. The storage medium, usually a wire or tape of ferromagnetic material, is drawn rapidly past the recording head. In this fashion, a pattern of magnetic variations corresponding to the original sound is built up on the medium, and the sound is stored. To reproduce the original sound, the magnetized medium is run through the same recording head, now functioning as a pickup coil, so that voltage variations will be produced for reconversion to sound. It is essential that the medium pass through the head in the same direction as in recording; thus, it must be rewound before playback.

In the storage of sound by magnetic, photographic, or phonographic means, it should be noted that it is the thing-in-itself that is stored, not a coded representation of that thing. The sound is <u>converted</u> to another representation, and its extension in time temporarily changed to extension in space, but it is not <u>translated</u> to a coded form or from one code to another. Aural words are coded by means of an alphabet and stored as printed characters on paper; music is coded through the use of an elaborate symbolism and stored on paper; music is coded in another way on the music rolls of a player piano. In every case, the storage is macroscopically discontinuous, made up of discrete code elements. On the other hand, when sound is stored without translation, the storage is effectively continuous, to correspond to the original sound.

The technique of magnetic recording and reproduction of sound was invented by Valdemar Poulsen, a Danish physicist, about 1898.[20,21,22] A picture of one of Poulsen's early machines, called a telegraphone, is shown in Figure 3. A long piece of steel wire was wound helically around the central cylinder, which was rotated manually at fairly constant speed. Recording and reproduction were accomplished by means of the same head, which moved across the cylinder in following the wire. A wire velocity of about 0.5 meter/second was employed, and maximum playback time was about a minute.

Poulsen developed other machines using tape and disks instead of wire, developed a method of erasing the magnetic patterns by saturating the material with a strong d-c magnetic field, and invented the two principal methods of magnetization: longitudinal and perpendicular. In perpendicular recording the medium passes between the poles of the recording head, and the magnetic flux lines thus pass through the medium perpendicularly. On the other hand, the pieces are side by side for longitudinal recording, and the medium passes over, rather than between, the poles; hence the flux lines are approximately parallel to the medium. In early magnetic recordings, perpendicular magnetization was not much used for wire because twisting of the wire shifted the direction of magnetization on playback and produced a distorted output. Both longitudinal and perpendicular recording were

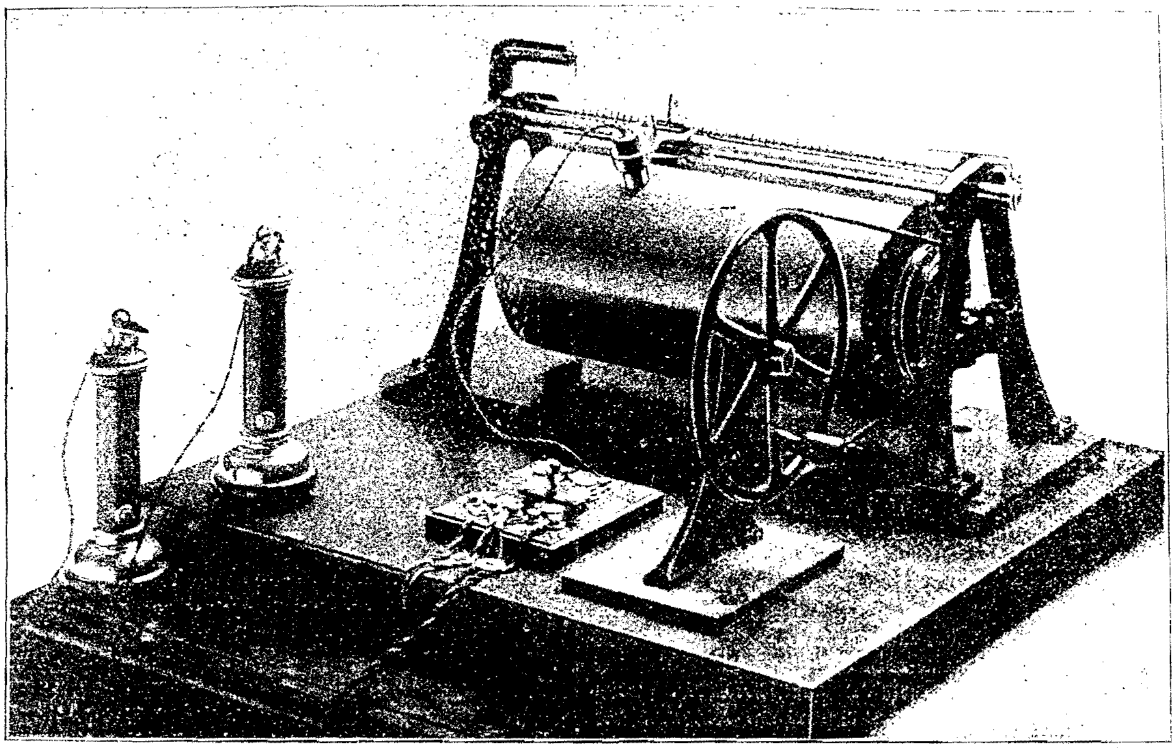
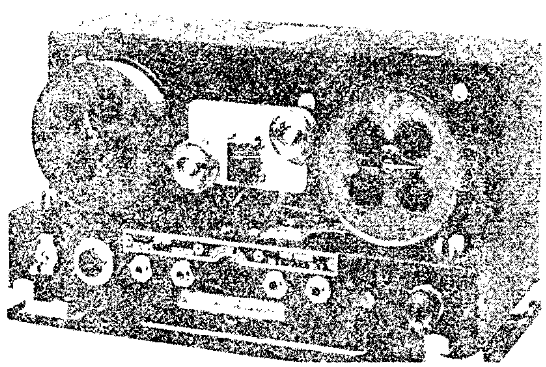
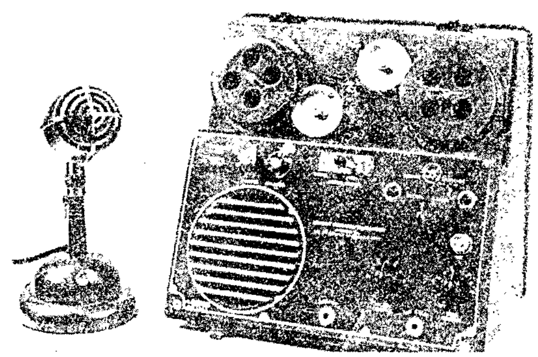


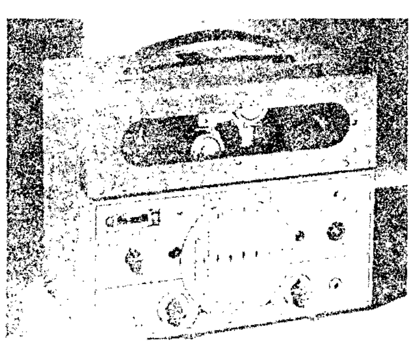
FIG. 1.—GENERAL VIEW OF THE POULSEN TELEGRAPHONE. Ref. 20, p. 5.



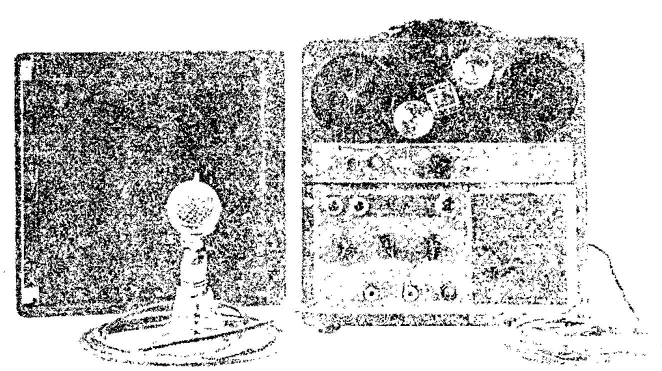
A — Radiotechnic Laboratory model 22



B — [illegible]



[illegible]



[illegible]

Ref. 22, p. 321.

Fig. 3 Old and New Magnetic Wire Recorders used with tape, however; but longitudinal recording required a longer length of medium for the same fidelity.

About 1905, the use of magnetic recording began to decline. Its novelty had worn off; there was keen competition from the well-established phonograph; the volume level of existing machines was less than that of the telephone; and the apparatus required frequent overhaul. The greatest need at that time was for an adequate amplifier. The vacuum-tube amplifier was applied to magnetic recording by 1920, but it was not until the 1930's that large-scale interest in and development of this method of recording revived.

In 1921, a very significant advance in the field was made but was not recognized as such at the time. W.L. Carlson and G.W. Carpenter invented the method of supersonic biasing, in which a signal of ultrasonic frequency is combined with the audio signal at the recording head.[23] The ultrasonic frequency commonly used is of the order of 25 to 50 kilocycles/second, and so is inaudible. When the magnetic medium is subjected to a combined field of this character, a series of minor hysteresis loops results. With proper adjustment of the magnitude and frequency of the ultrasonic component, the remanent magnetization depends (to a close approximation) only upon the instantaneous value of the audio field. Thus, the magnetization curve is effectively straightened out through the origin, and distortion is minimized. Also, noise is decreased and signal level increased by the method. Supersonic biasing has been further developed and applied by Marvin Camras and D.E. Wooldridge since 1941.[24,25]

During the 1920's, there were several relatively unsuccessful attempts to use magnetic recording for motion picture sound, and attention was concentrated upon the possibility of using a magnetic coating on paper and film instead of a solid magnetic material. In 1928, Pfleumer, in Germany, produced a fairly adequate coating of magnetic particles on paper or plastic, and in 1935 a dictating machine employing coated tape and achieving a 20 decibel signal-to-noise ratio was produced commercially in Germany.[26]

In the years just prior to the war, the Bell Telephone Laboratories, the Brush Development Company, and the Armour Research Foundation began extensive development of the art of magnetic recording, while during and since the war, more companies have initiated their own development programs.[22,28] Such renewed interest has led to a number of important advances in both the experimental and theoretical side of magnetic recording.

In 1943, Marvin Camras developed a very practical wire recorder using longitudinal magnetization of 0.004-inch diameter steel wire. This recorder employed an improved recording head, and used both supersonic biasing and supersonic erasing. Eleven thousand, six hundred feet of wire were used to record either 66 minutes of speech or 33 minutes of music. Wire is often used in place of tape because it is inherently less bulky. Camras's recorder, which allowed a longer recording time than previously possible for a given weight of magnetic material, was used extensively during the war. Several modern wire recorders are shown in Figure 3.

Recently, D.E. Wooldridge has published a new and improved theory of noise in magnetic recording.[26] According to this theory, noise is chiefly caused by many random magnetic irregularities less than 0.001-inch in average dimension. A statistical variation in the net flux entering the pole pieces of the pickup head occurs because of the finite size of the magnetic domains of the material. In a magnetic medium, there are many of these small saturated regions, so oriented as to cancel one another's fields; however, according to Wooldridge, there must be local imperfections in this cancellation process that result, at any instant, in the passage into the polepieces of a net flux different from zero. It is this misalignment of magnetic domains that sets the lower limit on noise in magnetic recording.

Wooldridge also found that magnetic tape erased by the same ultrasonic frequency used in biasing was 10 to 20 decibels less noisy than tape that had been erased by a strong d-c field. In the Bell Laboratories tape recorder described by Wooldridge, the useful volume range is of the order of 50 decibels. This machine uses a tape 0.05-inch wide and 0.0022-inch thick, run at 16 inches/second. At this speed, the frequency response can be equalized flat between 100 and 8000 cycles/second, comparable to the response of commercial phonograph records. Another improvement developed at the Bell Laboratories is the use of wide, offset polepieces to decrease the reluctance at the recording medium. A combination of longitudinal and perpendicular magnetization is produced and the output signal level increased.

Considerable work has been done in the last few years to develop recording media that have high coercivity and are at the same time relatively inexpensive. Bell Laboratories has used an alloy called vicalloy, consisting of cobalt, vanadium, and iron, which has a coercive force of from 200 to 250 oersteds, while Armour licencees generally use a stainless steel wire with a coercivity of 250.[28] The Brush Development Company has perfected a process by which low-cost ductile wire, such as brass, is uniformly plated with a magnetic alloy.[26,28] The coercivity of this plated wire is of the order of 300 oersteds, its frequency response is relatively poor (see Fig. 4), and its cost very low. It is probable that in those applications where both cost and space must be limited, coated wire will find an important sphere of usefulness.

There are two distinct types of magnetic material currently employed to coat paper tape magnetically.[26,28] The first material is an emulsion of iron oxide used to form a magnetic layer 0.5 mil thick. The second type is not an oxide, but rather a finely-powdered, metallic material. It has been found that the coercive force of a layer of such material is dependent upon particle size. By reducing this size, the Indiana Steel Products Company has been able to produce tape with a coercivity of 500 oersteds. Tapes made with both types of material are comparatively cheap, but their signal-to-noise ratios have not as yet been raised over 40 decibels, and fidelity is poor above 6000 cycles/second (see Fig. 4). Because tapes can store more energy per unit length than can wire, it is possible to run them at slower speed than wire for equivalent frequency response. At eight inches/second, the Indiana Steel Products Company coated tape has an equalized frequency response flat between 50 and 5000 cycles/second.

For solid materials, either wire or tape, frequency response is not necessarily limited. By running the medium through the head at a fast enough rate, fine fidelity up to 25,000 cycles/second or more can be obtained. The faster the speed, however, the more of the medium is used in a given recording time, so that in practical cases a compromise must be made between playing time, frequency response, and the length of material employed. The speeds in use at present compare favorably with those used for phonograph records (14 to 28 inches/second) and for sound-on-film (18 inches/second for 35 millimeter film).[29] A common wire diameter in use today is 0.004-inch. Through the use of such small-diameter wire, a rather good space factor can be achieved: an hour's recording with good fidelity can be wound on a spool approximately three inches in diameter by five-eighths inch thick.

Magnetic recording has many advantages. Of great importance is the fact that continued re-playing of the record neither affects the quality of reproduction nor appreciably decreases the volume level (see Fig. 5). The medium is permanent yet may be easily erased. The recording procedure is extremely simple and ~~there is~~ no processing is necessary afterwards. Noise level and frequency response can be made comparable or better than those of phonograph records, and a magnetic recording can be stored in considerably less space than would be necessary for a phonograph record or film

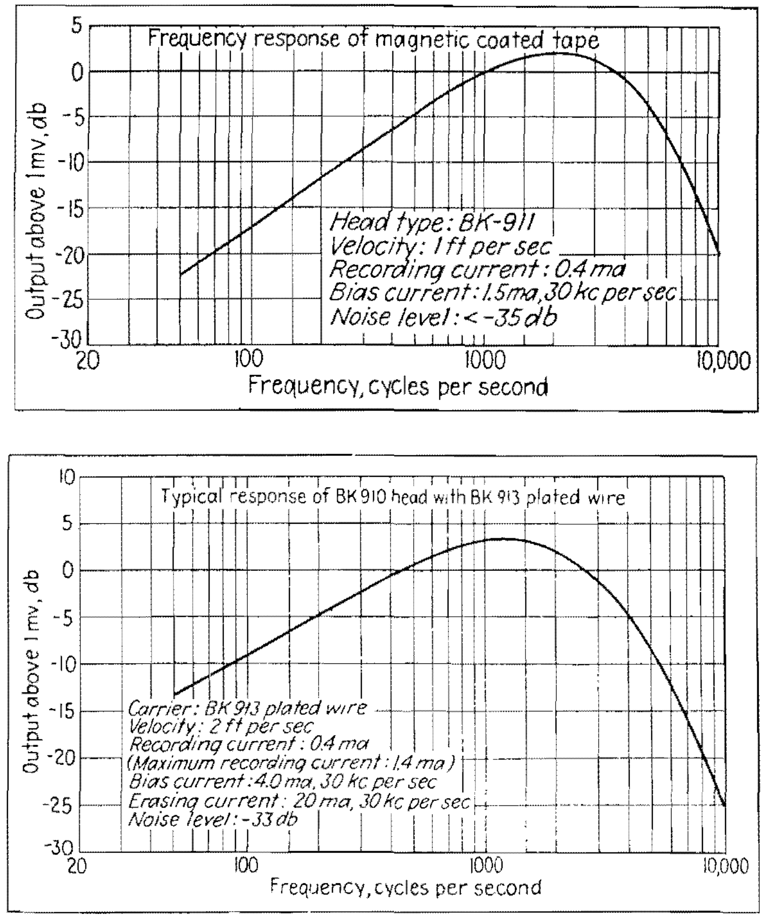


Fig. 4 Frequency Response Curves Ref. 28, p. 108.

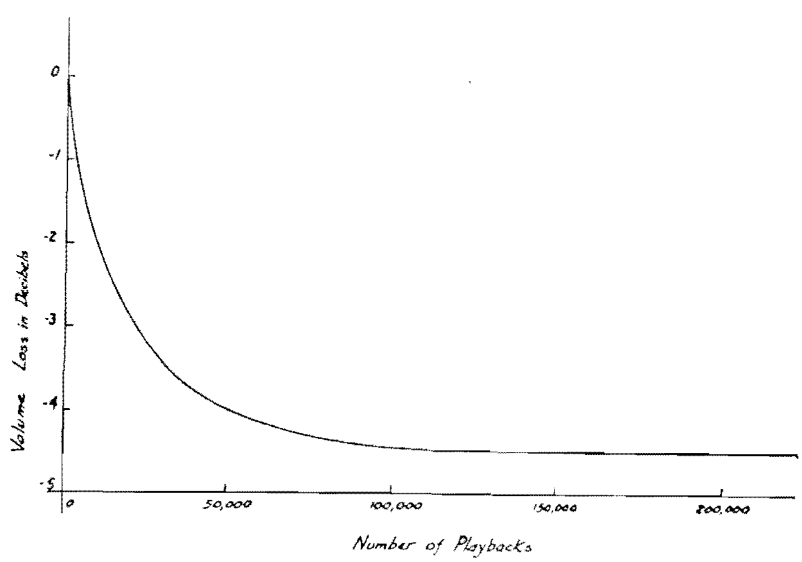


FIG. 1. Effect of continued playing upon volume.

Fig. 5 Volume Loss with Playback Ref. 27, p. 539.

recording of equal length. Recording itself is relatively unaffected by vibration and shocks, making it possible to use the system on vehicles. Also, as evidenced by Figure 5, the equipment necessary for both recording and reproduction is quite portable and compact.

There are several disadvantages inherent in magnetic recording, but they are relatively unimportant in comparison to its advantages. The record must be rewound after recording or playing. Since rewinding time may be much shorter than playing time, this disadvantage is of importance only for very long records. Also, it is difficult to design the motor drive system so that the velocity of the medium will be kept constant. Reproduction in large quantities is not as yet easily feasible. Recording a number of records at the same time from a master record seems the most convenient method at present, but large quantity reproduction would be very time consuming. In spite of these disadvantages, there are many important uses for magnetic storage. It will be invaluable in home recording because it can be easily spliced and erased. It can be used for recording interviews, automatic recording, industrial recording, record players on vehicles, and possibly may eventually become an important rival of the phonograph record.

III

COMPUTATIONAL STORAGE METHODS

INTRODUCTION

Computing and automatic control devices usually require two basic types of storage for most efficient operation. The first of these types is "external" storage and is characterized by low cost, large storage capacity, and slow speed of recording and reading out information. External storage exists outside of the machine proper, although when it is in use, it is controlled by the machine. The second type of storage necessary is "internal" storage. It is constructed as an integral part of the machine, and is usually of high cost, limited capacity, and high speed.

It is not proposed to consider, in this chapter, the reasons for the need of these two types of storage and their interrelations in a computing device. Instead, the development of the more important storage mechanisms that satisfy this need will be traced. A description of the modern representatives of these storage methods will be given, and the efficiency of each method analyzed. In the next chapter, the applications of these storage devices to modern computers will be illustrated, first, in terms of the general storage needs of a computer, and then with regard to the actual storage methods used in several specific computers.

A. LOW SPEED STORAGE

External Storage

a. Punched Paper Tape

One of the oldest types of ~~explicit~~ external storage now used in computing devices is punched tape. In its long history, punched tape has been employed to store many kinds of information of as diverse types as weaving designs and Morse code. One of the earliest recorded applications of moving paper tape was that of Basile Bouchon in France in 1725.[30] Bouchon used an endless band of perforated paper to control the pattern of cloth woven on a loom. The holes in the tape allowed only certain of the needles of the loom to come into play at certain phases of the weaving; thus, the pattern was determined by the punching of the tape. In 1728, M. Falcon replaced this form of tape by a number of perforated cards, which, in later developments of the art, were laced together to form an endless sequence. Such laced cards form the basis of the Jacquard loom, first exhibited in 1801, and still in use today.[31,32]

In 1842, Seytre was granted a French patent for his use of punched paper tape to control a player piano.[33] In this application, holes in the tape controlled air pressure, which, in turn caused the various hammers of the piano to operate. Meanwhile, Alexander Bain, one of the inventors of the telegraph, was experimenting in England with punched tape as a means of sending telegraphic code automatically at high speed.[34,35] He punched dots and dashes in the paper tape and converted these holes into electric impulses by means of feeler fingers, which, when they encountered a hole, passed through and made a contact. In order to record messages sent at the high transmission rates possible with this system, he employed a receiver of his own design, which depended upon the chemical effect of electric current passing through impregnated paper. Thus, in this system, information was stored on both a sending and a receiving tape. Bain developed his method of automatic telegraphy in 1846, but the speeds it made possible were unnecessary at that time, since telegraphy had not then become widespread. Consequently, Bain abandoned the automatic system and returned to manual transmission. It is interesting to note, however, that he was granted a Scotch patent for the use of punched tape in the player piano in 1847.[33] Bain's idea of tape-controlled telegraphy was later developed by Charles Wheatstone, who patented an improved system in England in 1858.[34,35] He used a refined tape transmitter and a sensitive mechanical ink printer, both driven by clockwork. The tape was punched by a perforator with three keys, struck manually with a small mallet. As is the practice today, the tape was moved forward in steps and read while stationary. Through these contributions and improvements, Wheatstone laid many of the foundations of modern automatic telegraphy.

Another interesting use of punched tape was that of Donald Murray, who, in 1898, used punched tape to control the operation of a typesetting machine to increase the composition speed.[36] Using

Murray's technique, in conjunction with automatic telegraphy, Chicago newspapers were set from tape in New York for several years. There is a typesetter in use at present which employs paper tape not only to set but also to justify lines of type.[37] The Monotype machine consists of a perforator with a keyboard similar to that of an elaborate typewriter, and a caster. The tape is first punched with the material to be set up, with each letter represented by a particular combination of perforations. At the end of each line, a pointer on the keyboard indicates what special keys are to be touched to ensure justification of the line, when eventually cast in metal. After the tape is complete, it is inserted in the caster in reverse. Consequently, the information punched on the tape by the justifying keys comes first in each line, rather than last, and is used to control the spacing of the line. The Monotype thus secures line justification by reversing the sequence of operation.

