AUTOMATIC COMPUTING MACHINERY

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Technical Developments

Magnetic Drum Storage for Digital Information Processing Systems

Introduction.—Automatic digital computers belong to a class of devices which may be described by the term "information processing systems." Some further examples of information processing systems (hereinafter abbreviated IPS) are statistical analysis machines, airline reservation tallying systems, airport traffic control systems, and inventory record systems. A requisite component of every such device is a storage section which serves as a repository for a number of separate items of information. These items, which we shall call "words," may be numerical quantities, alphabetical material, machine instruction codes, or combinations of these.

In many applications it is required to be able to refer at random to any word in storage. Each position in storage which may be occupied by a word is therefore designated by a number called an "address." This type of information store is analogous to a function table, since to each value of the argument, or address, there corresponds a single function value, or stored quantity. In such systems it is necessary to be able to read the word stored at a given position an indefinite number of times without deterioration of that word or of its neighbors. It is also generally necessary to be able to replace or alter the word at a given storage position without disturbing the contents of neighboring positions. Alterable information storage may be physically realized in a number of different ways. Well-known examples of these are electromechanical relays and stepping switches, acoustic delay lines, electrostatic storage tubes, and various magnetic recording devices.

The choice of storage media to suit a given application is governed by several considerations. One of these is the degree of physical stability required of the stored data. In certain applications it is necessary to retain stored information for extended periods, perhaps for weeks at a time. Under such circumstances it is a distinct advantage if the retention of data in storage does not depend on or require the continued operation of electric circuits. For if the stored information is not "volatile," it is possible to shut down the equipment for overnight periods, or for the purpose of maintenance, without loss of data. The *combined* properties of alterability and non-volatility are exhibited by very few of the known physical means of storage. Among these few are stepping switches, latching relays and signals recorded on magnetizable media.

A second consideration governing the choice of storage media is the required capacity, a quantity usually expressed as the number of binary digits or bits of information to be stored. Where large storage is required, the bulky relays and stepping switches present a serious space problem. A two-position relay is capable of storing only a single binary digit of information, while an n-position stepping switch stores only $\log_2 n$ binary digits of information.

With magnetically recorded signals, on the other hand, a large quantity of information may be stored in relatively compact form, as will be shown.

A third consideration is the permissible "access time" or maximum waiting time which may be tolerated in searching for a given storage position and reading or altering the word stored there. Many applications require quick access to any position in the storage. One practical way to satisfy the need for quick random access is to scan the entire mass of stored data continuously at a rapid repetition rate. In the storage system to be described information coded in terms of the binary digits 1 and 0 is recorded on a magnetizable medium on the surface of a continuously rotating cylindrical drum. The small magnetized areas corresponding to individual digits are arranged in parallel peripheral tracks about the drum. Near each track is a single stationary magnetic head for reading and writing the digits in that track. Once in every revolution every magnetized area on the drum is thereby accessible for the effectively instantaneous operations of reading or writing. The maximum access time in this instance is equal to the rotation period of the drum.

The information is recorded in binary coded form so that it is necessary to distinguish between only two magnetic states for each elemental area. There is no need for over-all linearity of the recording and reproducing processes. Specifically, these two magnetic states correspond to positive and negative magnetization of the medium in a direction parallel to its motion. The binary coding requirement imposes no limitation on what may be stored, since information of any kind is readily expressed in a "1 − 0" or "on-off" code. Thus, decimal digits may be recorded as 4-digit binary code groups, and alphabetical characters may be recorded as 5- or 6-digit binary groups. This technique is commonly used in telegraphic systems and in electrical computing devices.

It is the purpose of the present paper to describe a practical method for the alterable, nonvolatile storage of information. For applications requiring these properties, the magnetic drum storage system provides what is felt to be a reasonable balance of the factors: access time, storage capacity, and bulk and cost of equipment.

Utilization of the Storage Surface.—Each word appears on the drum surface in parallel rather than in serial fashion. That is, each binary digit of a 30-digit word, for example, is represented by a single elemental magnetized area, or "cell," in each of 30 separate tracks, rather than by 30 cells in one track. As the drum rotates, the 30 digital cells representing one word pass simultaneously under the magnetic heads in their respective tracks. If each track should contain 4000 digital cells around its circumference, then a group of 30 tracks would store 4000 30-digit words. Several such groups of tracks may be needed to provide the required storage capacity.