Figure 6 shows a modern telegraphic tape and the code represented by the positions of punched holes. A complete telegraphic layout consisting of printer, transmitter, and perforator is shown in Figure 8.[38] Printing is accomplished automatically from the telegraphic impulses, with no temporary storage of signals between reception and printing. Electromagnetic punching of the proper code for each letter is carried out mechanically by the keyboard-operated perforator. The tape transmitter has five contact-fingers corresponding to the five possible hole positions on the tape. The tape is moved forward in steps by means of a sprocket which engages the center holes one by one. Each time the tape is moved, the fingers drop down on it, and those that encounter holes pass through to close contacts in corresponding circuits. In this fashion, the code on the tape is converted into an electric impulse representation which is transmitted over the line to the automatic printer. The chief advantage of automatic transmission is that it economizes the time that the telegraph line is actually in use; by high-speed transmission, the line is used for a much shorter period than if the same information were sent at a slower manual rate.

Punched tapes are used to a considerable extent as input and output storage media in several modern computers (see Fig. 7).[32,39,40] In such applications, each particular combination of perforations on the tape, representing a stored digit, is read off by a sensing device and converted into the electric pulses that represent the number in the machine. An important disadvantage to the use of punched-tape external storage in high-speed computers is that the speed with which information can be read from the tape, while extremely fast compared to manual operations, is yet very slow in comparison to the computing speed of such computers. Also, it is time-consuming to search for information stored on a long tape. Another disadvantage is that paper tape, unlike magnetic tape, is not erasable. Nevertheless, punched tape fulfils a necessary and important storage function in those devices for which it is adapted.

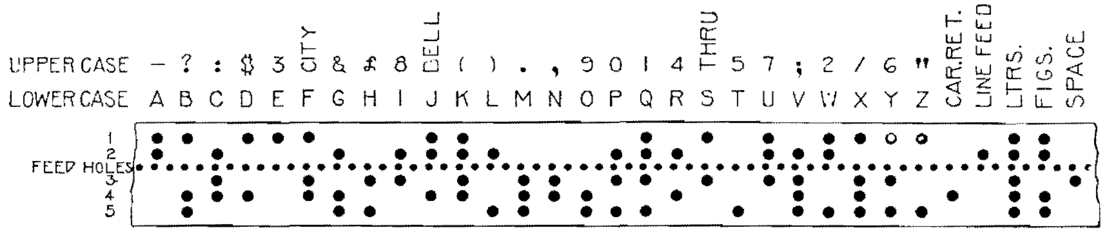
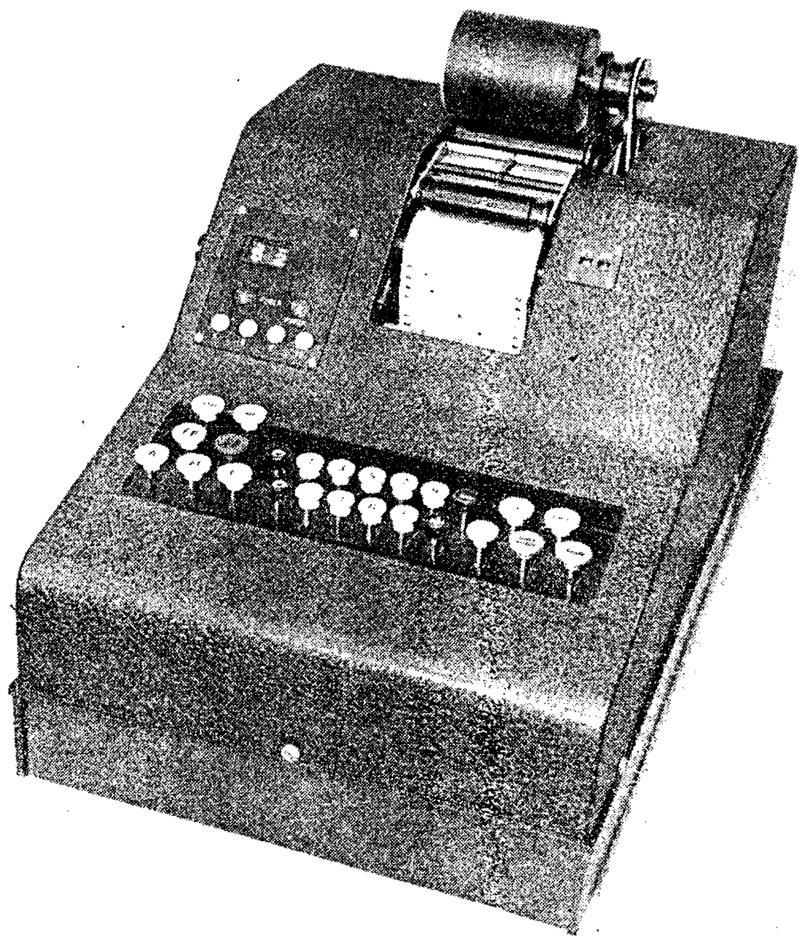


Fig. 4 Ref. 38, p. 3, sect. 4.

Fig. 6 Telegraphic Tape Code



M. I. T. Photo

Special tape punch used for preparing the A-, B-, and C-tapes. These tapes control the interconnections of the machine as called for by the equation to be solved, establish the proper scale factors, and adjust the analyzer for the correct initial conditions, respectively. Ref. 78, p. 34.

Fig. 7 Differential Analyser Tape Punch

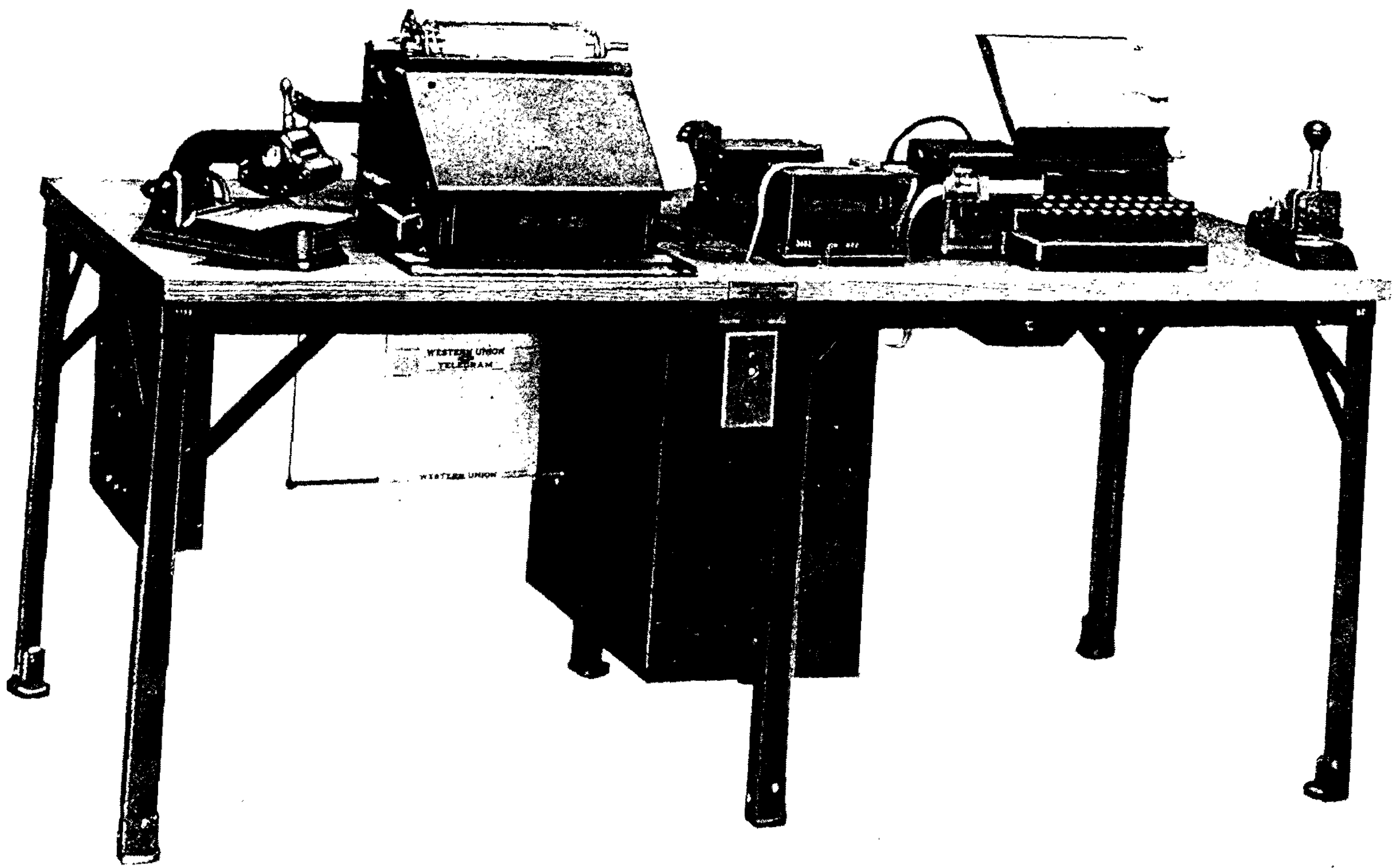


Fig. 6

Ref. 28, p. 5, Sect. 7.

Fig. 8 Telegraphic Sending and Recieving Installation

b. Moving and Fixed Cards

Punched cards represent another relatively old method of storing information. Unlike paper tape, cards have the advantage that they may be permuted; this property makes it possible to group and select, out of a much larger number of cards, those cards having common informational characteristics, and so is valuable for tabulating data.

Falcon, in 1728, was one of the first to use punched cards for informational storage, applying them to the control of weaving patterns.[30] It was an English inventor, Charles Babbage, who first proposed the application of punched cards to automatic computers, however.[32] In the 1830's, Babbage conceived the idea of his "analytical engine," the first automatic computer. He planned to use cards similar to those employed in the Jacquard loom and originally developed by Falcon. Several decks of cards were to be used both to store partial results and to control the sequence of machine operations. This idea of sequence control, originated by Babbage, is fundamental to all modern arithmetical computers and so was an important milestone in the struggle to minimize unnecessary mental labor. Unfortunately, the analytical engine itself was never completed because of lack of funds and the inadequate development of the machine tool industry at that time.

Dr. Hermann Hollerith, a noted statistician engaged by the United States Government during the census of 1880, made one of the most important advances in the computational application of punched cards.[41,42] He noted that some mechanical means of speeding up the transcription and tabulation of the vast amount of data obtained by the census would be highly desirable. Especially would some such device be necessary by the census of 1890 because of the rapid rate of population increase of that period. Hollerith finally decided to transcribe the census information on paper strips by means of punched holes in place of written numbers or yes-no questions. Each question on the census was assigned a definite position on the paper strip, and by punching the holes within this position in a proper manner, the answer to the question could be uniquely indicated. Dr. Hollerith developed mechanical accounting and tabulating machines to work in conjunction with the paper strips or cards; and it was found that information could be transcribed three-fourths faster and could be tabulated eight times faster using this machinery than by the best previous method. The punched card system was used with great success in the census of 1890.

Since Hollerith's pioneer work, considerable electric apparatus has been developed to carry out operations with punched cards and has added materially to the speed and versatility of the punched card storage method. The International Business Machines Corporation (IBM) has been instrumental in the development of modern punched card equipment, and has aided in the application of punched cards to as diverse problems as astronomy, mathematics, and sociology.[43] Figure 9 shows two

IBM cards, full size, one unpunched and the other completely punched. It will be noted that there are 80 columns and 12 rows, making a total of 960 possible punching positions. Information is recorded on the cards by means of a keyboard-operated magnetic punch. The first ten rows of each card are given decimal designations so that numbers can be explicitly represented. The closing of an electrical circuit at a definite time and at a definite fixed position on the card is the basis upon which the various electrical accounting machines function. In the card reader (Fig. 10), the cards pass under brush contacts which permit an electrical impulse to be made through the card at the position of the punched hole. Unlike punched tape, however, cards cannot easily be moved forwards and backwards.

In several computers, moving punched cards are used instead of tape to supply input data, and in some instances to augment the internal storage of the machine.[3[illegible],44] Recently, there has been some consideration of the possibility of using fixed punched cards to supply input data for computers.[45,46] In the application of moving cards to high-speed computers, where data is needed very quickly, there are serious difficulties of acceleration and control of the initially-at-rest cards. Also, moving cards are not well adapted to situations where the data may be required in a sequence that is non-monotone with respect to the initial order of the cards. For a finite external storage capacity, both of these difficulties may be obviated through the use of fixed cards. Each card is punched with the proper

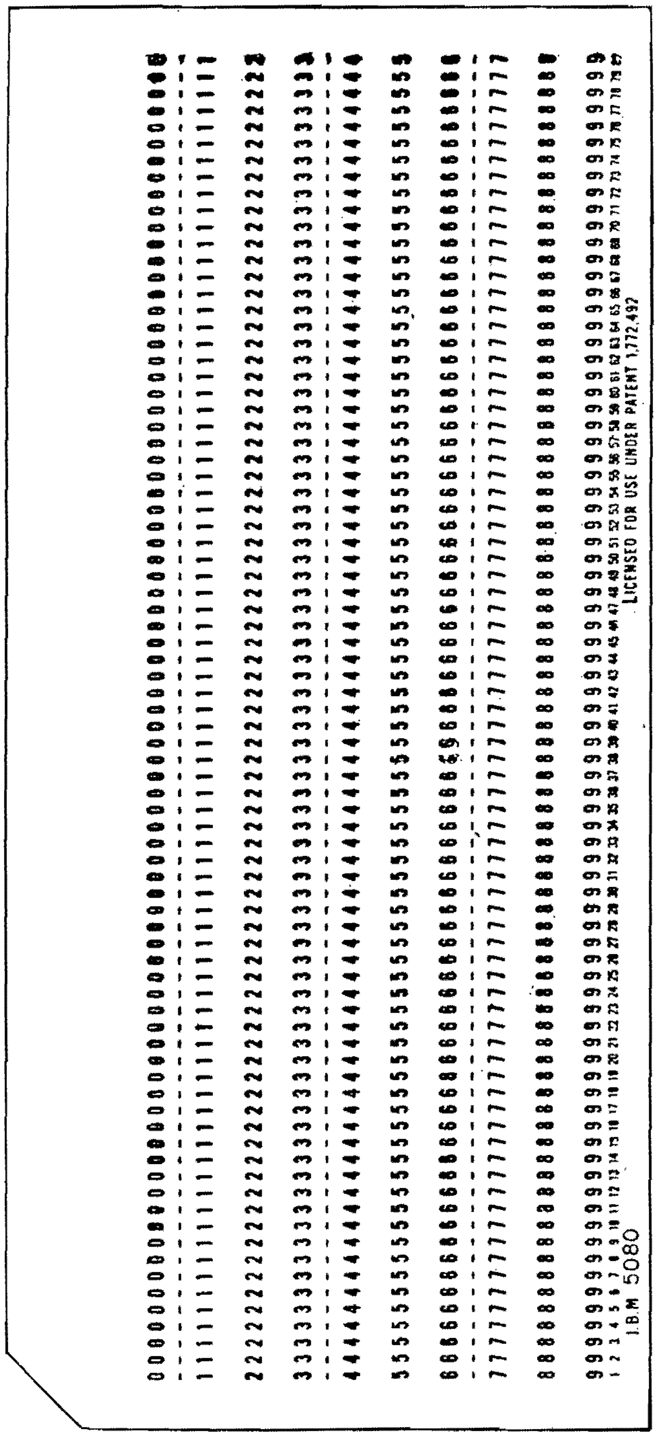


FIG. 1

A blank tabulating card; Ref. 42, p. 3.

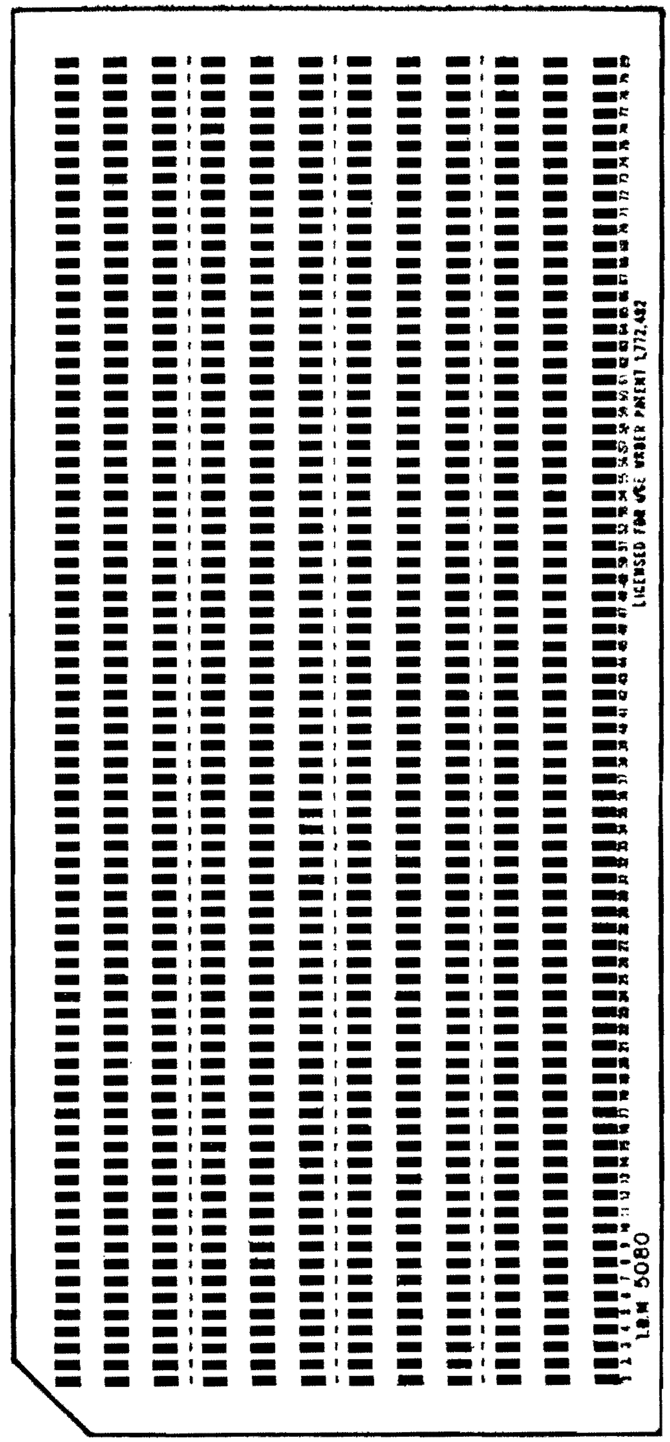


FIG. 2

An 80 col. tabulating card, fully punched, Ref. 42, p.5.

Fig. 9 IBM Tabulating Cards

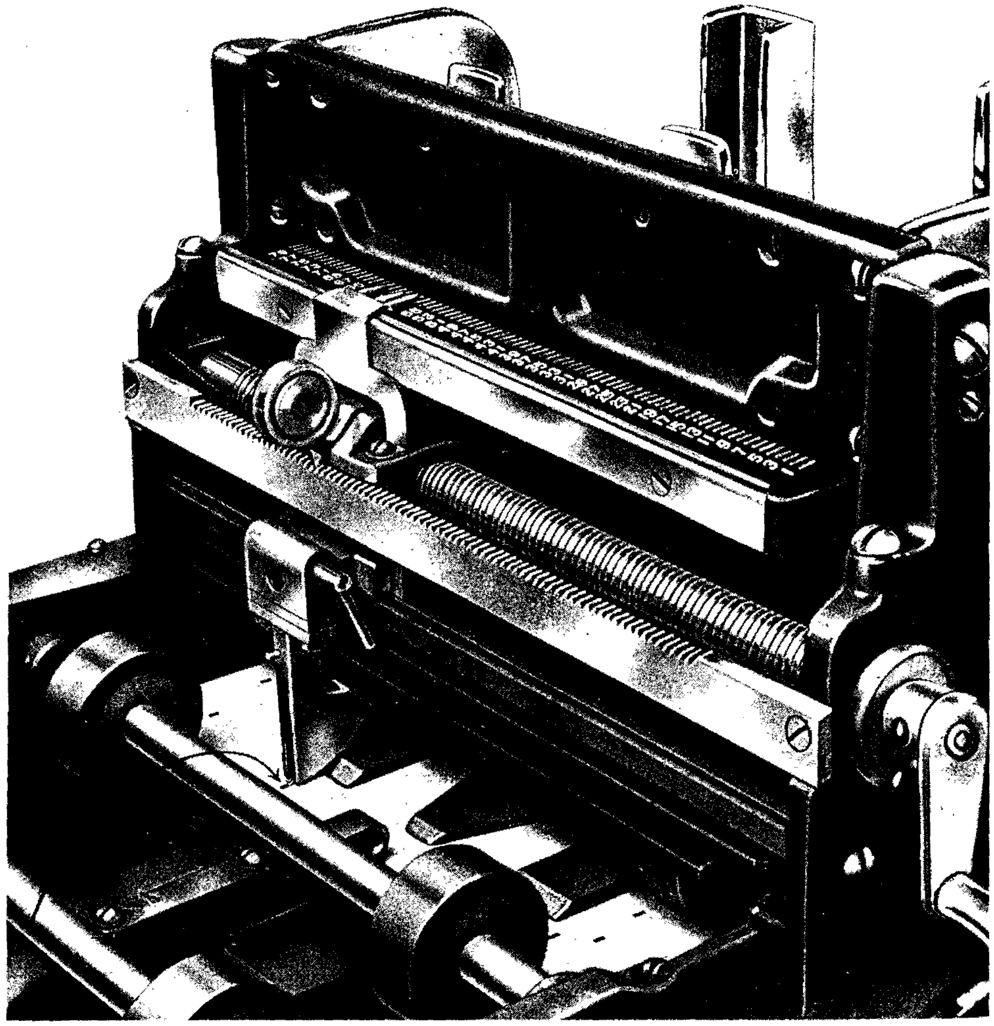


Fig. 5

THE OPERATING PRINCIPLE OF THE PUNCHED CARD METHOD (HOLLERITH PATENTS)

A tabulating card, acting as an insulator, passes between a wire brush and a brass roller.* A hole punched into the card causes the brush and the brass plate to make contact (see arrow Fig. 5) and closes an electric circuit which, in turn, actuates an electro-magnet. In the case of the sorting machine (illustrated) this magnet opens a chute along which the card slides until it falls into the proper receptacle.

In the tabulating and accounting machines a row of brushes, corresponding to the columns of the card, takes the place of the single brush shown above. The contacts, similarly made, energize counters or print banks.

In either case, the classification to be made, the values to be added or subtracted, or the letters to be printed, are determined by the position of the card at the time the contact is made.

* The contact roller is not visible here, being completely covered by the tabulating card (see page 41).

Fig. 10 Card Reader (Sorting Machine) Ref. 48, p. 10.

information and placed in position before a bank of photocells or photoelectric tubes. When it is desired to read a given number (which is assumed to fill an entire line on the card) from the card, a light source behind it is pulsed, and light, shining through the holes in the card, strikes the bank of photocells. Only the particular line of photocells that corresponds to the desired line on the card is energized, and hence an output is derived which represents only that single line. The system has not been fully developed, but it is theoretically sound and may yet be of value as a computational storage method.

c. Film and Magnetic Storage

The use of film and magnetic storage techniques for transferring data into and from a computer allows several unique advantages, not shared by punched cards or tape, to be obtained. As yet, there are no operating computers using these methods of external storage, but they are to be used in several projected machines.

Photoemulsion-coated film will be used only for storage of input data and command sequences, since it is non-erasable and requires a relatively long processing time.[47] Important in this connection is the new photographic process recently announced by E.H. Land of the Polaroid Company.[48] In Land's system, a dry print and negative can be produced within fifty seconds after exposure. There is every reason to suppose that, with the proper application of this method, photographic control tapes, ready for use, can be produced as quickly as an operator can record data on the film from a number keyboard. When such speed has been achieved, film will be the equal of punched tape in this respect.

In order to make full use of the capabilities of film, it will be necessary to record a large number of signals per unit length. Optical sensing and recording, unlike mechanical, allows the resolution of an extremely large number of small, closely-spaced signals. Thus, on 35 millimeter film, perhaps 50 channels could be recorded across the width of the film and 100 such rows recorded per inch of length. Data obtained from the Eastman Kodak Company indicates that the recorded signals, consisting of oblong spots on the film, must be greater than 25×10^{-6} square inches in area for reliable reading.[47] It is interesting to note that a film used to store numbers in this fashion is nothing more or less than a microfilm record; therefore, many of the well-developed recording and reading microfilm lens systems may be used almost unchanged. Recording of numbers might be accomplished either by means of gas-discharge or cathode-ray tubes, and reading, with a bank of photo-tubes, as in the fixed-card reader.

The speed with which numbers might be introduced into a computer with this film storage method would be primarily limited by the linear speed of the film, assuming that the minimum spot size could not be reduced. With 50 channels and 100 rows per inch, almost 100,000 yes-no signals a second could be read out at the usual film speed of 18 inches/second. This rate of input data transmission is adequate for any currently-considered computer.

Another film storage technique now under development uses light-sensitive phosphors in place of photoemulsion. The Eastman Kodak Company hopes to be able to develop a composite phosphor coating which can be raised to an excited metastable energy level by ultra-violet light in less than a millisecond, and can be read by exposure to infra-red radiation, which causes visible light to be emitted.[47] This system would have the advantage that recording could be carried out at the same speed as reading, and the record would be erasable; thus, it would be valuable for supplemental storage of partial results when the internal storage of the computer was filled. There are still many technical problems to surmount, however, before phosphor coated film will be useful for computational storage.

Magnetic wire and tape are two other storage media which may be used for the external storage of both input data and partial results.[49] Initial preparation of wire or tape records can be conveniently carried out with a manual number keyboard or special typewriter. Magnetic tape, rather than wire, will doubtless be used in those applications where very high speed is necessary, because multiple channels can be recorded on it. It will probably be practical to record a channel for every ten mils of tape width; with such separation, 40 or 50 channels could be placed on a half-inch tape. Since running the tape at a speed of ten feet/second allows an effective frequency response of over 25,000 cycles/second to be obtained, it should be possible to record a pulse on each channel every 40 microseconds. In this fashion, over 1,000,000 pulses a second could be transmitted to or from the magnetic tape.

Magnetic wire, being less bulky than tape, will be useful for slower speed applications. At a wire speed of ten feet/second, more than 200 pulses per linear inch of wire can be recorded. Thus, 12,000 feet of wire, weighing about one-half a pound, wound on a spool four inches in diameter and one inch wide, would store as many yes-no signals as could 30,000 80-column tabulating cards, completely filled. The saving in bulk and weight is self-evident. In addition, wire and tape are much easier to handle than cards; recording and reading are much more convenient and faster; and the materials are reversible and erasible. Although it is not obvious that sorting and cross-plotting of data stored on magnetic materials could be easily accomplished, it is actually true that these operations could be carried out in response to commands from the computer itself at a much higher speed than that possible by any existant card-handling machines.

Internal Storage

a. Mechanical Registers

A storage register may be defined as a group of discrete storage elements, each of which is capable of storing only one digit. The entire register is thus able to store a complete many-digit number. Such a number is arbitrarily called a "word" when it is used for computational purposes and represents the number with which calculations are normally carried out in the computer.

Registers are the most expensive type of storage available because it is necessary to use an individual storage element for each digit of each word stored. Some computers use registers as their only type of internal storage, but because of the high cost and large amount of space needed to secure storage of many words, such computers must have a very limited internal storage capacity. In addition to these types of computers, all computers use a small number of storage registers to augment their normal internal storage. Since registers may be set slowly and read quickly, these auxiliary registers are used to bridge the gap between the slow reading and recording rates of external storage media and the higher operation speeds of the machine. Thus, a word may be read out from the external storage to the register and held until the exact moment it is needed in the sequence of operations. Conversely, a final or partial result transmitted from the computer at high speed may be held on a register during the time necessary to record it on the external storage medium. Such use of registers allows the internal operation of the computer to be greatly speeded up.

The use of registers, however, did not originate with modern computers. Many types of registers, developed for other purposes, have recently been adapted for computer use. The earliest kind of storage register was purely mechanical, consisting, in its simplest form, of a number of wheels or gears with the decimal digits inscribed on their circumferences. This type of register was used in the first calculator, invented by Blaise Pascal in 1643 (see Fig. 11).[30] There were, however, many aids to calculation before the Pascal machine. These aids used storage of a kind, in that they represented numbers by the positions of discrete physical objects, such as the beads of an abacus. This use of easily manipulated material objects, be they beads, pebbles, or knots on a string, enabled the operator to see his calculation while at the same time he thought it out.

The advance made possible by mechanical calculators was to eliminate the need for the operator to carry out the problem himself; after setting up the data on the number registers, he let the machine produce the required result. Charles Babbage, in the early part of the nineteenth century, realized that it was possible to carry the process one step further: storage could be utilized to eliminate the human operator completely, and the solution of complicated problems carried out automatically through the use of a predetermined, stored sequence of orders to control the successive operations of a calculator. This basic idea has made possible all modern large-scale digital computers. Therefore, a computer may be distinguished from a calculator by its ability to carry out automaticlly a succession of simple mathematical operations like addition and

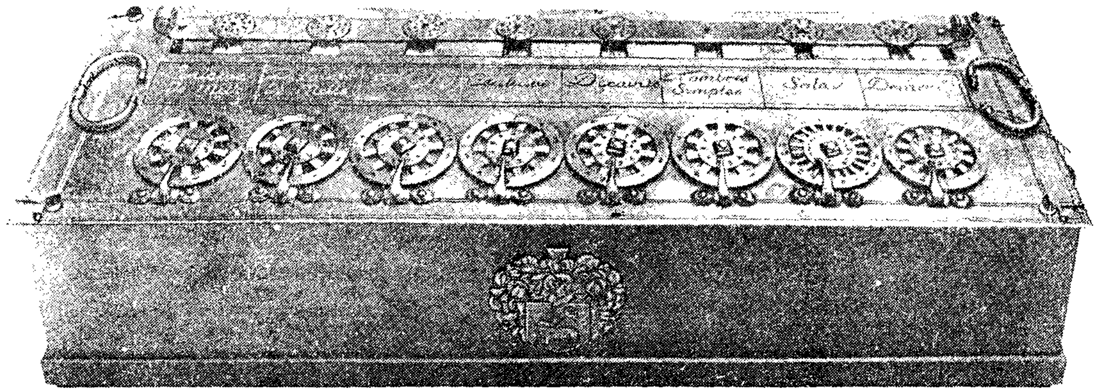
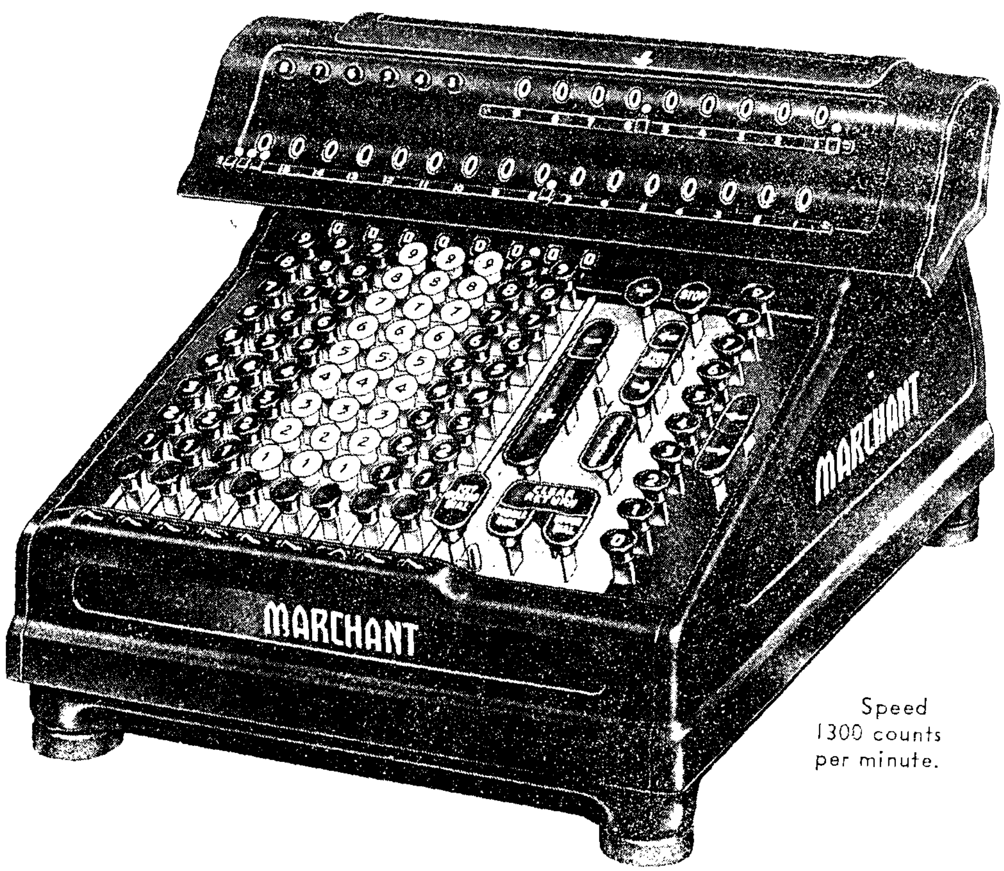


Figure 1 Ref. 50, p. 10.

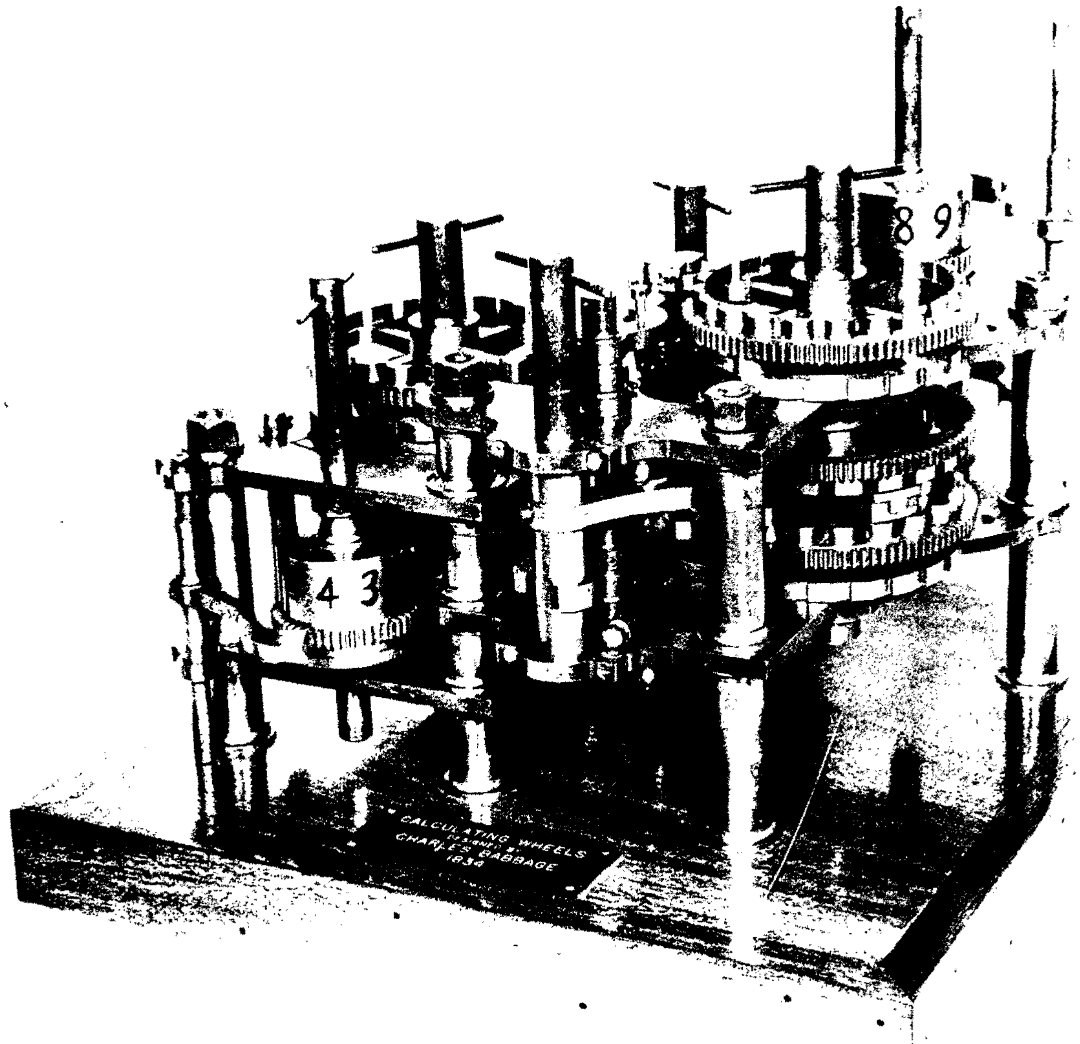
Pascal Calculator



Speed
1300 counts
per minute.

Fig. 11 Old and New Calculating Machines multiplication, whereas only one such operation is performed automatically by a calculator.

Babbage's projected analytical engine was designed to store numbers on a large quantity of mechanical registers. These registers, called the "store," were to consist of a vast array of wheels with inscribed digits. A small portion of the wheels to have been used by Babbage is shown in figure 12. The analytical engine was originally designed to have a store capable of containing a 1000 50-digit numbers, but the machine was never completed. Mechanical storage registers probably reached their highest point of development in the Babbage machine and have been replaced in modern computational applications by different kinds of electro-mechanical registers.



I Calculating Wheels designed by Charles Babbage

Fig. 10 Ref. 32, opposite p. 1.

b. Electro-Mechanical Registers

Some of the earliest work on electro-mechanical registers was carried on in connection with the development of automatic telephone exchanges.[51,52,53] The Western Electric Company began work on the Rotary automatic system in 1899. This type of exchance was developed to a commercial point in 1910, and a test installation set up in New York City. Unlike the Step-by-Step automatic system (also known as the Strowger system), rotary exchanges employ storage of the dialled digits received from calling telephones. Each digit of the dialled number is stored in an individual electro-mechanical counter. The group of counters necessary to store the complete number is actually a storage register, but in telephone work each individual counter is termed a "register", as well as the totality of counters which go to make up a register proper. Two stages in the development of telephone "registers" are shown in Figure 16. The picture at bottom right shows a modern rotary-register installation with associated relay equipment.

In operation, the magnetic clutch at the bottom of the counter is engaged for each incoming impulse of a dialled digit. Thus, each impulse causes the center spindle to rotate one position and with it attached ebonite cams (see picture at bottom left). These cams are constructed with circumferential projections which can engage switch contacts, so that a given rotation of the spindle causes certain connections to be made and broken. There are actually [illegible] positions in a complete rotation, but a cycle of operation is performed in a

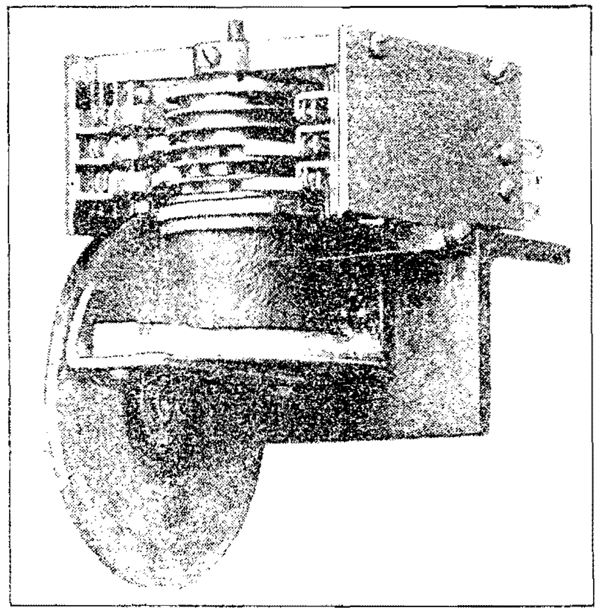


Fig. 107.—Number register (full automatic)

About 1912 Ref. 51, p. 258.

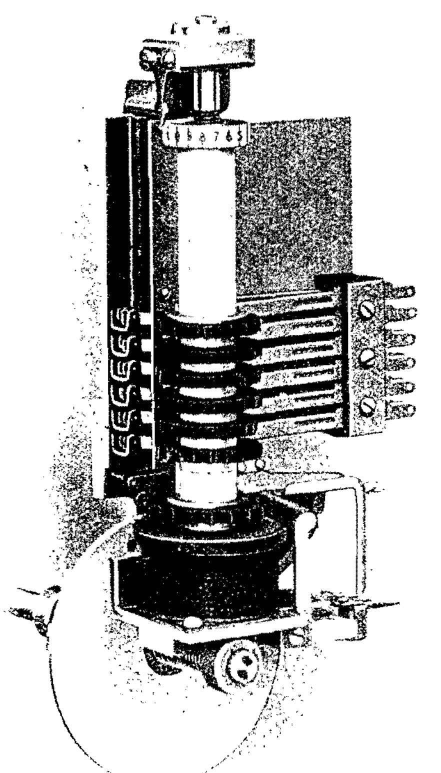


Fig. 91. Rotary System Register.

About 1920 Ref. 52, p. 122.

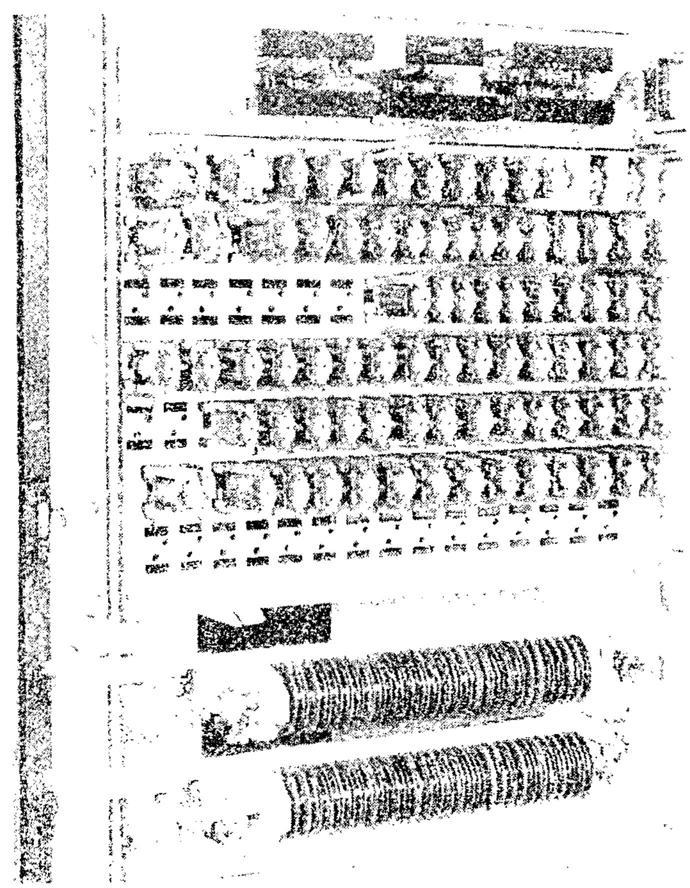


Fig. 351. Register

Modern Register Installation Ref. 53, p. 590.

Fig. 13 Telephone Counters and Register

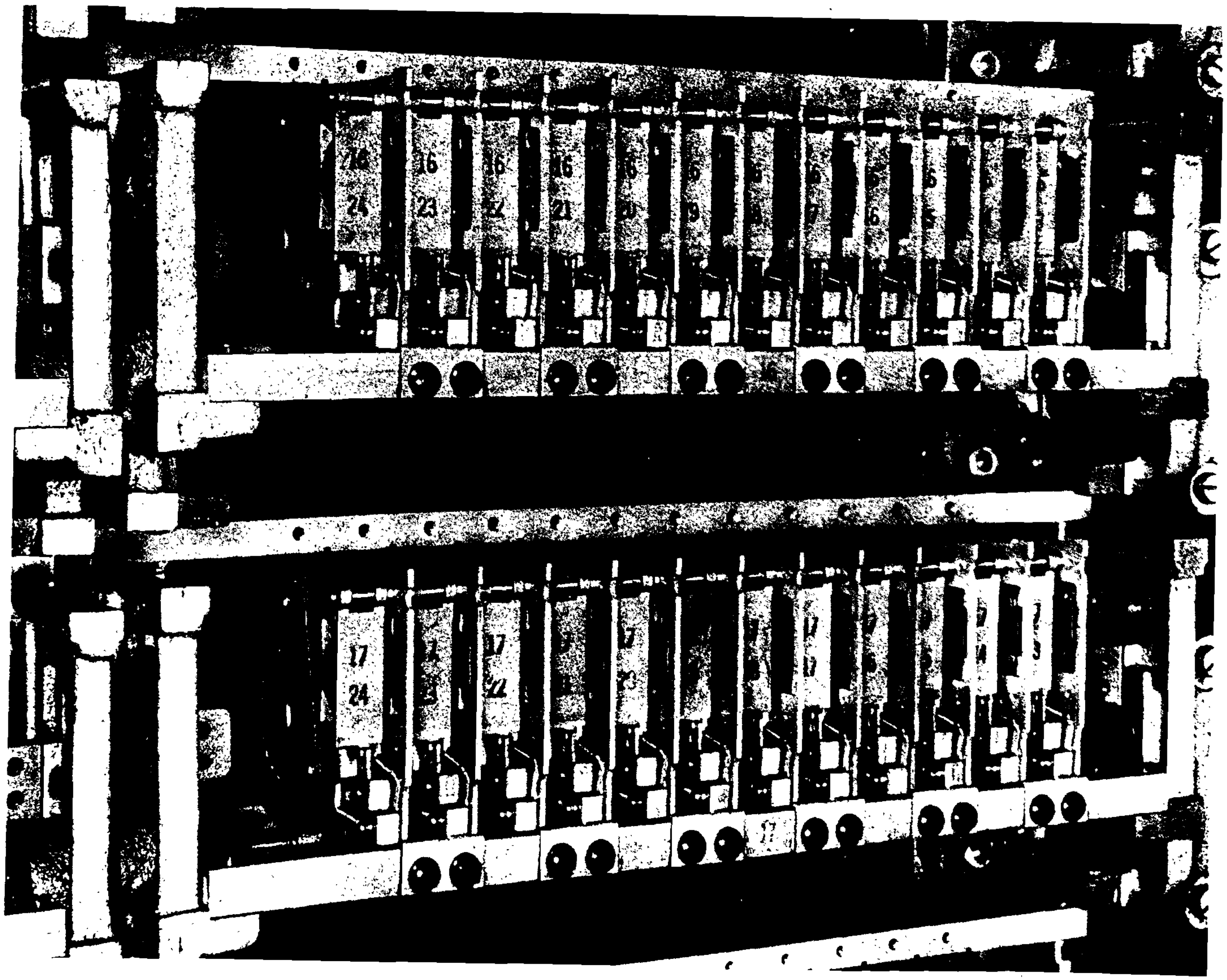
half-revolution. An incoming digit is recorded in the counter when the spindle has turned through a number of positions equal to the number of impulses sent in. This number is often the complement of the dialled digit; thus, for the number four, six impulses are sent, and the spindle moves through six positions. When the digit is read out of storage, the spindle moves forward to zero through the succeeding positions, and thus transmits the original digit dialled. The individual counters need not wait until all the digits of the telephone number have been dialled before sending out preceding digits: as soon as one counter has received the first digit, it may be read out, thereby speeding up the operation of the system. The use of registers in automatic telephony is valuable because it allows both rapid dialling and storage of the dialled digits until the seeking switch has found the required connections.