The number of elemental areas per track and the number of groups of tracks on a drum are determined by the storage requirements of the application. Suppose that it is desired to store W words of b binary digits each, with maximum access time of T milliseconds. Let R represent the standard scanning rate, i.e., the number of digital cells passing a given magnetic head in a millisecond. Since there is a single read-write station per track, the drum rotation period may be made equal to T. Each head then scans RT digital cells in a revolution. In other words, each track stores RT binary digits. A group of b tracks stores RT words. To provide storage for W words, W/RT such groups of tracks are needed.

For economy of equipment and space it is desirable that the number of binary digits of stored information under the control of each magnetic head be made as large as practicable. Since each track stores RT digits, this calls for a large value of the scanning rate, R. The scanning rate is equal to the product of the drum surface velocity and the number of digital cells per unit length of track. The values at which these quantities have been standardized are 1600 inches per second and 80 digital cells per inch, respectively, corresponding to a value of 128 digital cells per millisecond for R. These are conservative design constants which have been found entirely adequate for reliable discernment of the value of every stored binary digit.

There are eight tracks per axial inch along the drum. Since 80 binary digits are stored in each peripheral inch of track, the storage capacity of the drum surface is 640 digits per square inch. In other words, each binary digit is allocated a rectangular zone having effective dimensions of 0.125 inch parallel to the drum axis and 0.0125 inch peripherally, or perpendicular to the drum axis. This rectangular zone constitutes a digital cell. Whether the stored digit is a 1 or a 0 is established by the magnetic orientation or polarity of a slightly smaller region within this zone. The magnetic polarity of the surrounding area corresponds to the convention chosen to represent 0. A plot of the magnetic intensity along the center of a peripheral track will disclose regions oriented positively and negatively in a direction parallel to the track. If the positive polarity represents 1 and the negative polarity 0, a series of 0's would be characterized by uniform magnetization along the track. A series of 1's, on the other hand, would show up as a series of spots of positive polarity separated by small regions of negative polarity.

Magnetic Heads and Drum Surface Coating.—The magnetic head is a specially designed form of electromagnet with an elongated ring-shaped core. The core has a fine gap on the side adjacent to the drum surface. To write, a winding on the core is energized with a brief pulse of current. The minute area of drum surface under the gap at that instant is magnetized in a direction determined by the polarity of the current and the sense of the winding. The same head serves for reading. As successive digital cells pass under the gap, characteristic signal voltages are induced in a pickup winding on the core. These signals have amplitudes on the order of tenths of a volt. The reading operation does not disturb the stored data in any way.

Although the tracks are spaced eight to the inch along the drum, each magnetic head in its mounting assembly occupies a circular area approximately one inch in diameter, projected on the drum surface. For this reason all of the heads are not placed in a single line parallel to the drum axis but are staggered in position.

The magnetizable medium on the drum surface is a smooth, sprayed-on coating of magnetic iron oxide, the same material which is used on magnetic sound recording tape. This surface is protected by a thin over-coating of a hard lacquer.

Each digital cell passes under its magnetic head many times per second at a 90 mile per hour relative speed. These conditions preclude the use of the contact technique commonly employed in recording on magnetic tape. A clearance of 0.002 inch is therefore maintained between the magnetic head and the drum surface. This noncontact clearance is the principal factor limiting the number of reliably resolvable digital cells per inch of track.

Functional Description of System.—The functional block diagram of a magnetic drum storage system is shown in Figure 1. The dotted boundary surrounds those units which would be considered part of the storage section of an IPS. The channels by which the storage section communicates with other sections of the IPS are shown along the lower edge of the boundary.

The external functions of the storage section are simple. If a word is to be written into storage, the information which must be transmitted to the storage section consists of: (1) the address of the desired storage position; (2) the word to be written; and (3) a control signal specifying that the operation is to "write." If the word occupying a given storage position is to be read, the required information consists of: (1) the address of the desired position; and (2) a control signal specifying that the word at that position is to be "read" to one of several possible destinations (buses to two destinations are shown).

The units with which the storage section communicates are determined by the nature of the IPS. In a computer, for example, the address and the control signals originate in the central program control of the computer. The word to be written may come from the arithmetic section. The destinations for words read out of storage may be the program control section, the arithmetic section, or a printing device.