Electro-mechanical registers are also of great value in speeding up the operation of modern electric-drive calculating machines. In such applications, the individual wheels of the register are turned electrically in response to finger-tip pressure on the keys. Such a modern calculator presents a tremendous contrast to the early Pascal machine (see Fig. 11).

The Harvard Automatic-Sequence-Controlled Calculator uses electro-mechanical registers as its main type of internal storage.[32,54] This machine is a modern electrical counterpart of Babbage's original analytical engine, with electro-mechanical registers replacing the mechanically-controlled wheels of the Babbage machine. Each register consists of a group of 24 counters, one for each of 23 decimal digits and one for algebraic sign. Portions of two registers are shown in Figure 14. A partially exploded view of an individual counter may be seen in Figure 15. The counter is composed of a commutator having ten segmental contacts numbered from zero to nine and a half slip ring, a pair of rotatable brushes that can connect the slip ring to one of the contacts, a continuously rotating wheel, and a magnetic clutch to couple the brush mounting to the wheel at the proper time.

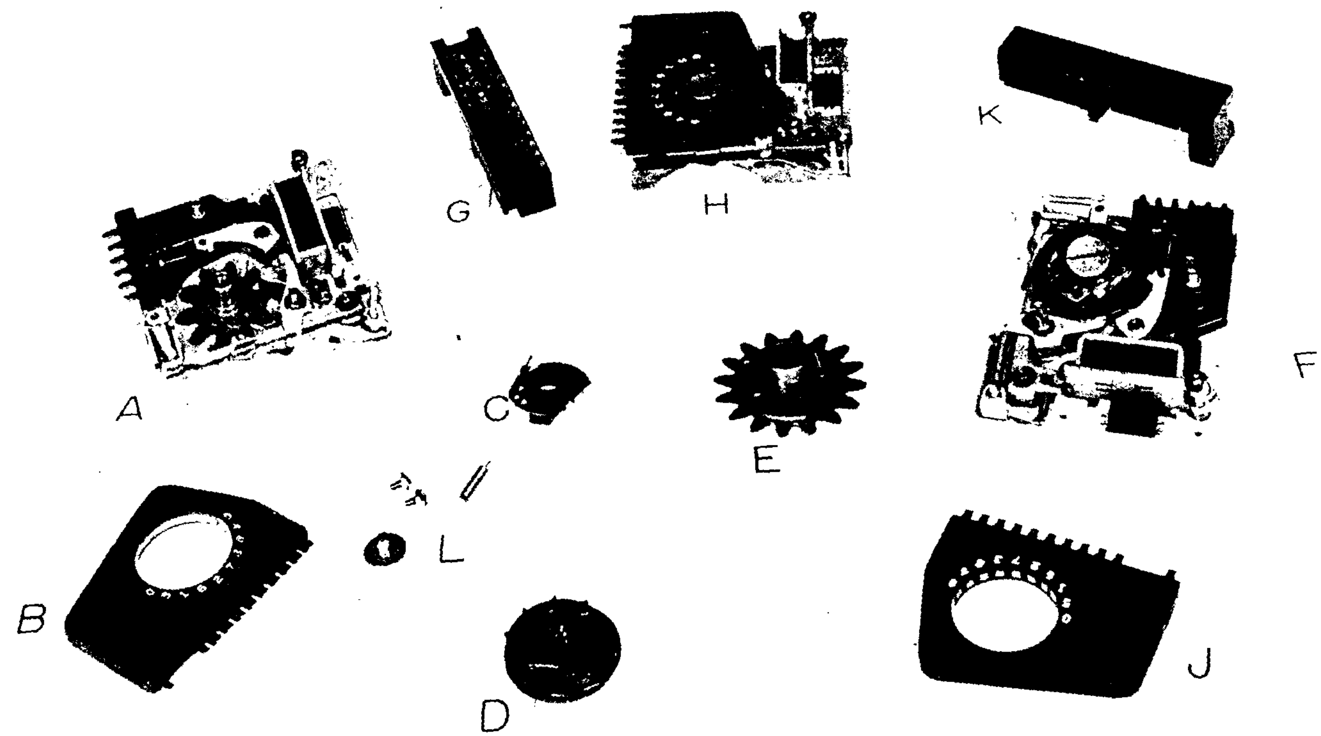
Unlike telephone registers, which are only used to hold numbers, the registers of the Harvard machine are designed to accumulate as well as store. Consequently, a number sent to a register which is already holding another number will be added to the original number. This function requires a more complicated counter structure than that necessary in telephone counters, since provision must be made for "carry" when the counter wheel passes through ten. Also, numbers are introduced into the counters in a different way: each decimal digit is represented by a single pulse of length proportional to the magnitude of the digit, instead of by a series of pulses. During the pulse, the magnetic clutch engages the counter wheel, so that the rotation of the wheel is proportional to the pulse length. Since the amount of rotation is not dependent upon the initial position of the wheel, any number introduced into the counter will be added to whatever number is already stored therein.

Relays, rather than counter wheels, may also be used to form electro-mechanical registers. Several modern computers use relay



IX Storage Counters

Fig. 14 Ref. 32, opposite p. 17.



XVII Storage Counter

Fig. 16 Ref. 32, opposite p. 55

registers as their only internal storage system; others use such registers to hold numbers during their transmission into and from the machine at slow speed. Any two-position relay can function as a storage device, since, when closed, it represents the storage of the impulse that caused it to close. Locking relays are used in relay registers so that each relay will energize its own holding magnet upon closing and therefore remain closed after the original impulse is over. If decimal digits are to be stored, several relays must be used for each digit, since there must be ten possible on-off configurations. Each set of relays counts the number of incoming impulses, and the final on-off condition of the group represents the stored digit. Relay registers were first developed for telephone applications and are slowly replacing rotary registers in storage-type automatic exchanges.[56] They are well adapted for intermediate use in relatively high speed computers, but their size and cost prohibit their use for obtaining large amounts of internal storage.

B. HIGH SPEED STORAGE

Discrete Media

a. Vacuum-Tube Registers

The specific registers discussed thus far have been alike in having ten distinct states possible in each separate storage element or counter. These ten states corresponded to the decimal digits from zero to nine. However, computational numbers, or words, can often be advantageously represented by other than decimal number systems in which each decimal digit of the word is itself represented as a series of zeros and ones. Such a representation allows all types of registers to be both simpler and faster, but it is particularly valuable for vacuum-tube registers. If ten separate states are to be distinguished in a vacuum-tube circuit, it is possible to use either ten tubes or ten different operating conditions in a single tube. The first possibility is employed in "ring-of-ten" vacuum-tube counters, but the second is never used in computational applications. Because of change in operating conditions and tube characteristics, it is not at present possible to design a vacuum-tube circuit with which ten distinct operating conditions can be consistently distinguished. On the other hand, it is quite possible to use vacuum tubes solely as on-off elements, so that correct operation can be assured with almost absolute accuracy.

There are several non-decimal number codes in use in modern computers. The "binary" system is the most used in computational work for several reasons. In this system, a number base of two instead of ten is used, and there are thus only two digits, one and zero. All larger numbers are represented by combinations of ones and zeros: two is written 10, three as 11, four as 100, five as 101, and so on. The use of such a system requires about 3.3 times as many individual digits to represent a given many-place number as required in the decimal system. Although input and output numbers usually must be converted from decimal to binary and from binary to decimal respectively, the use of the binary system in an electronic computer to allow on-off operation of its vacuum tubes is so important that the conversion problem is trivial in comparison. Two other codes sometimes used are the coded-decimal and the bi-quinary systems. Both systems represent each decimal digit as a combination of four binary digits. Using such a method of coding, a ten-digit decimal number requires 40 binary digits for its representation. On the other hand, in the true binary system, only 34 binary digits are necessary to represent the same number. Since each digit that must be carried in a computation involves considerable extra equipment, the binary system is the most economical of apparatus.

"Trigger pairs", or "flip-flop" circuits, are the individual storage elements in vacuum-tube registers. Such circuits have two states of stable equilibrium; thus, one state can represent a one, and the other, a zero. Two tubes are used and are so connected that an input pulse or trigger will cause the "on" condition to transfer from one tube to the other. The Eccles-Jordan trigger circuit, invented by W.H. Eccles and F.W. Jordan in 1919, still forms the basis for almost all types of flip-flop storage circuits.[56] It has been considerably improved since that time, but the basic form of the circuit has remained virtually unchanged (see Fig. 16). An interesting modification of the Eccles-Jordan circuit was made by H.J. Reich in 1938.[57] In Reich's circuit, pentodes are used in place of triodes, and the necessary feedback between tubes is obtained by cross-connection between opposite plates and suppressor grids, rather than between plates and signal grids, as in the Eccles-Jordan circuit. Because of this method of interconnection, the circuit responds only to negative input pulses. Earlier flip-flop circuits had achieved this desirable condition by the inclusion of series rectifiers of various types, as in the circuit of Figure 16.

For register applications in high-speed computers, it is important that flip-flop switching time be made as short as possible. Through special design precautions, both triode and pentode flip-flop circuits can be built with a switching time of less than 0.2 microseconds, but pentode circuits are somewhat the faster. Figure 16 represents a simplified triode flip-flop circuit for use in a storage register. As in electro-mechanical registers, the inclusion of a carry circuit between the individual elements of the register allows it to add and therefore to function as an accumulator as well as a register. If the binary system is used, addition is particularly simple. One plus one is zero and a carry-over of a one to the next digit place, and one and zero is one with no carry. Therefore, the carry circuit between adjoining flip-flops need only be a single connection, such that a carry pulse is transmitted when the flip-flop switches from the "one" to the "zero" condition, but no pulse is transmitted when the switching is from zero to one. In the circuit shown, a one is arbitrarily said to be stored when tube V_1 is on and V_2 off, and a zero stored when V_1 is off and V_2 on; hence, the presence of a one is detected as a low potential at the plate of V_1. A negative pulse at "Trigger" switches the flip-flop to its other state of equilibrium, no matter whether a one or a zero was initially stored. A negative pulse at "Set" always clears the flip-flop, leaving it with a zero stored, while a negative pulse input to "Reset" leaves it with a one stored. The set and reset connections are used for clearing and to provide carry inputs between adjacent elements of the register if it is used as an accumulator. A word is added into whatever is already in the accumulator by applying the individual digit pulses of the word to the trigger inputs of corresponding flip-flops.

In the past twenty years, the principal work on trigger circuits has been carried on in an effort to meet the needs of high-speed counting. Particularly have high-speed counting devices been desired for the counting of very rapid impulses from Geiger-Müller chambers used to detect radiation and charged particles. The usefulness of the trigger circuit in such applications

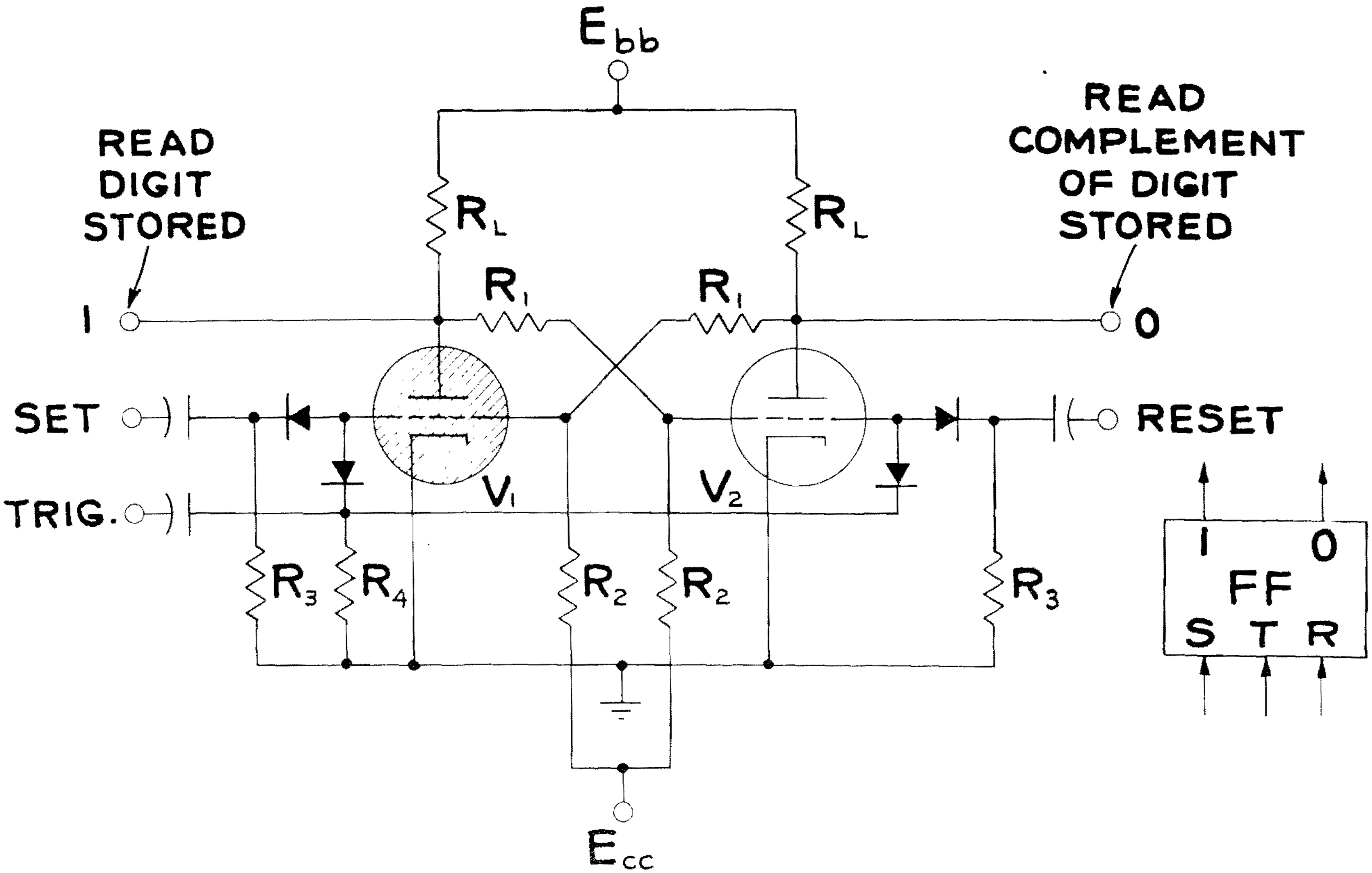


Fig. 16 Triode Flip-Flop Circuit

stems from its production of one output pulse of a given polarity for every two input pulses. By connecting a chain of flip-flops together, relatively large counting-down ratios can be easily achieved. Although the initial pulses may occur too rapidly to be counted by a mechanical device, the use of a chain of flip-flops will reduce the pulse occurrence rate to such a value that mechanical counters can be employed. C.E. Wynn-Williams first used thyratrons in 1931 to produce a five-to-one counting-down ratio, but it was not until 1937 that W.B. Lewis adapted the Eccles-Jordan circuit for counting purposes and produced the first vacuum-tube counting circuit.[58,59]

One of the most important types of counting circuit for storage applications is the ring-of-ten, or decade, counter. There are ten distinct storage elements in such a circuit, connected together to form a ring. Since only one element of the ring is activated at a given time, there are ten possible storage configurations. If a series of pulses is applied to the input of the ring, each pulse causes the activation to be transferred from one element to the next succeeding. In this manner, the device actually counts the incoming pulses, and produces an output for every tenth pulse. Triode flip-flop ring counters are used as storage accumulators in the Electronic Numerical Integrator and Computer (ENIAC) designed at the University of Pennsylvania.[44] The decimal system is used in this computer, making decimal counters a necessity. Since a separate counter is necessary for each decimal digit of a word, a large number of vacuum tubes is required for adequate storage capacity. Ten tubes are used to store each decimal digit, whereas only three or four tubes are necessary to store the same digit when coded in the binary system. And, although ring counters are much faster than electro-mechanical counters, they are much slower than binary counters. In the flip-flop register, only the on-off condition must be changed in registering a word, while a number of digits equal to the decimal digit to be stored must be applied in temporal sequence to the ring to set it. Consequently, recording may take nine times longer for a decimal than for a binary counter.

Continuous Media

a. Transmission Lines

Transmission lines of various types have long been used for transmitting information or power from place to place, but it has only been recently that they have been employed to store information explicitly. Since it takes a finite length of time for a signal to travel from one end of a transmission line to the other, the signal may be thought of as being stored on the line during the time it is in transit. In ordinary usage, the spatial extension of a transmission line is utilized to transport quantities from one location to another, and the delay introduced by the line is considered an unavoidable by-product. For storage applications, in contradistinction, a large delay is desirable, and the bulk of the line is undesirable.

Electric transmission lines have not thus far been used for signal storage because their extremely high velocity of propagation ~~is extremely high,~~ ~~making~~ makes it impossible to obtain delays of more than a few microseconds in a practical length of line. Through special design, it has been found possible to construct lines which have a delay of about 0.1 microsecond/inch, but this value is close to the maximum now attainable.[60,61] For the storage of computational information, however, delays of the order of 100 to 1000 microseconds are desirable; hence, other media than electric lines are used to obtain them. Nevertheless, electric transmission lines can be used to great advantage in computers to secure exact time coincidence between nearly coincident pulses. Thus, if two pulses of a tenth-microsecond width occur a half microsecond apart, it is possible to delay one of them half a microsecond in an electric line, and so cause them to occur simultaneously at a specified output point. In this fashion, two pulses may be made to operate a coincidence device such as a "gate tube" which will generate an output only when two simultaneous signals are applied to it.

A much more important application of transmission lines is that which makes use of acoustic rather than all-electric lines. In these lines, the information to be stored, which occurs as a sequence of electric pulses in definite temporal sequence, is used to modulate a continuous wave oscillator of ultrasonic frequency (usually 10 to 15 megacycles/second). The modulated output of this oscillator drives a piezo-electric crystal in intimate contact with a solid or liquid material. This crystal is designated the transmitter and converts the electric oscillations into supersonic waves which propagate through the material with the velocity of sound in that medium. At the other end of the line is a receiving crystal which converts the sound waves back into electric oscillations. During the time of transmission of information through the line, the information is actually stored continuously on the line in a series of compression waves moving through the medium. Because the speed of sound is so much smaller than the velocity of signals on electric transmission lines, large delays can be obtained in relatively short lengths of acoustic lines.

During the war, the British developed an acoustic delay line using water as the delay element for use in connection with moving target selectors for radar scopes. Mercury-filled delay lines were used in 1942 at the Moore School of Electrical Engineering of the University of Pennsylvania as accurate timing devices and in 1944 were adapted for computational storage.[62] However, the actual credit for the many individual stages of development of the acoustic delay line and other storage devices still to be discussed cannot be properly assigned at present because of both the recency of such developments and the recency of the war.

In the computational storage of information in a delay line, it is often desirable to store the information for more than one transit time of the line. Such storage is accomplished with the circuit shown in Figure 17. After passing through the delay line once, the stored signal is amplified and reshaped to compensate for attenuation and distortion introduced by the line. The pulses of the signal are also brought into exact temporal coincidence with "clock" pulses in the amplifier. The clock is an oscillator which produces pulses at the repetition rate of the computer; for correct operation, it is necessary that the pulses of the stored signal occur in synchronism with the clock pulses. If it is desired to read out the signal and at the same time store it again, a "read-out" trigger is applied which allows the signal to be transmitted through the right-hand gate tube. Since the central gate tube normally passes pulses, the signal is also transmitted to the driver. It is then used to modulate the supersonic oscillator and is introduced into the line once again. If it is desired to read out the signal without re-storing, a trigger is applied to the "clear" line, preventing the central gate tube from transmitting a signal. To introduce information into the line, a "read-in" trigger is applied to the left-hand gate tube, allowing it to transmit the incoming signal to the driver. The external circuit used with a mercury delay line requires about ten vacuum tubes.

Two conditions are necessary for the delay line feed-back system to function correctly: first, the total gain around the loop from input back to input must be unity; and second, the delay time of the line must closely approximate some multiple of the clock period. The first condition is necessary to keep the stored signals from increasing or decreasing in amplitude as they make successive trips around the system, and the second condition is needed to ensure that pulses which have passed through the line still occur close enough in time to a clock pulse to be brought into synchronism with it.

Solid materials are not often used as the delay element in acoustic delay lines because they have the disadvantage that there are several modes of propagation, each at a different velocity.[63] This disadvantage may be avoided by using a liquid, so that only the longtudinal mode can be propagated. Mercury is most commonly used because it has a low velocity of propagation, and, because of its density, has an acoustic impedance comparable to that of quartz crystals. Most of the attenuation occurs in the

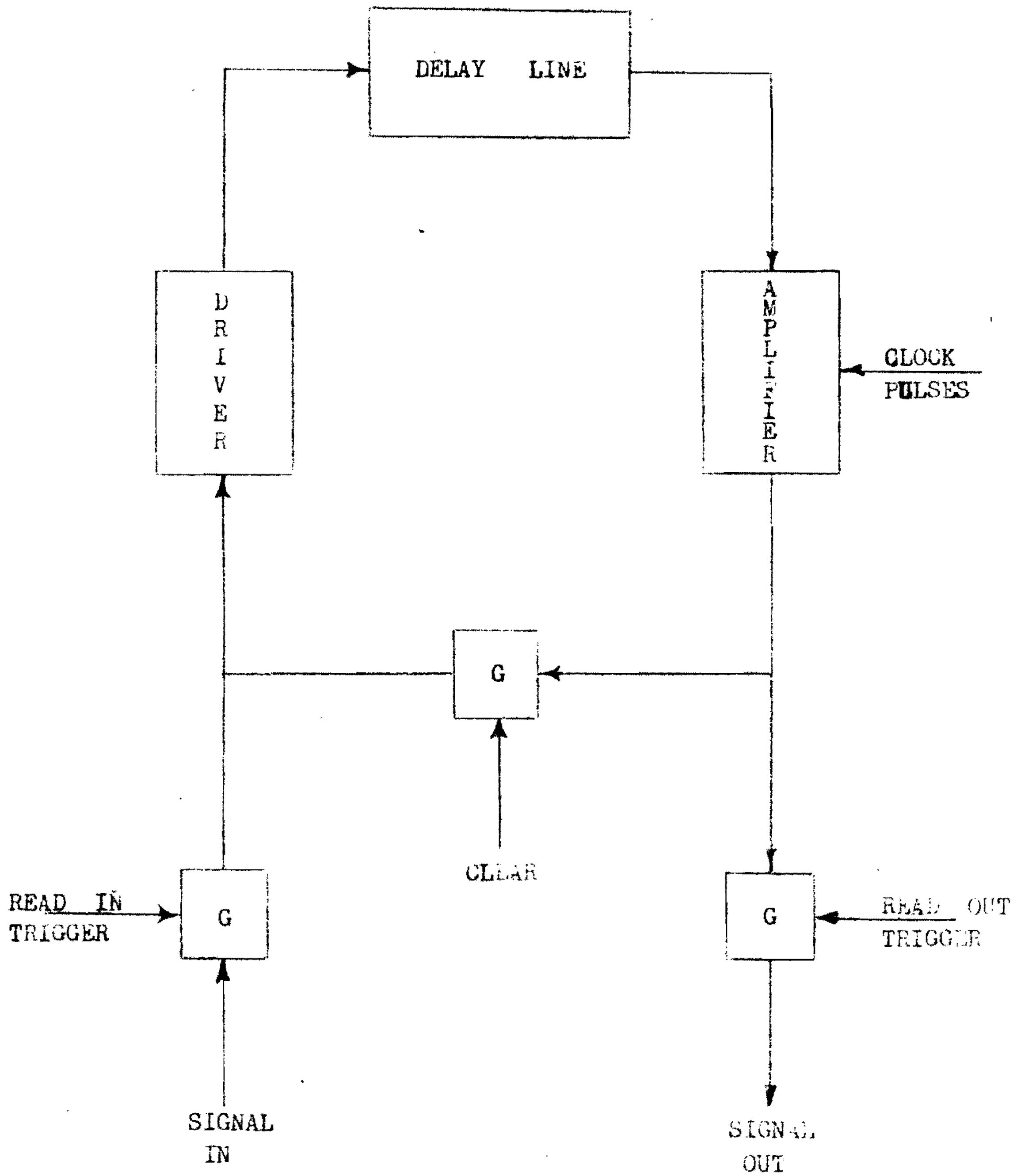


FIGURE 17 DELAY LINE

transmitting and receiving crystals, and so is almost independent of line length.[64] A mercury delay line having a delay of 1000 microseconds is approximately 57 inches long.

One disadvantage of mercury delay lines is the dependence of their delay times upon temperature. The temperature coefficient of mercury is such that the temperature of a 1000 microsecond line must be maintained constant within two-thirds of a centigrade degree to ensure that the delay of the line remain constant to within 0.2 of a microsecond. Thus, there is grave danger of loss of synchronism between stored signals and clock pulses if the temperature is not controlled. During the war, a delay line using multiple sound reflection in a fused-quartz block was developed. Not only does the use of such a delay medium ensure excellent impedance matching between input and output crystals, but also temperature control is unnecessary since the temperature coefficient of quartz is very small.

There is one disadvantage to storage in delay lines which arises from the length of the delay itself. Since as many as 25 40-digit words can be stored in a 1000 microsecond line at the same time, ~~there~~ may be a considerable wait necessary before a given word emerges from the line. Through suitable problem programming, such undesired delays can be made inconsequential in computers using serial digit transmission, but considerable time would be wasted in a high-speed parallel computer (see glossary for definition of serial and parallel transmission). For this reason, other types of storage are used in parallel computers.

b. Rotating Disks

Within the last seven years, there have been several proposals for the use of rotating disks or cylinders coated with a magnetic or light-sensitive material as a possible internal storage method. Separate disks, or multiple channels on a long cylinder, could be used to store a relatively large amount of information compactly. The disks or cylinders would be rotated at high speed in synchronism with the repetition rate of the computer and pulses recorded around their peripheries. Such a method of storage would constitute a serial storage system like the acoustic delay line, because, once a pulse was recorded, it could not be read out until it passed a pickup head.

The use of magnetic storage disks was probably first suggested at the Massachusetts Institute of Technology Center of Analysis, and is described in a 1942 Master's Thesis written by P.O. Crawford, who was working there at the time.[65] Crawford proposed that disks about 20 inches in diameter, rotating at approximately 15 revolutions/second, be used to provide the principal internal storage of a fire-control computer.

Recently, this type of magnetic storage has begun to be developed at Harvard.[66] Tests are being made on several disks 12 inches in diameter, rotated together at 60 revolutions/second by a common shaft. This angular speed corresponds to a linear velocity of almost 200 feet/second. A coded-decimal number system requiring four binary digits for each decimal digit is to be used. It is expected to be possible to store at least ten [illegible]-digit decimal numbers around the circumference of each disk. In order to reduce the maximum delay of 16 2/3 milliseconds caused by the serial nature of the storage system, ten pick-up heads may be used, thereby reducing the delay time to less than two milliseconds. An advantage not shared by other internal storage media is the static nature of magnetic disk storage: no outside agency is required to maintain storage; thus, stored signals remain until erased.

A light-sensitive phosphor coating may be used instead of the magnetic material of the disks. For such an application, the phosphor must have very short activation and decay times, so that a pulse can be erased in the time of travel of a point on the disk between an erasing and a pickup head. As in the case of phosphor-coated film for data input, suitable phosphors have not yet been developed. Both phosphor and magnetic disk storage media have the advantage that a relatively large amount of storage can be achieved at low cost; but difficulties of synchronizing the disk rotation with the computer, and the delay in reading out information, are important disadvantages.

c. Electrostatic Storage Tubes

Electrostatic storage tubes owe much of their development to previous work on cathode ray and iconoscope tubes. There are thus more distinct phases in their history than is the case for some of the other methods of high-speed storage which were either developed during the war, like the mercury delay line, or like the selectron tube, have been begun since the war. Stored information in an electrostatic storage tube is represented by the presence and absence of charge at a large number of small discrete spots on a dielectric or mosaic plate. The storage tube differs principally from the iconoscope tube used in television in that charging of the dielectric storage surface is produced by means of a high-velocity electron beam, instead of photoelectrically with light rays. Nevertheless, it was the iconoscope that first demonstrated that large-scale electrostatic storage was possible and practical.

The iconoscope tube was developed by V.K. Zworykin about 1933 as a device for converting optical images into corresponding electric signals.[67] The tube was not designed as a computational storage device, but it does store the information in the incident light beam for short periods of time. Light, falling upon a mosaic consisting of a large number of small, photoelectric, metallic grains on a dielectric surface, causes the grains to emit electrons in proportion to the light intensity. The individual grains are insulated from one another; therefore, a charge is built up on the surface by the loss of electrons. The potential image created on the plate is a replica of the original optical image. In television use, the potential pattern is converted into electric signals by an electron beam which rapidly scans and discharges the elemental capacitors of the mosaic. An output signal is derived by the capacitative coupling between each mosaic point and a conducting signal plate behind the mosaic surface. The discharge current causes a displacement current through the dielectric, so that the voltage of the signal plate for each point scanned is proportional to the original charge of that point.

The first instance of the use of a mosaic to store and recover a television image produced by a high-velocity electron beam, rather than by photoelectrons, was reported by M. Knoll and F. Schroter in 1937.[68] One of the first reports on the use of the iconoscope primarily as a storage device was that of G. Krawinkel, W. Kronjager, and H. Salow in Germany in 1938.[69] During the war, considerable research work was carried on to adapt the mosaic type storage tube for use as a moving target selector in radar installations, and R. A. McConnell, at the Radiation Laboratory, developed an improved theory of scanning with a moving beam.[70]

There are a number of storage tubes in the projected or developmental stage for use in various computer projects, but the initial model of the tube being developed at the Massachusetts Institute of Technology Servomechanisms Laboratory will be described, since it is fairly representative of the type and the most available.[71] Figure 18 shows a diagrammatic drawing of the storage tube. The inner structure consists of an electron gun, electrostatic deflection plates, and a specially designed storage assembly. An aquadag second anode held at +1500 volts with respect to the cathode is followed by a signal grid, the dielectric surface, and the conducting signal plate. Horizontal and vertical deflection amplifiers are used to supply the correct voltages to the deflection plates to select any particular spot position on the storage surface. In the final model of the tube, it is expected that there will be 32 storage positions in each direction on the dielectric surface, making a total of 1024 positions per tube. Recording, reading, and re-intensification of stored signals will all be accomplished with the same high-velocity electron beam and will take place while the beam is stationary.

The actual operation of the tube is relatively simple, but the mechanism of storage on a dielectric surface is itself not yet fully understood. When electrons strike the storage surface with high velocity, secondary electrons are emitted by the dielectric. If more secondary electrons are emitted than there are incident electrons, the secondary emission ratio is said to be greater than one. When this ratio is greater than one, more electrons leave the surface than reach it, and its potential increases positively. On the other hand, if the secondary emission ratio is less than one, more electrons reach the surface than leave it, and its potential falls. The secondary emission ratio itself depends upon the surface material and upon the

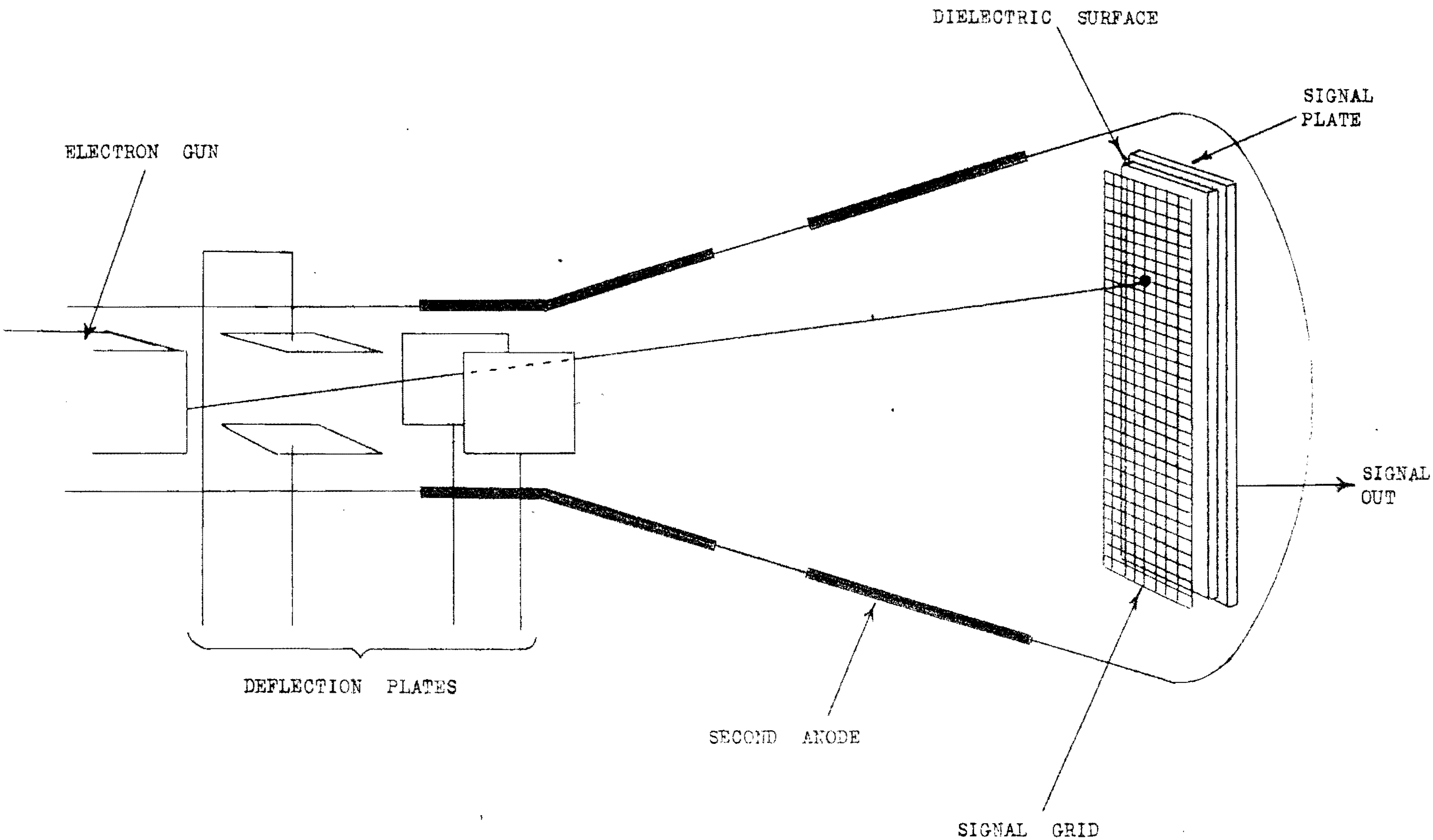


FIGURE 18 ELECTROSTATIC STORAGE TUBE

energy of the incident electrons. It is greater than one for most materials for electron accelerating voltages between about 50 to several thousand volts. However, in the storage tube, the signal grid potential can be adjusted so as either to collect or repel the secondary electrons emitted from the storage surface and so control the effective secondary emission ratio.

The electrostatic storage tube is designed to have two states of stable equilibrium and a neutral state. It is thus well suited for storage of numbers expressed in the binary system. In order to achieve high accuracy in the MIT tube, it is proposed to store a one as a positive charge on the dielectric and a zero as a negative charge, rather than as the absence of charge (corresponding to the neutral state). In one possible recording method, the signal grid is switched to a positive potential of the order of 100 volts to store a one. The beam deflection voltages are established to select the correct position on the storage surface, and the beam is turned on for a very short time. Secondary electrons produced by the incident beam are collected by the positive grid, and the spot selected builds up a positive charge, since the effective secondary emission ratio is greater than one as long as the potential of the spot is less than that of the grid. When the spot potential becomes approximately equal to that of the grid, the effective emission ratio drops to one, and the spot remains close to grid potential. After about a microsecond, the beam is turned off, leaving the spot with a positive charge. Since the storage surface is a dielectric, the charge will remain stored at the point of incidence until it eventually leaks away through the very high ohmic resistance of the dielectric surface or is altered by electrons incident at the spot position. Because of this gradual decrease in signal level, it will be necessary to refurbish stored signals from time to time by rewriting them at the same positions, in order always to maintain readable levels.

Storage of a zero is accomplished by setting the signal grid to a negative potential and pulsing the beam on. In this case, the incident electrons will still liberate secondaries, but since the energy of most of the secondary electrons is low, they will be repelled by the negative grid back to the storage surface. Consequently, a negative charge will be built up while the beam is on and will remain after it is switched off. Erasing before recording is not necessary, since the previous potential of the surface does not affect the storage of either a one or a zero.

In order to read a digit stored at a certain position on the dielectric surface, the beam deflection voltages are set to select that position, the signal grid is held neutral at zero potential, and the beam is turned on. A positive area, representing a one, will then collect electrons and fall in potential, and a negative area, representing a zero, will repel secondary electrons and rise in potential. The rapid change in potential of the dielectric spot is capacitatively coupled to the signal plate; hence, a one is read as a negative output pulse and a zero as a positive pulse. Reading causes erasure; therefore, it is necessary to rewrite the stored information after reading it if it is desired to use it again later. Rewriting can be most simply accomplished, when necessary, by coupling the output signal to the writing input of the tube.

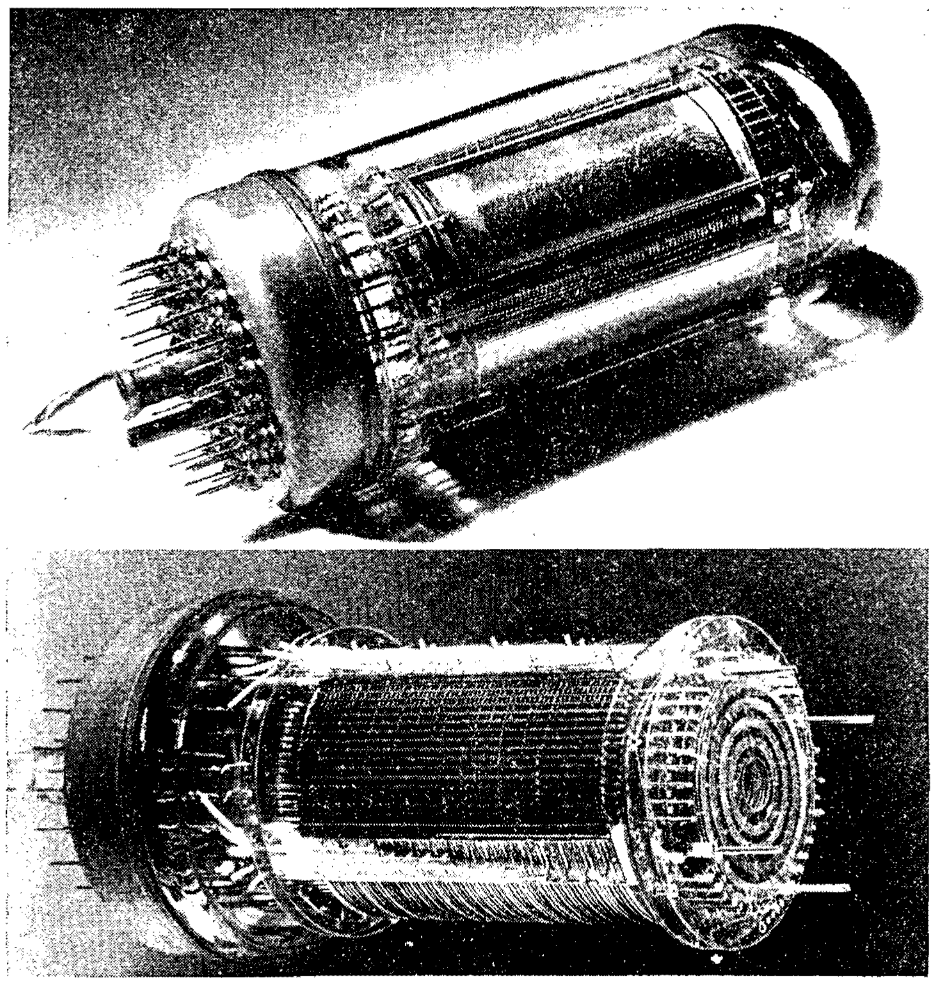
One of the principal problems in the design of a storage tube is control of secondary electrons. Since the stored signals must be spaced quite closely to conserve space, there is a good chance that not all of the secondary electrons emitted during reading and writing will remain close to their point of origin or will be collected: some of the secondaries will redistribute themselves at varying distances from their point of emission and in so doing will tend to charge adjacent positive areas, destroying stored ones. Various methods of secondary electron control have been proposed, and it is expected that the problem can be adequately solved. The storage tube combines relative simplicity with a fairly large, high-speed storage capacity and will be a valuable computational storage device when its development is complete.

d. Selectron Storage Tube

The selectron is a high-speed storage device now being developed by the Radio Corporation of America for use in the computer that the Institute for Advanced Study at Princeton is now building.[72,74] The selectron is an electrostatic storage tube which differs from the tube previously described in its method of selecting spot positions and reading and recording signals.

The tube itself is relatively complicated (see Figs. 19,20). It consists of a cylindrical cathode surrounded by various grids and anodes. The first grid outside the cathode is used to control space charge in the tube. Next is a screen which is maintained at about - 100 volts, followed by a rectilinear control-grid structure consisting of an inner section of separate vertical wires and an outer section of separate horizontal wires. The control-grid structure thus forms a large number of rectangular windows, each surrounded by four different grid wires. Outside the grids are vertical, radial fins maintained at - 300 volts, followed finally by the cylindrical dielectric storage surface. The storage surface consists of a mica cylinder with fluorescent material on its inner surface and a half-silvered outside surface (see Fig. 21).

In the tube under development, there are 64 grid wires in each direction, but, by ingenious interconnection, it is only necessary to have 52 sealed-in leads to these 128 wires. Selection of a given window is carried out by making all of its



Two views of memory tube in which a multiplicity of images may be stored for later release as, for example, in a calculating machine (RCA)

Ref. 73, p. 82.

Fig. 19 The Selectron

peripheral wires positive; a single negative wire on one side of a window is enough to inhibit electron flow through the window (see Fig. 22). There are 16 lead-in wires to the vertical grids, 16 to the horizontal grids, and each group of 16 wires is again divided into two groups of 8 wires. The interconnection in the tubes is such that each wire of each group is the neighbor of every other group once and only once.

The selection of any one of the possible 4096 windows is simply achieved by making one wire in each group positive, since the system of interconnection ensures that only one window will have all peripheral wires positive. If n is the number of lead-in wires necessary, the number of windows is given by $(n/4)^4$. Thus, a selectron with 128 lead-in wires would have more than a million windows, a tremendous storage capacity.