The storage section communicates internally and externally on a parallel channel basis, in that the several binary digits of a word are transmitted at one time over as many electrical channels. Heavy lines in Figure 1 represent multi-channel buses for the transmission of words or addresses. Light lines represent single or multiple channels for control information. In each external channel, the presence of a pulse indicates a 1 and the absence of a pulse, a 0. The channels within the storage section carry more specialized forms of signals, such as d-c potentials, for example.

The word to be written and the address of the desired storage position are held, until completion of the operation, in the Insertion Register and the Address Register, respectively. These registers consist of toggle-circuits, or static flip-flops. A toggle-circuit is an electron tube circuit having two symmetrical stable states so that it is capable of holding a single binary digit of information.

Upon completion of the specified writing or reading operation, a control signal announcing completion is sent out by the storage section. At the same time, the Address and Insertion Registers are cleared, so that the storage section is then receptive to further assignment.

In the interest of clarity, the operation of the system will be described in terms of an example having a specific set of storage characteristics: (1) word size, b: 30 binary digits; (2) capacity in words, W: 8192 or 2^{13}; and (3) maximum access time, T: 16 milliseconds. The number of words which can be stored in each group of 30 tracks is equal to RT, or 2048 (128 times 16). Four track groups must therefore be provided, plus several additional tracks for location and timing purposes. These are indicated in Figure 1.

The 8192 storage positions are designated by 8192 addresses. While the addresses may be *any* set of 8192 distinct binary coded designations, that set which consists of all the 13-digit binary numbers is the least redundant and most economical of equipment.

The 13-digit address is composed of two parts, a 2-digit "group index" and an 11-digit "angular index." The group index specifies one of the four, or 2^2, groups of tracks. The angular index specifies one of 2048, or 2^{11}, angular positions of the drum.

In addition to the 120 storage tracks, there are 11 angular index tracks and one timing track. These tracks contain permanently recorded information. The angular index tracks contain the 2048 11-digit angular indices. The timing track serves as a source of timing pulses, for precisely marking the instant at which the drum passes through each of its 2048 discrete angular positions. One of these timing pulses, selected on the basis of the desired angular index, denotes the instant at which the desired storage position is available for reading or writing.

Time-selection is performed by an 11-fold coincidence detector which continuously compares the desired 11-digit angular index in the Address Register with the outputs of the circuits which read the angular index tracks. As long as the scanned angular indices do not match the desired angular index, timing pulses cannot get through the coincidence detector. When the drum passes through the angular position at which a match occurs, a single time pulse is delivered to the storage control circuits for triggering of the appropriate writing or reading operation.

The function of the Writing Circuits is to replace the word at the specified storage position with the word standing in the Insertion Register. There is a Writing Circuit associated with each of the 120 storage track magnetic heads. A Writing Circuit contains two miniature thyratrons, each of which can discharge a simple network through a winding on the magnetic head. The 30 pairs of thyratrons in the selected group are simultaneously triggered by a pulse from the storage control circuits, but only one thyratron in each pair fires, one to write a 1, the other to write a 0. One of the thyratrons is prevented from firing by application of a negative bias to its shield grid. The choice of 1 or 0 is determined by the value of the corresponding digit in the Insertion Register.

It should be noted that there is no need for "erasure," as such, since the operation of writing a word into a storage position substitutes the new word for the previous contents of that position. The word stored at a given position is simply the one that was written there last.

The use of thyratrons instead of "hard" vacuum tubes in the Writing Circuits effects a significant saving in the number of tubes. The time which must elapse between successive writing operations is admittedly longer for thyratrons. However, the duty-cycle required of the writing operation is generally so low that this limitation is of little consequence.

The reading operation consists in transmitting to the specified destination the word stored at the position specified by the address in the Address Register. The units which participate in reading are indicated in Figure 1 as Reading Gates, Reading Circuits, and Output Gates.

Track group selection is accomplished in the Reading Gates. These are preamplifiers which are either blocked or operative, as determined by control voltages. Each of the 120 Reading Gates receives signals from its associated magnetic head, but only the selected group of gates transmits signals to the Reading Circuits.

The Reading Circuits are 30 in number and consist of amplifiers and wave-form shaping circuits. These operate continuously on the signals originating in the selected group of tracks.