Recording, in the selectron, is accomplished by pulsing the signal plate. A positive pulse will carry the dielectric surface positive with it by electrostatic induction. The desired window is opened, and the incident electrons that pass through that window strike the dielectric surface, causing secondaries to be emitted. The secondary electrons are attracted by the collector fins, leaving the particular spot on the storage surface positive. The pulse applied to the signal plate has a sharp leading edge and a slowly decreasing trailing edge to prevent induction from affecting the storage surface while it is being charged. The positive potential which the dielectric spot reaches is approximately equal to that of the collector fins and is stable. Below collector potential the

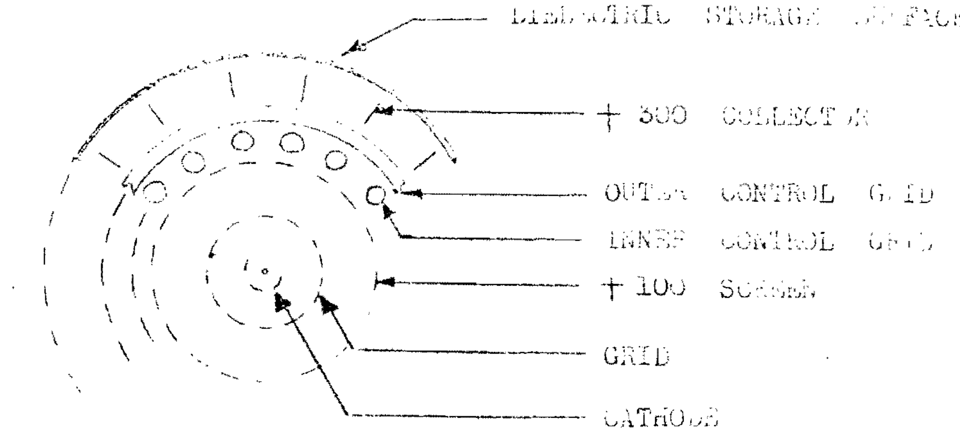


FIGURE 20 CROSS SECTION OF SELECTRON TUBE

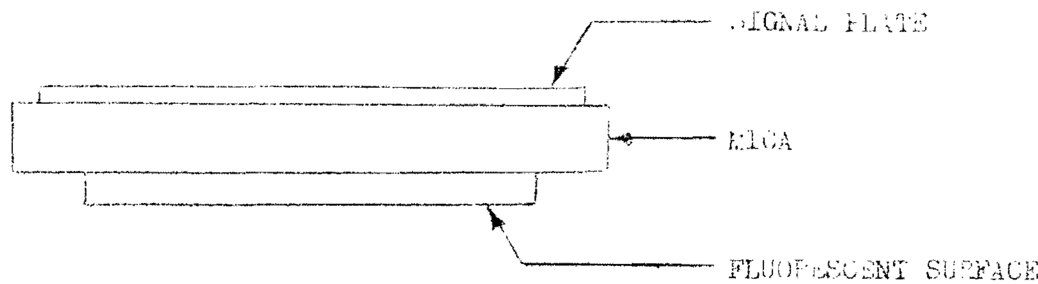


FIGURE 21 CROSS SECTION OF STORAGE SURFACE

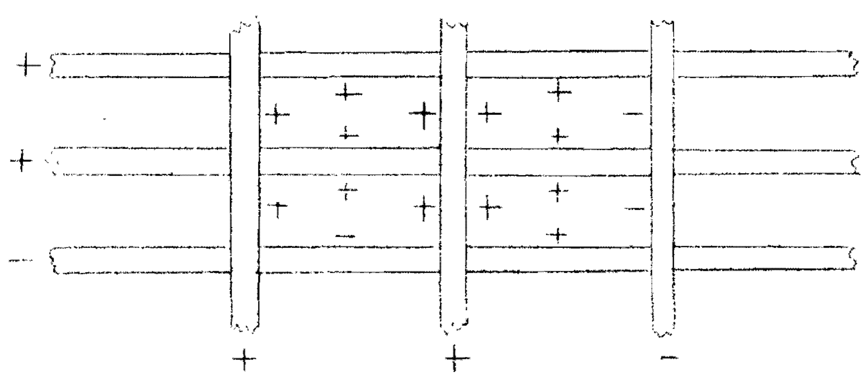


FIGURE 22 VIEW OF CONTROL GRID WINDOWS FROM CATHODE

effective secondary emission ratio is greater than one and above it the ratio is less than one. Therefore, the spot is driven to collector potential and sticks there. In the selectron, a one is represented by a positive charge and a zero by the absence of charge, or neutral potential. Erasing a one is the reverse of recording it; a negative pulse is applied to the signal plate so that the dielectric surface is momentarily driven to neutral potential and the window opened. The incident electrons which have not been collected by the collector fins are yet so slowed down by these positive fins that the effective secondary emission ratio of the surface is less than one. Consequently, the spot collects electrons and remains near the neutral potential. This condition is stable also, since no electrons will be collected if the surface goes negative. Potentials on the dielectric behind closed windows receive no cathode current and hence return to their original value along with the signal plate.

Reading out of a signal is accomplished by opening the window desired and noting if there is any fluorescence. Light may be detected by several phototubes arranged around the selectron or by a single phototube and mirror. If there is light, it indicates that the spot read was at the upper potential with a one stored there, since the electrons strike the surface with sufficient energy to cause fluorescence only when the storage surface is charged positively. The selectron may also be read by pulsing the signal plate; a stored one produces an output pulse, a zero, none. Unlike the storage tube previously discussed, reading does not cause erasure.

The selectron has not as yet worked satisfactorily, and the problem of interaction between storage elements encountered in the conventional electrostatic storage tube must also be faced in selectron design. The selectron has a somewhat smaller space factor than other types of storage tubes; e.g., more digits per unit volume can be stored in the selectron, but its cost promises to be much higher because of the precision workmanship necessary in its construction. It has the important advantage that all windows can be left open except when signals are to be recorded, read, or erased. Thus, the stored information in the tube is self-maintaining, and there is no chance of signals decreasing in intensity below the noise level and no need of special techniques of signal re-writing and re-intensification.

C. THE EFFICIENCY OF COMPUTATIONAL STORAGE DEVICES

A number of factors need to be considered in completely evaluating the efficiency of a storage device. Of these, the most important are cost and space efficiency, and reading and recording speeds. These factors have been analyzed in Table I for a number of storage media. The figures in this table should not be taken as exact, for some of the storage methods shown are still in the developmental stage, while complete information on others is not available. It is expected that the figures are correct to within an order of magnitude; such accuracy is adequate for general conclusions to be drawn from the table.

Several definitions are necessary for complete understanding of the table. "Accessibility time" for reading can be defined as the average time that is required to read out any given digit from storage; while "digit time" is that time necessary for reading out a digit when the digit adjoining it in time or space has just been read. A similar definition applies to recording. These two factors, then, are a measure of the reading and recording times of a storage device.

"Monetary economy" of a storage unit is defined as the number of digits stored in the unit divided by its cost (which includes necessary auxiliary equipment), and "spatial economy," analogously, is the number of digits stored divided by the space occupied by a single storage unit. There is another method of analyzing cost efficiency, however. The "cost-per-operation" of a storage element furnishes a relationship between inital cost and operating life of the device not provided by the simple "digits-per-dollar" factor.

Because transmission and reception of data to and from storage are the factors which make the actual storage itself of importance, it is useful to consider how many times a storage device can carry out these operations. Such a consideration is of greatest importance for those devices like relays or vacuum tubes that have a rather clearly defined operating lifetime. To a first approximation, the cost of a mounted relay is one half that of a flip-flop circuit. Assuming that the life of a relay is 10^8 operations and that of the vacuum tubes of the flip-flop, 10^8 seconds, it can be seen that the cost-per-operation of the two devices will be equal if the flip-flop operates twice a second. Although it is quite possible to make a flip-flop change its state a million times a second, the assumption that the flip-flop circuits in a binary computer operate about a thousand times a second on the average is closer to the truth. Using this figure, the cost-per-operation of the flip-flop is 500 times lower than that of the relay. Were more complete cost and lifetime figures available, it might be profitable to apply the cost-per-operation criterion to other types of storage. For most storage media, however, the digits-per-dollar factor is an adequate measure of cost efficiency.

The following general conclusions can be drawn from Table I: those storage media in which a large amount of information can be

STORAGE MEDIA	Monetary Economy digits/$	Spatial Economy digits/ft.^{3}	Access. Time, reading	Digit Time, reading	Access. Time, recording	Digit Time, recording	EXPLANATORY NOTES
Inerasible Systems							
a. Print on Paper	$2x10^7$	$3x10^9$	30 sec.	30 ms.			
b. Microprint	10^{10}	$3x10^{12}$	2 min.	30 ms.			Areal reduction ratio: 1000:1.
c. Punched Tape	$2x10^6$	10^7	1 min.	10 ms.	1 min.	10 ms.	
d. Punched Cards	$2x10^5$	10^6	1 min.	10 ms.	1 min.	10 ms.	Hollerith cards, 80-column.
e. Moving Film	10^6	10^{10}	1 min.	1 ms.	1 min.		Photoemulsion, 35 mm. 50 channels.
f. Cerebral Cortex		10^{11}	5 sec.	30 ms.	30 sec.	5 sec.	Man
Erasible Systems							
a. Patch Cords	10	$5x10^2$	1 us.	1 us.	30 sec.	10 sec.	
b. Mechanical Counters	5	$5x10^4$	200 ms.	200 ms.	200 ms.	200 ms.	Ten position counter.
c. Relays	1	50	1 us.	1 us.	10 ms.	10 ms.	Individual relay.
d. Thyratrons	1	10	1 us.	1 us.	1 us.	1 us.	Hydrogen thyratron.
e. Neon Tubes	5	10^3	1 us.	1 us.	25 us.	25 us.	Miniature bulbs.
f. Trigger Circuits	1	15	1 us.	1 us.	1 us.	1 us.	Miniature dual tube.
g. Magnetic Wire	$2x10^7$	$5x10^9$	1 min.	40 us.	1 min.	40 us.	Speed: 10 ft./sec.
h. Magnetic Disk	10^3	$5x10^4$	16 ms.	16 us.	16 ms.	16 us.	Diam.: 1 ft.; 60 r.p.s.
i. Mercury Delay Line	20	$2x10^3$	1 ms.	1 us.	1 ms.	1 us.	Delay: 1 ms.; pulse repition rate: 1 mc./sec.
j. Selectron Tube	2	$2x10^4$	5 us.	5 us.	5 us.	5 us.	Digits/tube: 4096.
k. Electrostatic Storage Tube	5	$5x10^3$	6 us.	6 us.	6 us.	6 us.	Digits/tube: 1024.

TABLE I

stored have a high accessibility time, making them unsuited for internal storage; those media with a shorter accessibility time are costly and have a much smaller capacity; finally, storage methods which are least costly and most economical of space, at both high and low accessibility times, are two dimensional: storage points are distributed on a two dimensional continuum. Extrapolating one step further, it would therefore seem that the most economical storage medium possible would be three dimensional, having storage points distributed along a three dimensional lattice or matrix. By building such a medium up out of layers and storing and reading electrically, low cost, great capacity and high speed might well be achieved. At present, there is some consideration at the Massachusetts Institute of Technology of the possibility of using a complex of gas discharge paths, distributed through a volume, to actually produce three-dimensional storage; but such storage is still in a nascent stage.

IV

S T O R A G E   I N   M A T H E M A T I C A L   C O M P U T E R S

A. GENERIC TYPES OF COMPUTERS

Before discussing storage in particular computers, it is necessary to describe briefly the methods of operation of modern computers, so that such computational storage can be understood in proper context.

There are two generic types of computers: analogue and digital. Analogue computers use continuously variable physical quantities, such as angular positions or lengths of rods, forces, or electrical voltages, to represent numerical values in the computation. Both the slide rule and the differential analyzer are analogue devices. Since numbers are represented by physical quantities, the accuracy of such analogue devices is necessarily limited both by the physical tolerances of the component parts of the machine and by the precision with which these physical quantities can be measured.

In contradistinction, digital computers represent numbers explicitly by means of quantities which vary in discrete steps only. Since numerical quantities can be handled as digits, rather than as physical measurements, the accuracy of individual numbers may be increased as much as necessary by using more digits in the words employed in computation. Because an analogue computer requires a physical computing element such as an adder or integrator for each mathematical operation in a given problem, the interconnection between these elements must be altered for each new problem. On the other hand, the physical connection of the elements of a digital computer is fixed and independent of the problem to be solved. Collections of digits, representing numbers, are transmitted electrically from one unit of the computer to another in accord with a stored program or order sequence which determines the successive arithmetical operations of the computer.

Since digital computers commonly have an arithmetical element capable of performing only the simple mathematical operations such as addition and multiplication, various reiterative approximation methods are used for more complicated operations like integration and extracting roots. By using enough digits in the calculation and making the approximation interval short enough, however, it is possible to achieve any desired degree of accuracy. Therefore, while analogue computers are designed to solve relatively limited classes of problems, digital computers may be used to solve any type of problem whose solution is obtainable by numerical methods.

Storage in an analogue computer is represented by the physical positions of the elements of the computer and by the interconnection between elements, corresponding to what has been termed herein as implicit storage. In a digital computer, however, storage is necessary for both partial results and the order program that determines the sequence of operation; such storage is thus of the explicit type.

In order to simplify digital computer design and to economize storage space, it is customary to reduce orders to a numerical code and to store them in the same storage device used for partial numerical results. A coded order usually consists of two groups of digits: the first to specify the storage position of a given word, and the second to set the switches that determine what arithmetical operation is to be carried out on the word selected by the order.

It is possible to construct an order program to control the solution of any problem in a general class, rather than that of a specific problem, by the use of two special orders: the substitution order and the conditional transfer order. So that the result of a preceding calculation can be introduced into the instruction controlling a later calculation, it is necessary to substitute the storage position number of the earlier result into the order which controls the next operation of the later calculation. Using substitution orders, the program can be initially made up without knowledge of the storage position of partial results, and a given general sequence of orders can be used many times with different numbers located in different parts of the storage.

The usefulness of the conditional transfer order is clearly explained by Burks, Goldstine, and von Neumann:*

> The utility of an automatic computer lies in the possibility of using a given sequence of instructions repeatedly, the number of times it is iterated being

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*Burks, A.W., Goldstine, H.H., and von Neumann, J., Ref. 75, p. 6.

> either preassigned or dependent upon the results of the computation. When the iteration is completed, a different sequence of orders is to be followed, so we must, in most cases, give two parallel trains of orders preceded by an instruction as to which routine is to be followed. This choice can be made to depend upon the sign of a number (zero being reckoned as plus for machine purposes). Consequently we introduce an order (the conditional transfer order) which will, depending upon the sign of a given number, cause the proper one of two routines to be followed.

By storing a certain order sub-sequence like that by which interpolation is accomplished and using it whenever such a process is necessary in the progress of the solution, it is possible to simplify greatly the construction of order programs, and thus ~~thereby~~ extend~~ing~~ the sphere of usefulness of the automatic digital computer.

It is interesting to compare the function of the sequence control in a computer with that of the chromosomes in an animal. Not only does the computer program determine the range of possible paths that can be followed in the solution of a problem, but also, by controlling the arithmetical processes of the computer, it causes the actual solution to be produced. According to Schrodinger, the situation is almost entirely analogous in the case of the chromosomes:*

> ...It is these chromosomes, or probably only an axial skeleton fiber of what we see under the microscope as the chromosome, that contain in some kind of code-script the entire pattern of the individual's future development and of its functioning in the mature state. ...But the term code-script is, of course, too narrow. The chromosome structures are at the same time

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*Schrodinger, E., Ref. 76, pp. 19-21.

> instrumental in bringing about the development they foreshadow. They are law-code and executive power -- or, to use another simile, they are the architect's plan and builder's craft -- in one.

Thus, both chromosomes and memory find close counterparts in the modern computer.

Two main kinds of digital computer can be distinguished by the type of data transmission employed. In the serial computer, the digits of a word (order or pure number) are transmitted one after another in time sequence over a single wire or distribution bus. The individual digits are timed to occur synchronously with the clock pulses of the computer and are usually all of the same length. It is possible to use a variable-length pulse to represent a decimal digit, but most fast computers now being developed will use some kind of binary number code, with ones represented by the presence of pulses, and zeros by their absence. Therefore, in serial computers, the length of time of transmission of a word is dependent upon the length of the word.

In parallel computers, on the other hand, the individual digits of a word are transmitted simultaneously over a number of distribution lines equal to the number of digits in the word. In this case, the transmission time is chiefly governed by the repetition rate of the computer and is much faster than that possible with serial operation. Besides increasing the operating speed of a computer, parallel operation also simplifies the necessary equipment by reducing the number of different elements necessary and considerably simplifies switching and programming. Storage reading and recording times are materially shortened through the use of parallel operation. In serial operation, it is necessary to switch the beam of an electrostatic storage tube to a different position for each digit of a word read or recorded in the tube. With parallel operation, on the other hand, a number of tubes equal to the number of digits in a word is used, with each digit of a given word stored in the same equivalent position in each tube. Reading or recording is then accomplished by switching the beams of all tubes together and takes little longer than a single switching time.

Figure 25 is a simplified block diagram of a high-speed digital computer. Input and output devices are necessary to establish connection between the computer and the outside world; the sequence of controlling orders and initial data are introduced through the input device from the external storage medium to the internal high-speed storage at the beginning of a problem. Orders are withdrawn from storage one at a time, usually in monotonic sequence, and sent over the distribution bus to the control unit where they are used to determine the succeeding arithmetical operations. Upon the completion of an operation, the partial result is either immediately used or sent over the distribution system back to storage until later needed. Finally, at the solution of the problem, the results are sent to external storage through the output unit.

The types of storage used in connection with a digital computer form a hierarchy of speeds. Zero speed is represented by

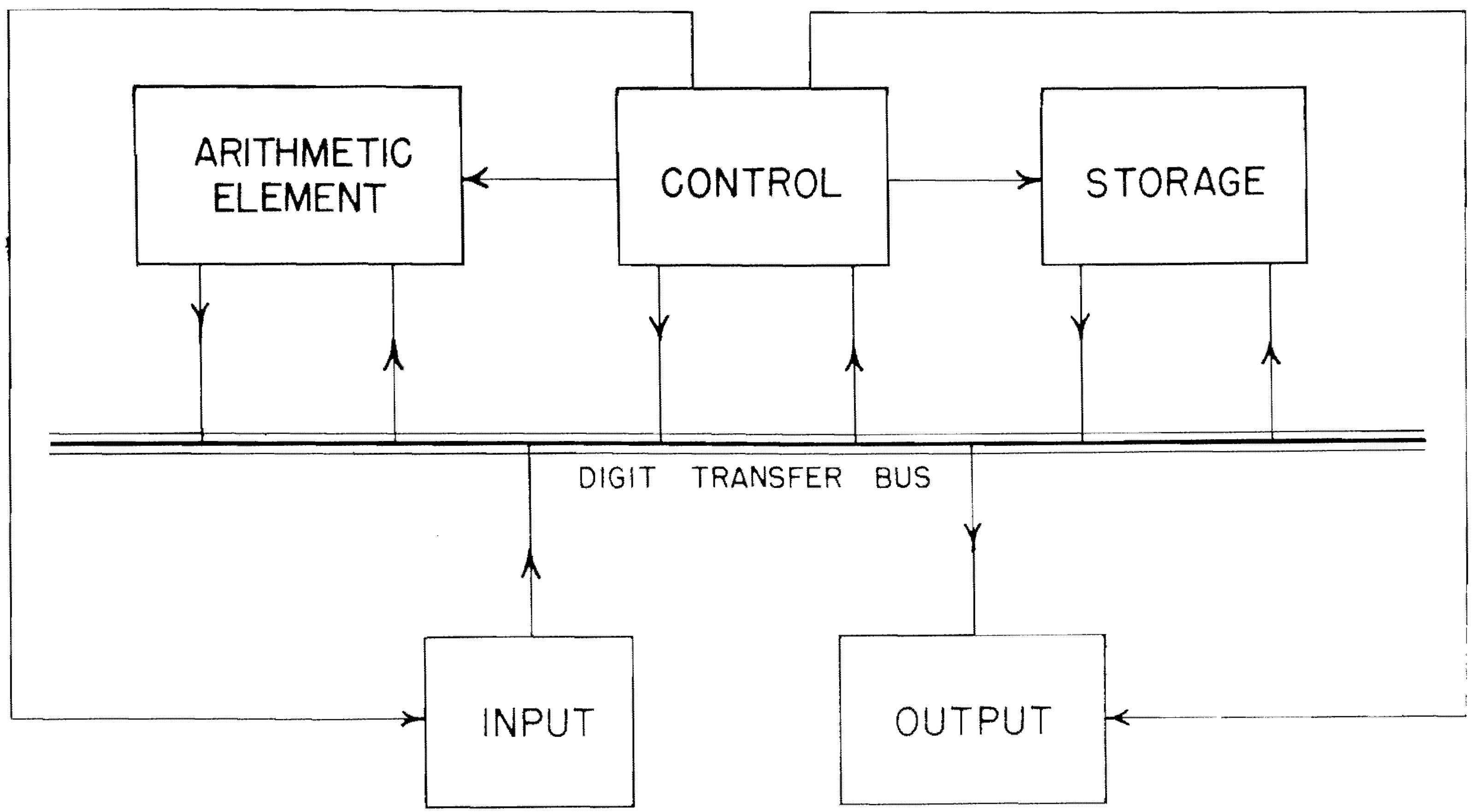

Fig. 33 Digital Computer Block Diagram

the library of control tapes that is built up for use in solving different classes of problems. Such a library is termed "dead storage." When a control tape is connected to the computer by means of the input device, it becomes "live" external storage and represents the next speed level. External storage is used to introduce data into the machine (and sometimes to augment internal storage) because the speed of data transmission can be made much higher than would be possible manually. Finally, high-speed internal storage is necessary so that the internal operations of the computer are not slowed down by using data which must be supplied from the slower external storage. Because internal storage must be very fast, it is relatively expensive and bulky; thus, though it might be ideally desirable to have so large a permanent internal storage capacity that a great number of order sub-sequences could be permanently stored there and called into use when needed for a given problem, such a capacity is at present impractical for high-speed machines. Consequently, only those sub-sequences that will be used repeatedly during the solution of a given problem are stored in the internal storage. Because it is used so much, the size and speed of the internal storage of a computer are the factors that principally determine how complex a problem can be economically solved by the computer.

B. SPECIFIC COMPUTERS

Eight modern computers are analyzed in tabular form on the succeeding pages with greatest emphasis placed upon the storage methods used in each machine. In this manner, the types of internal and external storage used in completed or projected computers are contrasted, and the storage devices that are used to satisfy the varying needs and speeds of these machines are shown. Blank spaces are left where information is inadequate, and dashes are used to indicate inapplicable questions.

Because the main storage in an analogue computer is of the implicit type, only one analogue machine is included for comparison with the digital computers. Although the terms and table entries are largely self-explanatory, special discussion of the new M.I.T Whirlwind II Computer is necessary. Diametrically opposed to the new M.I.T. Differential Analyzer, an analogue machine with a digital output, the Whirlwind II is to be a digital machine with a possible analogue input. In addition to normal use as a general-purpose computing instrument, the Whirlwind II is being designed to serve as an aircraft analyzer. By solving the equations of flight of a real or postulated aircraft very rapidly, it will produce signals which will actuate cockpit instruments and controls to simulate the response of an aircraft in flight. Conversely, signals derived from the "pilot's" manipulations of the controls will be transmitted to the computer, converted to digital data, and used to modify the equations being solved so that the proper cockpit control reactions and instrument readings will be obtained.

New M.I.T. Differential Analyzer[39,77,78]

The new M.I.T Differential Analyser is so designed that many of the disadvantages usually associated with analogue machines are obviated. Initial connection of individual units is carried out very simply and quickly by means of three punched tapes used to set relays which cause the different units of the machine to be connected automatically and set up the proper gear ratios and initial conditions. By building up a library of such tapes, the machine can quickly be connected for the solution of many types of problem.

Another unusual feature of the new Differential Analyzer is its provision for digital output. The positions of the rotating output shafts of the machine are measured at given intervals of the independent variable (time) and stored until these results can be used to actuate the automatic typewriter output. This process is accomplished as follows:*

> ...Whole turns and tenths of turns are detected and stored by a set of contacts which control a group of cold-cathode gas relay tubes. When an actuating signal is received, the tubes which are at that instant connected to the signal line conduct current and because of the gas they maintain conduction until the indication is cleared by interrupting their plate circuits. The digits which represent tens, hundreds, and thousands of turns are obtained from ordinary contacts operated by cams. These contacts operate storage relays which hold the reading until the recording is completed.

Thus, in addition to solutions in the form of plotted curves, the actual numerical values of dependent variables are tabulated at short intervals of the independent variable.

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*Bush, V. and Caldwell, S.H., Ref. 39, pp. 298,300.

Name:	New M.I.T. Differential Analyzer (see Fig. 24).
Status:	Placed in operation in 1942.
Type:	Analogue.
Number System:	Decimal output.
Transmission of Data:	———
Repetition Rate:	———
Internal Storage	
Type:	Implicit: rotating shafts and interconnection of units.
Size:	Limited by number of integrators (18).
Equivalent Decimal Capacity:	———
Accessibility Time, Recording:	———
Accessibility Time, Reading:	———
External Storage	
Main Type:	Punched tape (see Fig. 7).
Recording Speed:	———
Reading Speed:	———
Other Input Devices: ...	Manual and automatic function tables.
Other Output Devices: ..	Automatic typewriters and function plotters.
Type of Dead Storage: ..	Library of connection tapes.
Treatment of Orders: ...	Orders on punched tape used for initial interconnection of the machine.
Multiplication Speed: ..	———
Speed of Connection: ...	3 to 5 minutes.
Number of Tubes:	About 2000.
Number of Relays:	Several thousand.
Comments:	For most problems a precision of 1 in 10^4 can be attained.

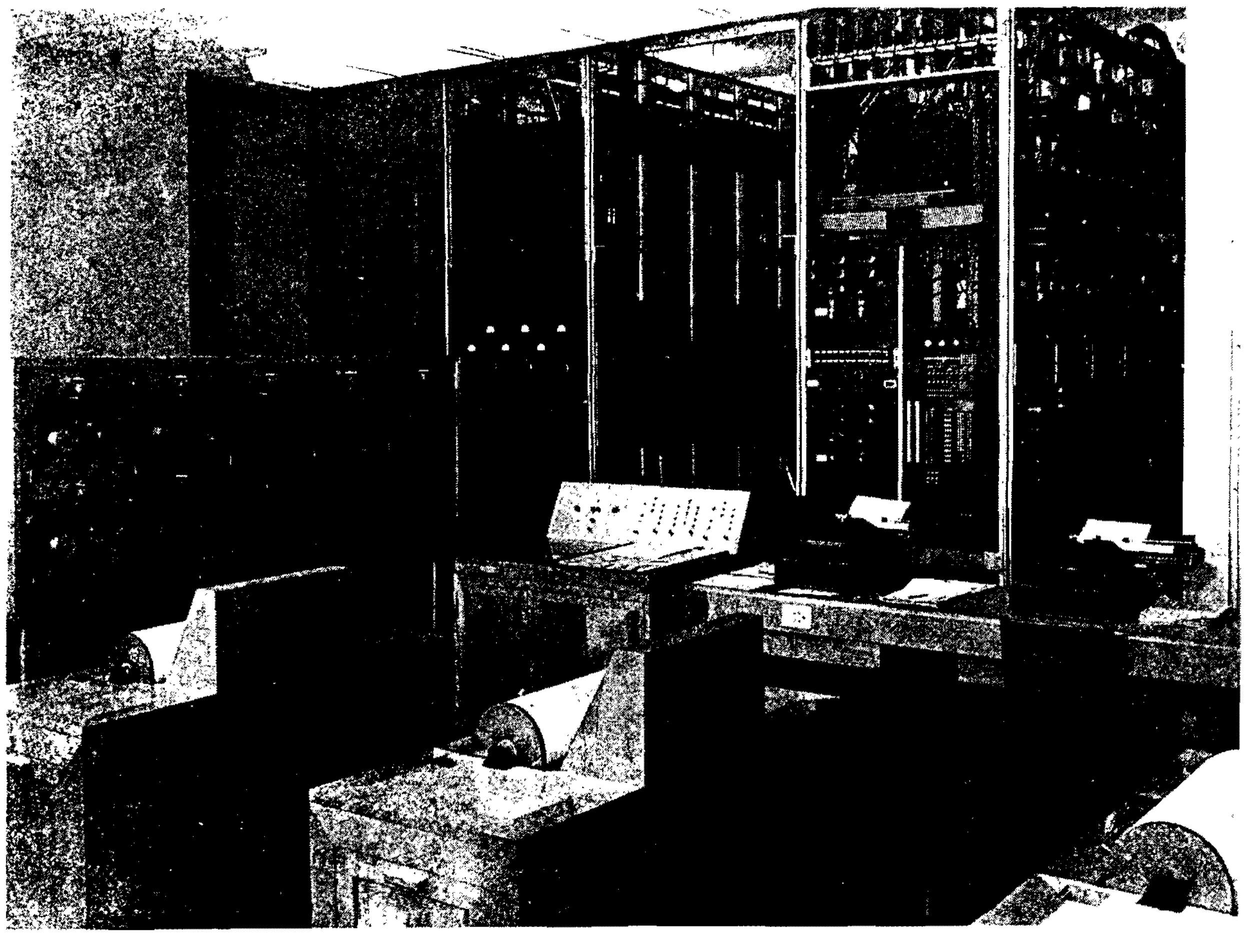
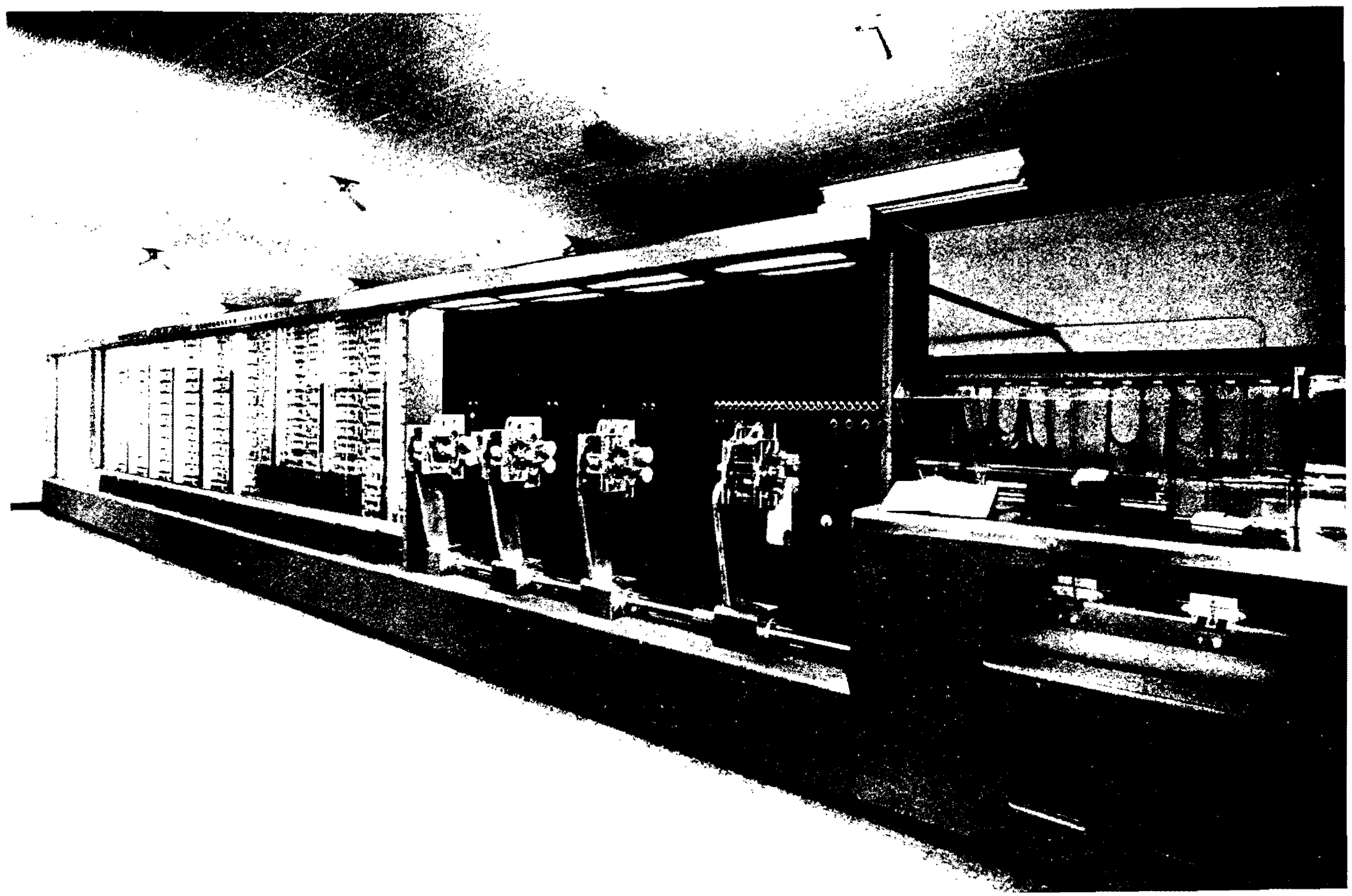


Fig. 41. General view of machine.
Ref. 59, p. 310.

Fig. 24 New M.I.T. Differential Analyzer

Name:	Harvard Mark I (see Fig. 25).[32,79]
Status:	Placed in operation in August, 1944.
Type:	Digital.
Number System:	Decimal.
Transmission of Data:	Serial.
Repetition Rate:	3 1/3 cycles/second.
Internal Storage	
Type:	Electro-mechanical registers.
Size:	72 registers; 23 decimal digits each.
Equivalent Decimal Capacity:	1656 decimal digits.
Accessibility Time, Recording:	0.3 seconds.
Accessibility Time, Reading:	0.3 seconds.
External Storage	
Main Type:	80-column IBM tabulating cards.
Recording Speed:	
Reading Speed:	
Other Input Devices: ...	24-hole control tape; manually-set switches holding 60 23-digit decimal numbers.
Other Output Devices: ..	2 automatic typewriters.
Type of Dead Storage: ..	Library of control tapes.
Treatment of Orders: ...	Coded on wide tape.
Multiplication Speed: ..	6 seconds (2 23-digit decimal numbers).
Speed of Connection: ...	Automatic.
Number of Tubes:	———
Number of Relays:	
Comments:	Weighs about 5 tons; 51 ft. long, 8 ft. high.

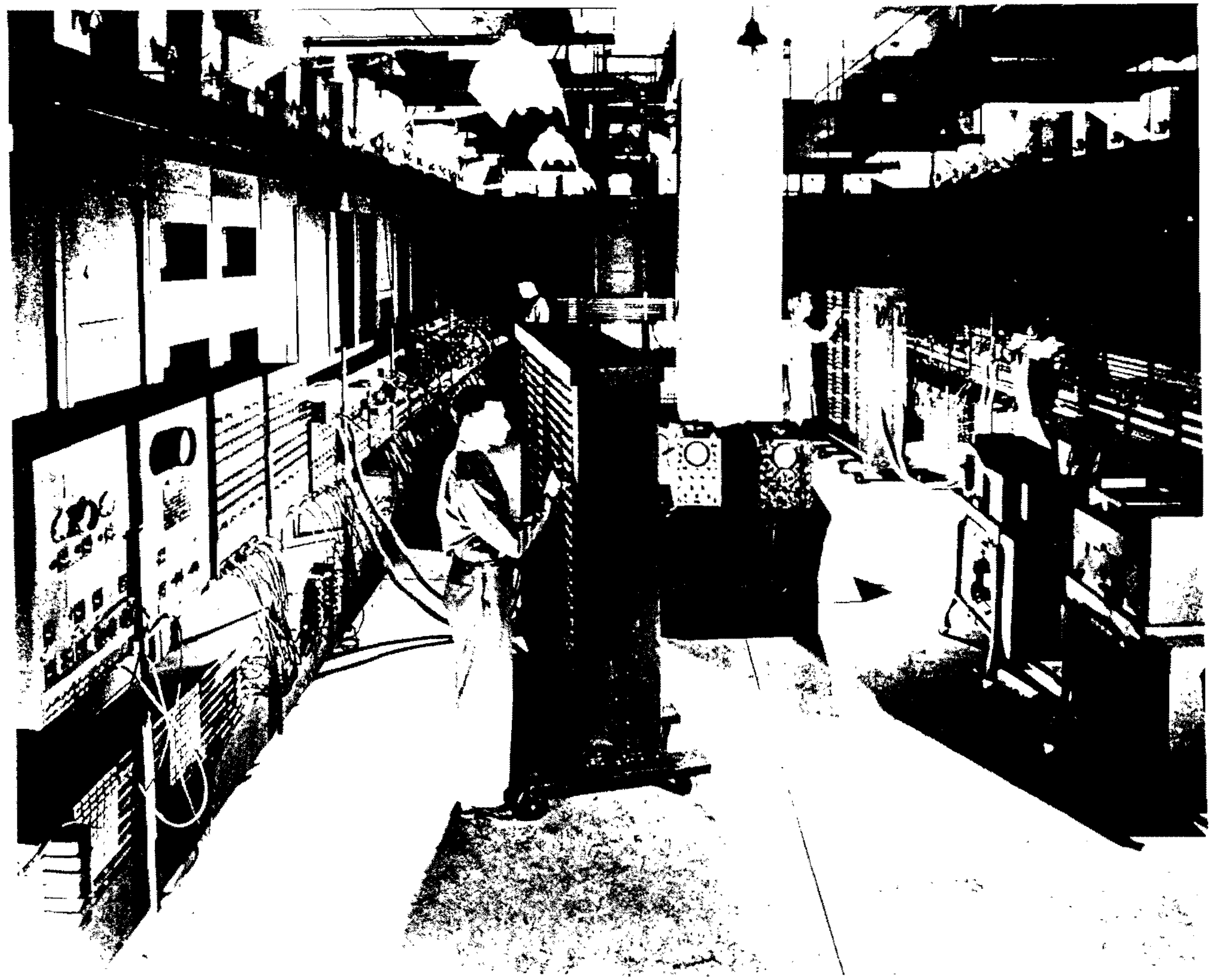


III Front View of the Calculator

Ref. 52, opposite p. 7.

Fig. 25 Harvard Mark 1 Computer

Name:	Electronic Numerical Integrator and Computer (ENIAC) (see Fig. 26).[44,80,81,82]
Status:	Full-time operation begun in 1945.
Type:	Digital.
Number System:	Decimal.
Transmission of Data:	Parallel.
Repetition Rate:	100,000 cycles/second.
Internal Storage	
Type:	Decade-counter accumulators.
Size:	20 accumulators; 10 decimal digits each.
Equivalent Decimal Capacity:	200 decimal digits.
Accessibility Time, Recording:	200 microseconds.
Accessibility Time, Reading:	200 microseconds.
External Storage	
Main Type:	80-column IBM tabulating cards. (Data transmitted from cards to internal relay register).
Recording Speed:	70 milliseconds
	— 10-digit decimal number.
Reading Speed:	35 milliseconds
Other Input Devices: ...	3 manually-set function tables.
Other Output Devices: ..	None.
Type of Dead Storage: ..	None.
Treatment of Orders: ...	Programs manually set up with patch cords and switches.
Multiplication Speed: ..	2.8 milliseconds (2 10-digit decimal numbers).
Speed of Connection: ...	Slow: often a day or more is necessary.
Number of Tubes:	18,850.
Number of Relays:	1500
Comments:	About 250 ft.² floor area required.



THE ENIAC
FIG. 1.

Fig. 26 Ref. 80, p. 96.

Name:	Bell Laboratories Relay Computer.[40]
Status:	Placed in operation in December, 1946.
Type:	Digital.
Number System:	Bi-quinary; floating decimal point.
Transmission of Data:	Parallel.
Repetition Rate:	100/7 cycles/second.
Internal Storage	
Type:	Relay registers.
Size:	15 registers; 7 decimal digits each.
Equivalent Decimal Capacity:	105 decimal digits.
Accessibility Time, Recording:	7/100 second.
Accessibility Time, Reading:	7/100 second.
External Storage	
Main Type:	Western Union teletype tape.
Recording Speed:	
Reading Speed:	
Other Input Devices:	None.
Other Output Devices: ...	None.
Type of Dead Storage: ...	Library of tapes.
Treatment of Orders:	Coded on endless tapes.
Multiplication Speed: ...	1 second (2 7-digit decimal numbers).
Speed of Connection:	Automatic.
Number of Tubes:	--------
Number of Relays:	
Comments:	Installed at Langley Field.

Name:	Harvard Mark II Relay Computer.[83]
Status:	Completion expected by Summer of 1947.
Type:	Digital.
Number System:	Coded decimal; floating decimal point.
Transmission of Data:	Parallel.
Repetition Rate:	30 cycles/second.
Internal Storage	
Type:	Relay registers.
Size:	100 registers; 10 decimal digits each.
Equivalent Decimal Capacity:	1000 decimal digits.
Accessibility Time, Recording:	1/30 second.
Accessibility Time, Reading:	1/30 second.
External Storage	
Main Type:	Teletype tape.
Recording Speed:	2 10-digit decimal numbers punched in 3 sec.
Reading Speed:	2 10-digit decimal numbers read in 3 sec.
Other Input Devices: ...	Manual switches.
Other Output Devices: ..	Automatic typewriters.
Type of Dead Storage: ..	Library of tapes.
Treatment of Orders: ...	Coded on tape.
Multiplication Speed: ..	0.7 second (2 10-digit decimal numbers).
Speed of Connection: ...	Automatic.
Number of Tubes:	
Number of Relays:	13,000.
Comments:	Many "latch relays" requiring no holding power used.

Name:	Electronic Discrete Variable Computer (EDVAC) [62,64,65]
Status:	Under development at the Univ. of Pennsylvania.
Type:	Digital.
Number System:	Binary.
Transmission of Data:	Serial.
Repetition Rate:	1 megacycle/second.
Internal Storage	
Type:	Mercury delay lines.
Size:	128 352-microsecond lines; 8 44-digit binary numbers each.
Equivalent Decimal Capacity:	13,300 decimal digits.
Accessibility Time, Recording:	≦352 microseconds.
Accessibility Time, Reading:	≦352 microseconds.
External Storage	
Main Type:	Magnetic wire or tape; punched paper tape used for recording on magnetic record.
Recording Speed:	100 words/second to and from paper tape.
Reading Speed:	20,000 words/second between magnetic record and internal lines of computer.
Other Input Devices: ...	None.
Other Output Devices: ..	3 dark-trace cathode-ray viewing tubes.
Type of Dead Storage: ..	Library of magnetic and punched tape records.
Treatment of Orders: ...	On magnetic records.
Multiplication Speed: ..	2 milliseconds (2 13-digit decimal numbers; assuming no delay in abstracting from storage).
Speed of Connection: ...	Automatic.
Number of Tubes:	About 2000
Number of Relays:	
Comments:	Will probably require about 25 ft.^{2} floor area.

Name:	Institute for Advanced Study Computer.[75,86]
Status:	Completion expected by 1948.
Type:	Digital.
Number System:	Binary or octal.
Transmission of Data:	Parallel.
Repetition Rate:	1 megacycle/second.
Internal Storage	
Type:	Selectron storage tubes.
Size:	40 selectrons; 4096 binary digits/tube.
Equivalent Decimal Capacity:	50,000 decimal digits.
Accessibility Time, Recording:	About 5 microseconds.
Accessibility Time, Reading:	About 5 microseconds.
External Storage	
Main Type:	Film or magnetic records.
Recording Speed:	
Reading Speed:	
Other Input Devices: ...	Typewriter.
Other Output Devices: ..	Cathode-ray viewing tubes.
Type of Dead Storage: ..	Library of control records.
Treatment of Orders: ...	Coded on external storage medium.
Multiplication Speed: ..	120 microseconds (2 40-digit binary numbers).
Speed of Connection: ...	Automatic.
Number of Tubes:	About 2000.
Number of Relays:	
Comments:	Initial cost over $1,000,000. To be used for scientific computing and for collating weather data

Name:	M.I.T. Whirlwind II Computer.[67]
Status:	Under development at M.I.T.
Type:	Digital.
Number System:	Binary.
Transmission of Data:	Parallel.
Repetition Rate:	1 megacycle/second; possibly 5 megacycle/sec. in parts of machine.
Internal Storage	
Type:	Electrostatic storage tubes.
Size:	640 tubes; 1024 binary digits/tube.
Equivalent Decimal Capacity:	195,000 decimal digits.
Accessibility Time, Recording:	About 6 microseconds.
Accessibility Time, Reading:	About 6 microseconds.
External Storage	
Main Type:	Photoemulsion or phosphor coated film.
Recording Speed:	
Reading Speed:	About 1000 40-digit binary numbers/second.
Other Input Devices: ...	Typewriter; cockpit signals.
Other Output Devices: ..	Cathode-ray tubes; cockpit instruments and controls.
Type of Dead Storage: ..	Library of control films.
Treatment of Orders: ...	Program controlled by continuous tape.
Multiplication Speed: ..	About 35 microseconds. (2 40-digit binary #'s).
Speed of Connection: ...	Automatic.
Number of Tubes:	
Number of Relays:	———
Comments:	To be used for general scientific computing and as an aircraft analyzer.

V

THE FUTURE OF STORAGE

A. FUTURE COMPUTERS

The highest function of computing devices is to set man free from repetitive mental labor and thus to give him more time for creative endeavor. Storage is necessary for both the control and the partial results of repetitive computations; as these computations come to reflect more and more the increasing complexity of modern society, larger storage capacity will be necessary. The normal trend in computer design is therefore towards greater storage capacity and increased speed.

There are many problems is both pure and applied mathematics and engineering that would require a vast storage capacity for complete solution. Partial differential equations, in particular, require an extensive capacity because many variables and net points must be stored throughout the calculation. Many of these problems have not yet been attempted, not because they are impossible, but because so much calculation is involved that their solution by any but high-speed computational methods would be economically unjustified and inordinately long.

Computing machines are well suited for the solution of all types of problems where a large amount of data can be collected and must be analyzed quickly. The essential difference between problems of this type and problems of pure mathematics is that the former must, for some reason, be solved in "real time," rather then in "computer time." Computer time is essentially unlimited, but many problems must be solved in a specific short time to be of value. To this class belong such diverse problems as sociological analysis and the solution of the guided-missile control equations. Both of these problems must be solved before external conditions change so much that solutions founded on past data are valueless. An important problem of this type is that of weather analysis. At present, the modern meteorolgist receives more data from automatic weather-reporting stations than he can interpret in the short time before succeeding data should be analyzed. By using computational techniques both to store and analyze the data as it comes in, this difficulty could be obviated. All data could be used almost at its arrival to modify previous solutions and thus keep the solution of the weather problem always up to date. Because of the great computing speed possible, trends toward dangerous weather conditions could be detected long enough before crises developed to enable them to be controlled or prepared for. There has already been some consideration of such a use for computers, and it is expected that the computer being built at the Institute for Advanced Study will be applied to the weather-analysis problem.[86]

The problems that have been discussed thus far can be solved by computing machines that differ from present machines only in increased speed and capacity. During the war, a different kind of computing machine was developed in Germany.[88] Such a machine, called a logic computer, calculates with circumstances and conditions rather than with arithmetical numbers. The logic computer deals with formal symbolic analysis, solving problems in logic instead of problems in arithmetic. Since all such problems can be analyzed into the fundamental operation of conjunction (and), disjunction (or), and negation (not), a machine which can manipulate data by these operations can solve problems in logic. The initial values introduced into the machine and stored therein consist of enough true and false declarations to specify the problem. New declarations can be constructed from the initial declarations by application of the fundamental operations of logic. Through the use of the logic computer, not only can problems in pure logic be solved, but composite computers can be built which will automatically derive the formulae and set up the program for the solution of a mathematical problem as well as carry out the actual numerical calculations involved. No more can be gotten out of such a computer than is put in; therefore, only the programs of the limited class of problems whose general method of solution is known can be derived by a logic computer. But this function itself will aid greatly in further reducing the repetitive labor necessary in setting up a problem.

B. THE MEMEX

One of the most interesting and important future uses of storage may be that envisioned in the memex. According to Dr. Vannevar Bush, who proposes the memex as a possible future solution of the informational storage problem, the memex is "... a device in which an individual stores all his books, records, and communications, and which is mechanized so that it may be consulted with exceeding speed and flexibility. It is an enlarged supplement to his memory."* The key to the importance of the memex is in the last sentence. The memex is to be more than an individual and personalized library; it will be a mechanism in which stored information can be classified associatively, as in the brain. By establishing an associative connection between pieces of related information upon initial storage, the memex will render obsolete many present-day applications of selective classification. Great amounts of connected information, distributed at random throughout the mass of stored material, may be consulted as though the individual items were bound together like the pages of a book.

Except for the projection forward of current mechanisms, the constructional features of the memex will be conventional. It will consist of a desk into which all of an individual's records can be inserted and classified in the form of microfilm. By using a linear reduction ratio of the order of 100 or greater, it will be possible to store almost an unlimited amount of material in a small portion

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*Bush, Vannevar, Ref. 6, pp. 106-107.

of the desk. Most of the interior will be devoted to the mechanisms necessary for reduction, classification, selection, and projection of the stored material. Not only will it be possible to insert material already on microfilm, such as books, articles, and newspapers, but it will also be possible to enter full-sized material directly by means of a built-in microfilm camera. Thus, pictures, typescript, longhand notes, in short, any material that it is desired to record permanently can be converted to microfilm and stored. In order to facilitate the operation of the memex, Bush states that dry photography will be used. In July, 1945, when the article on the memex appeared, dry photography was a dream; now it is practically a reality, for it is very possible that E.H. Land's "one-step photographic process" (see page) can be adapted for memex-like machines.

One important prerequisite of the memex is thus almost here; others are in developmental stages. The development of fast switching techniques for use in modern computers, together with the consideration of photographic external storage, are contributing greatly to an understanding of the selection and control methods that might be used in the memex. Items that are to be stored will first be given an ordinary selective code number. Such a number might be represented by a pattern of dots on the microfilm for photocell reading. When a code number is specified by means of an external number keyboard, the interior selection mechanism of the memex will first select the approximate storage position designated by the first number of the code, then a closer position as determined by the second number, and so continue until the actual item is reached. Then the item will be projected for reading on a ground-glass viewing surface built into the desk. Selection of actual pages of a book could be easily accomplished by control levers or buttons.

Associative linkage of information will be achieved by making use of the same selective classification numbers. Two items are joined by having each other's classification numbers recorded at specific positions on the microfilm. A trail of items could be built up in this manner by having one piece of information lead on to the next. The trail could be followed either backwards or forwards, and any item could belong to several different trails. In this fashion, it would be possible to interlock a large amount of connected, pertinent data. No longer, then, would it be necessary to trust exclusively to the forgetful associative trails of the brain to establish connection between important items.

Storage would enter in the memex in several ways. Most important would be the storage of a vast amount of microcopy, perhaps representing a specialized worker's entire literature as well as his own relations and inter-relations to it. Next, would be the storage of code numbers on the record. These numbers would store the positions in the memex of the items to which they referred. Finally, it might be useful to increase selection speed in some cases by using a permanent high-speed storage device to store the connection between the code numbers of important items and their precise storage locations.

The memex is virtually a necessity today. The amount of material in almost any modern field of intellectual endeavor is so vast that the possibilities offered by the memex cannot be ignored. By combining the functions of a library and the memory, it offers a practical way of making large amounts of information more alive and useful. As Dr. Bush says:*

> Wholly new forms of encyclopedias will appear, ready-made with a mesh of associative trails running through them, ready to be dropped into the memex and there amplified. ...There is a new profession of trail-blazers, those who find delight in the task of establishing useful trails through the enormous mass of the common record. The inheritance from the master becomes not only his additions to the world's record, but for his disciples the entire scaffolding by which they were erected.
>
> Thus science may implement the ways in which man produces, stores, and consults the record of the race.

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*Bush, Vannevar, Ref. 6, p. 108.

C. FUTURE CLASSIFICATION DEVICES AND TECHNIQUES

Because of the vast extent of the stored knowledge of modern civilization, many interesting and important classification problems have arisen. Most of these problems occur because information is desired in different forms and used in different ways; therefore, no present system of classification is uniquely best.

Three different types of classification may be distinguished according to the kind of path used to locate desired information. First, there is the ordinary selective classification employed in library indexing in which title, author, or subject may be used to lead to the specific information desired by being correlated with a selective code number specifying storage position. Next is associative classification as used in the brain and proposed for the memex. Besides very swift selection afforded by microfilm storage and computational switching, information stored in the memex could be located by following associatively connected trails until the desired items were reached. However, these trails would be necessarily limited in scope and would be only one-dimensional: items would usually be connected in a trail because of one common characteristic, not because they shared a plurality of such characteristics. Great complication would be involved if trails were set up to link associatively all items having a number of common characteristics into a multi-dimensional array of trails such that there would be a separate trail or grouping for each combination of characteristics.

Nevertheless, this type of information is often desired. In chemistry, patent searching, bibliographical work, and many other fields, desirable information frequently occurs in the form of a number of items belonging to a class defined by several generic characteristics. While it is possible to derive such information from an ordinary selective search of the stored material, the labor involved is excessive and extremely time-consuming. The third type of classification, which will be discussed in more detail later in this section, is proposed as an extension to the selective system whereby the above eclectic grouping of information could be accomplished rapidly and automatically. With such a system, information would be selected by a relatively large number of generic characteristics, rather than by a small number of specific qualities.

One of the most interesting future applications of ordinary selective classification is its possible use in connection with the large-scale storage of informational material on microfilm and micro-sheets or micro-cards. Whether microfilm or micro-sheets should be used for a given storage problem would depend primarily upon the type of information desired. Using the rapid selection machine to be presently described, information stored on micro-film could be selected very quickly on the basis of a number of general characteristics. On the other hand, specific items such as books or articles in periodicals are often required. Without the necessity for complicated machinery, the time necessary to find such a specific item could be considerably shortened and the bulk of the stored material greatly decreased through the use of a large number of short, flat micro records.

The use of such flat micro records has been advocated by a number of workers concerned with the problems of general storage.[3,14,17] Fremont Rider has even suggested the use of micro-cards as a possible solution of the entire problem of rapidly expanding libraries. One of Rider's micro-cards is shown in Figure 17; it consists of an ordinary three-by-five file card with reduced record material on one side and full-sized bibliographical information and an abstract of the stored material on the other side. The linear reduction ratio employed in this micro-card is about 10. Space could be further conserved by reducing the ordinary printed material by a factor of two or three (leaving it still readable with the naked eye) and by using a larger reduction ratio for the stored text.

Figure 17 shows the potentialities of micro-card storage; with future techniques, it is easy to conceive of an entire long volume stored on a single file card. A library of such books would require no storage space at all; only filing-card space would be needed, and the process of looking up the file card of a given volume would at the same time locate the volume itself, saving the time usually lost in searching for the volume. Reading could be accomplished by projection at the library, or a few cents would pay for rapid duplication of the volume for memex storage or home projection. Since projection reading is not as convenient and pleasant as the reading of full-size material, a

MISSIONS — CHINA

Hodgkin, Henry Theodore, 1877-

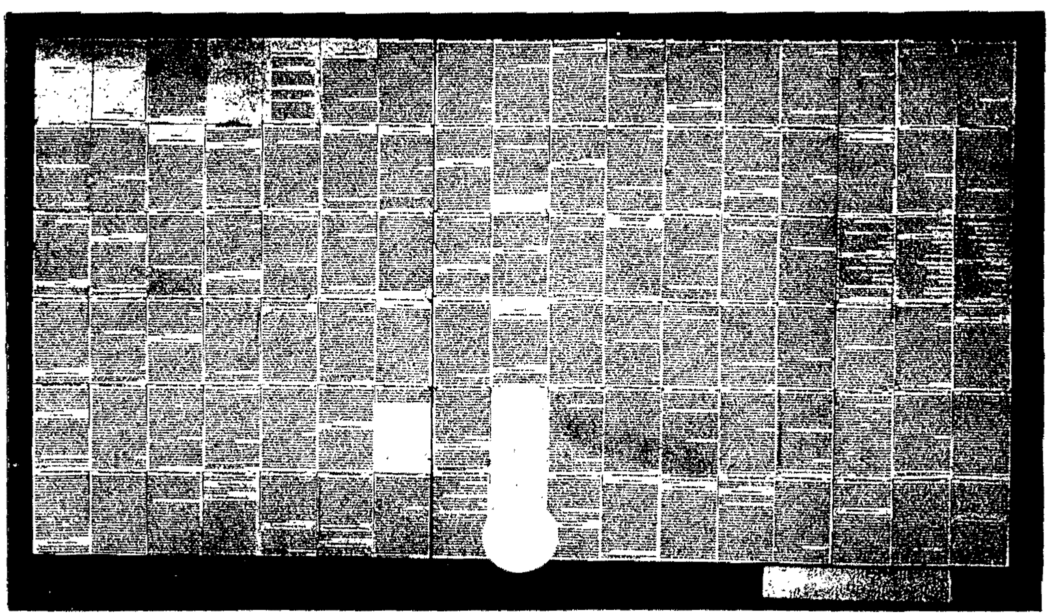
Living issues in China and the possible direction of their solution . . . New York, Friendship press [1932]

(viii, 215p. double map. 19cm. — "Reading list": p. [204]-210.)

Discusses China's government, educational system, social organization, economic conditions, health problems, international relations and religion, and how Christian missionaries can help in solving her problems. Author, a medical missionary in China, 1905-10, served ten years as secretary of the Friends' Foreign Mission Assoc. and seven as secretary of the National Christian Council of China traveling throughout China in its interests. He has written several other books on religion, especially on its missionary aspect.

[1st of 2]

Front, or Catalog Card, Side of a Micro-Card (The "1st of 2" means that the micro-text of this particular book runs over on to two cards, of which this one is the first.)



Back, or Micro-Text, Side of a Micro-Card (This photogravure reproduction of the original micro-text is merely an attempt so show the general appearance of the card; for, being a reproduction of a reproduction, it is not readable.)

Ref. 3, frontpiece.

Fig. 27 A Micro-Card

future technical library might well have a few thousand of the most popular books and current periodicals available unreduced in size. Through the use of micro-cards, storage space could be reduced almost 100 percent, and the time spent in searching for a volume after its classification number was known could be eliminated entirely.

During the 1930's, a machine called the "Rapid Selector" was developed by V. Bush, H.L. Hazen, J.H. Howard, and others at the Massachusetts Institute of Technology.[69] The Rapid Selector is a device which will scan informational items on a film at a rate up to 1000 items a second and automatically select and photographically record all items having a given code designation. The operating principles of the machine are illustrated in Figure 28. A large amount of condensed information is stored as microcopy on 1000 feet of 35 millimeter "index" film. Each separate film frame can contain 250 words of material reduced about 35 times so that a frame occupies 0.1 inch along the film. A code section, consisting of 12 transparent dots, is recorded on the film for each informational frame. Each dot can be recorded in any one of 27 separate positions; therefore, there are 27^{12} code combinations available. As the index film is moved through the machine at the rate of 500 feet/minute, the code selections are scanned by photoelectric cells and a flash lamp energized whenever an item having a specified code is detected. The light from the flash lamp causes each item so selected to be photographed on a 16 millimeter recording film. Because the flash duration is only about a microsecond, it is not

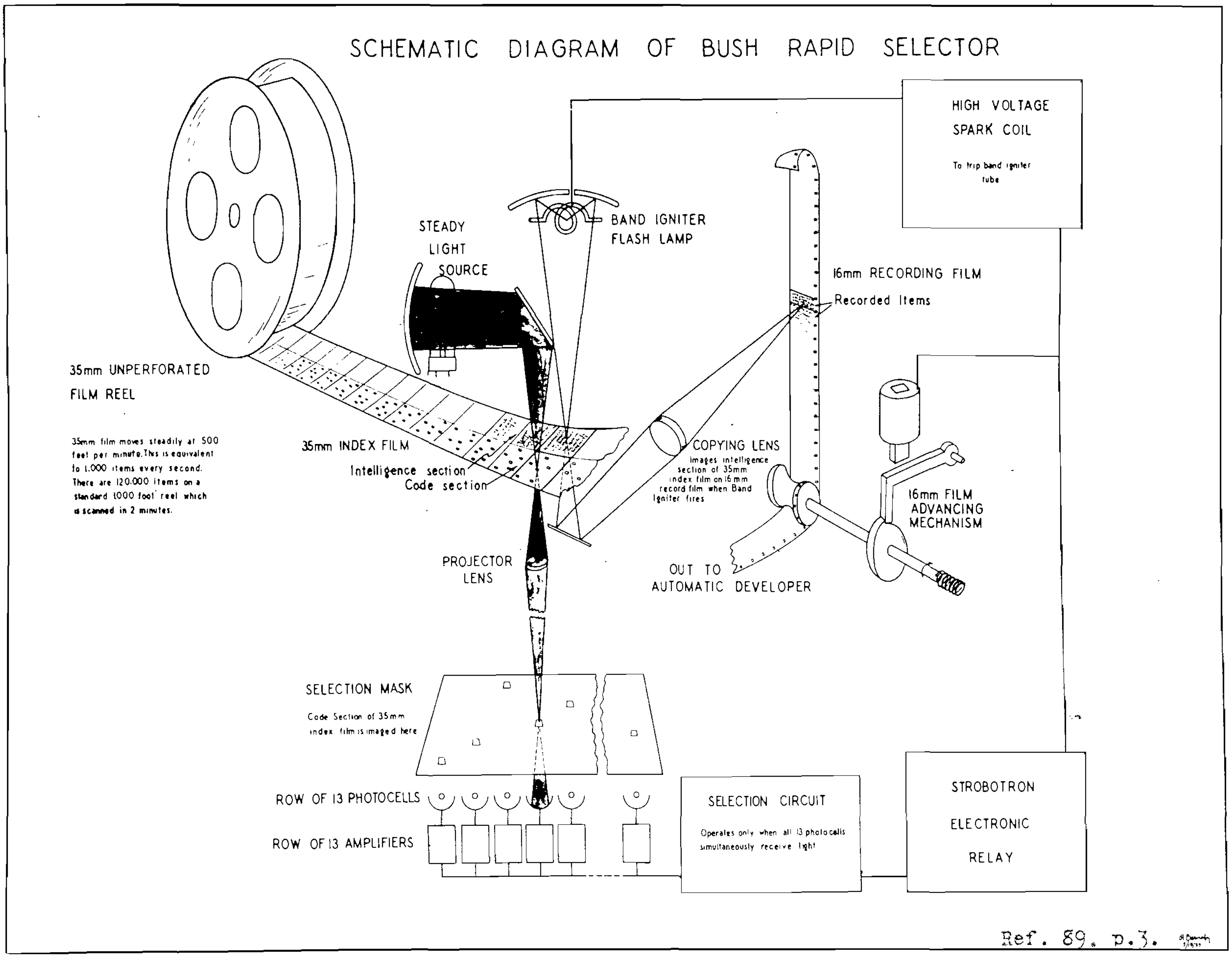


Fig. 28 The Rapid Selector

necessary to slow down the index file for such photography, and clear, unblurred images are produced. Thus, the Rapid Selector is able to select all items having a common code designation from a large body of information and record these items for use outside the machine.

The Rapid Selector is still in a state of incomplete development, but an initial model has been built that indicates that the principles involved are sound. Consequently, here is another example of a device or technique nearing completion which could be used to great advantage in a memex. It should be noted that selection is made on the basis of one code number. Since there are an extremely large number of possible codes available, it might be possible to assign a given code to each combination of characteristics that might be used to specify a given class. A much better scheme, however, would be to use several code numbers for each informational unit or frame. Unless special modifications were made, the first coding method would allow only those units having all the characteristics specified by the code number to be selected. But often a unit might be desired which had these characteristics as well as others; using a single number, the units would have to be assigned to one or the other of the two classes. On the other hand, if several code numbers were used for each unit, it would be possible to cause the flash lamp to be energized only if one, several, or all of the code numbers corresponded to the desired designation. In this fashion, a code could be used for each characteristic of the informational unit, and the unit could be selected by entering any combination of these characteristics in the form of their code numbers. Thus, the third kind of classification previously mentioned could be achieved, and there could be a large number of distinct paths leading to each informational unit. And, unlike ordinary library indexing, even with micro-cards, selection from a vast body of data could be carried out extremely rapidly.

There may be one other place where computational techniques may be used to aid in the problem of classification and selection of data. The Rapid Selector is essentially a statistical device; that is, it operates on data which have been entered on its record medium in accordance with a limited, standardized plan or coding scheme. This scheme is used to determine those ideas in a specific item which might be coded to aid in selection of the item. Not only is such a process extremely long and difficult, but it is dependent upon the background of the person making the choice and so extremely subject to individual variation. By using a logic computer to analyze the items which were to be entered, it might be possible to eliminate such variation and to speed up the process. Since neither the logic computer nor the Rapid Selector is fully developed, such speculation is interesting but not at present profitable.

D. THE CONTROL OF COMPLICATED AUTOMATIC OPERATIONS

Storage has always been used to minimize human labor. The whole trend of mechanization has been toward the substitution of various automatic devices for repetitive human effort. The several sequence-controlled automatic computers already discussed furnish excellent examples of the great saving in time and mental effort that can be effected by the use of a stored control sequence. There is no reason why this same technique cannot be applied to the control of other operations which, although complicated in themselves, are composed of a repetitive sequence of simpler operations. Then, just as an automatic computer economizes mental labor, it would be possible to economize physical effort.

Recently, two Canadians, E.W. Leaver and J.J. Brown, advocated that such control methods be applied to factory processes.[90] They propose an automatic factory in which machines do all repetitive work and where these machines themselves are controlled by other machines. Even more recently, D.P. Campbell, at the Massachusetts Institute of Technology, has stated that several large companies are considering building experimental pilot plants of just such automatic factories.[91]

The main point brought out by Leaver and Brown is that, in contradistinction to current practice, it should be possible to specialize any given machine in terms of its function rather than its product. The primary disadvantage to the accepted specialization in terms of product is that it is extremely inflexible, making it usually impossible to employ a complicated modern machine for anything but what it was originally designed to do. On the other hand, it is theoretically quite possible to analyze the construction of a given product into a finite number of basic functions, such as forming, holding, and cutting. If machines capable of performing these operations were available, it would then be possible to produce a wide variety of end products by altering the sequence of operations.

Leaver and Brown state that "the fully automatic factory requires three types of machine units, all available in reasonably efficient form. These basic units fall into three classes: (1) to give and receive information, (2) to control through collation, and (3) to operate on materials."* Four main types of informational units are also necessary to obtain, carry, and store information, and to carry out calculations. The informational units are also used to supply necessary orders to the collation units, which are servomechanisms providing controlled amounts of power for the machines that carry out the actual fabrication processes.

There are many advantages in the substitution of automatic factories for present-day assembly lines. Besides the most obvious advantage of freeing man from stultifying repetitive labor, the widespread adoption of such an automatic manufacturing technique would lead to a higher standard of living. Because operation

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*Leaver, E.W. and Brown, J.J., Ref. 90, p. 192.

could be continuous and wages unnecessary, goods could be produced more cheaply. An important advantage of the automatic factory, not mentioned by Leaver and Brown, would be the elimination of the major amount of accounting and bookkeeping normally associated with the operations of a factory. These functions could certainly be accomplished most advantageously through the use of automatic calculating machines and computers integrated with the other automatic operations of the factory.

Several different types of storage would thus be necessary in an automatic factory. The most important storage would be that containing the necessary sequences of controlling orders. By storing these orders on tape, libraries of tapes could be built up, as in computational work, so that it would be possible to change the product being manufactured merely by changing the control tape. In a completely automatic factory, a separate computer might be associated with both the fabrication processes and with the bookkeeping and accounting part of the installation. These computers would certainly require several storage media themselves, and it would be unlikely that the same media would be best suited for each.

It seems virtually certain that the transition to an economy partly based on automatic production would cause widespread sociological changes. The adoption of automatic factories would displace more workers than it would make jobs for, but it would yet be instrumental in raising the average technical level of future employment. Although the automatic factory may be slo in arriving and spreading, it presents the possibility of eliminating a great amount of menial labor and of raising the standard of living. Therefore, its eventual acceptance seems inevitable.

G L O S S A R Y

Accesibility Time:	The average time required to introduce or withdraw a given digit to or from storage.
Analogue Computer:	A computer in which numbers are represented by means of continuously variable physical quantities, such as lengths or angular positions of rods, voltages or current, etc.
Binary Number System:	A number system of base (radix) two. All numbers are written as combinations of the two digits 0 and 1. Two is written 10; five, 101; six, 110; seven, 111; etc.
Calculator:	A device capable of accepting two numbers and automatically carrying out one of the simple mathematical operations on them.
Carry-Over:	The process of shifting a unit from one digit place to the next higher place when the first digit place becomes filled through addition and reaches the base of the number system.
Clock:	An internal oscillator of a computer which determines its repetition rate.
Computer:	A machine capable of carrying out automatically a succession of simple mathematical operations and storing the necessary intermediate results.
Conversion:	The process of passing from one representation of a symbol to another (i.e., from punched tape to an internal register).
Decade Counter:	A vacuum-tube counter having ten states of stable equilibrium (also "ring-of-ten" counter).
Digit Time:	The time required to introduce or withdraw a given digit to or from storage when the digit adjoining it in space or time has just been recorded or read out.
Digital Computer:	A computer in which numbers are represented by means of quantities which vary only in discrete steps (also "arithmetical" computer).
Explicit Storage:	Storage which was developed or is now used specifically because of a realized need for storage.
External Storage:	Storage which exists outside of a computer proper and is used to introduce information into the computer and often to augment the internal storage capacity of the machine.

Flip-Flop:	A vacuum-tube circuit with two stable states such that the introduction of a voltage pulse will cause the circuit to switch from one stable state to the other.
Gate Tube:	A vacuum-tube coincidence device so connected that an output is generated only when two or more signals are applied simultaneously to individual inputs.
Implicit Storage:	Storage which did not originate or is not used principally because of a specific need for storage.
Internal Storage:	Storage which exists inside a computer proper and is used to hold partial results of computations and order sub-sequences.
Monetary Economy:	The number of digits stored by a storage device divided by the cost of the device in dollars. As used herein, the cost includes the switching circuits and auxiliary apparatus necessary for storage in the device.
Order:	An operational instruction in coded form to control a computer operation.
Parallel Transmission:	The transmission of the digits of a number (word) in spatial rather than temporal sequence. Therefore, a number of transmission wires equal to the number of digits of the number is required.
Program:	The coded sequence of orders which control the arithmetical operations necessary for the solution of a problem in a digital computer.
Reading Out:	The process of extracting and transmitting information from storage (also "reading").
Recording:	The process of transmitting and introducing information into storage (also "writing").
Serial Transmission:	The transmission of the digits of a number in temporal rather than spatial sequence. Therefore, only one transmission wire is required.
Spatial Economy:	The number of digits stored by a storage device divided by the volume in cubic feet of the device.

Storage Register: A group of discrete storage elements, each capable of storing only a single digit at one time.

Translation: The process of passing from one code to another (i.e., the transition from aural to written words).

Word: As used in computer applications, the many-digit number with which calculations are normally carried out in a computer.

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