The amplified signals from the Reading Circuits are impressed on two sets of Output Gates, one for each destination. At the instant denoted by the selected time pulse, the appropriate set of Output Gates is pulsed. This operation, by sampling the signal stream from the Reading Circuits at the correct time, transmits the desired word to the specified destination.

The Storage Control Circuits consist of electronic switching and gating circuits for translating the group index code, the selected time pulse, and the external control signals into the appropriate group, time, and destination signals. The Storage Control Circuits also include automatic lockout delays which prevent a storage reference operation from following a previous one too closely to permit complete circuit recovery. These delays are of the order of 50 microseconds, except in the special case of a writing operation which follows a previous writing operation. In this case, the second writing operation must not take place until about 2 milliseconds after the first. If a storage reference operation is initiated too soon after a previous one and the desired angular index comes up before the lockout delays have cleared, the effect is simply to delay execution of the operation for one drum revolution.

TABLE I

Characteristics of 36 Magnetic Drum Storage Systems

Capacity (Wb), binary digits	Max access time (T) milliseconds	Drum dimensions, inches		Magnetic heads	Word size, b = 15 binary digits				Word size, b = 30 binary digits				Word size, b = 60 binary digits			
		Diameter	Length		Words (W)	Track groups (W/128T)	Electron tubes	Tubes per 1000 digits	Words	Track groups	Electron tubes	Tubes per 1000 digits	Words	Track groups	Electron tubes	Tubes per 1000 digits
61,440	8	4.3	10	71	4,096	4	500	8.1	2,048	2	630	10	1,024	1	910	15
122,880	8	4.3	18	131	8,192	8	690	5.6	4,096	4	820	6.7	2,048	2	1090	8.9
245,760	8	4.3	33	251	16,384	16	1080	4.4	8,192	8	1200	4.9	4,096	4	1460	5.9
122,880	16	8.5	10	72	8,192	4	510	4.2	4,096	2	640	5.2	2,048	1	920	7.5
•245,760	•16	•8.5	•18	•132	16,384	8	700	2.8	•8,192	•4	•830	•3.4	4,096	2	1110	4.5
491,520	16	8.5	33	252	32,768	16	1090	2.2	16,384	8	1210	2.5	8,192	4	1480	3.0
245,760	32	17	10	73	16,384	4	520	2.1	8,192	2	650	2.6	4,096	1	930	3.8
491,520	32	17	18	133	32,768	8	710	1.4	16,384	4	840	1.7	8,192	2	1120	2.3
983,040	32	17	33	253	65,536	16	1100	1.1	32,768	8	1230	1.3	16,384	4	1490	1.5
491,520	64	34	10	74	32,768	4	530	1.1	16,384	2	660	1.3	8,192	1	940	1.9
983,040	64	34	18	134	65,536	8	720	0.73	32,768	4	850	0.87	16,384	2	1130	1.2
1,966,080	64	34	33	254	131,072	16	1110	0.56	65,536	8	1240	0.63	32,768	4	1500	0.76

The timing pulses in the storage section need not be synchronized with the clock or timing pulses in other portions of the IPS, since all digital and control information transmitted to the storage section is received and temporarily held in toggle-circuits. Information transmitted from the storage section is received on a toggle-circuit or relay register at the destination, which provides similar buffer storage. The property of asynchronism obviates the need for precise control of the angular velocity of the drum.

Characteristics of Typical Systems.—The principal characteristics of 36 typical drum storage systems are listed in Table I. These examples are all similar to the one shown in the block diagram of Figure 1, with variations in access time, storage capacity, and word size. All designs are based on a common set of physical parameters: 128 digital cells scanned by each head per millisecond; 80 digital cells per inch of track; and 8 tracks per axial inch of drum.

Each of the 12 horizontal lines of the table corresponds to a drum of given diameter and length. Four values of diameter and three values of length are represented. The four diameters correspond to drum rotation periods or maximum access times of 8, 16, 32, and 64 milliseconds. The three lengths are for drums having 60, 120, and 240 storage tracks (in addition to angular index and timing tracks). Each line of the table contains characteristics of three systems corresponding to word sizes of 15, 30, and 60 binary digits. Characteristics of the particular example described in connection with Figure 1 are identified in the table by asterisks.

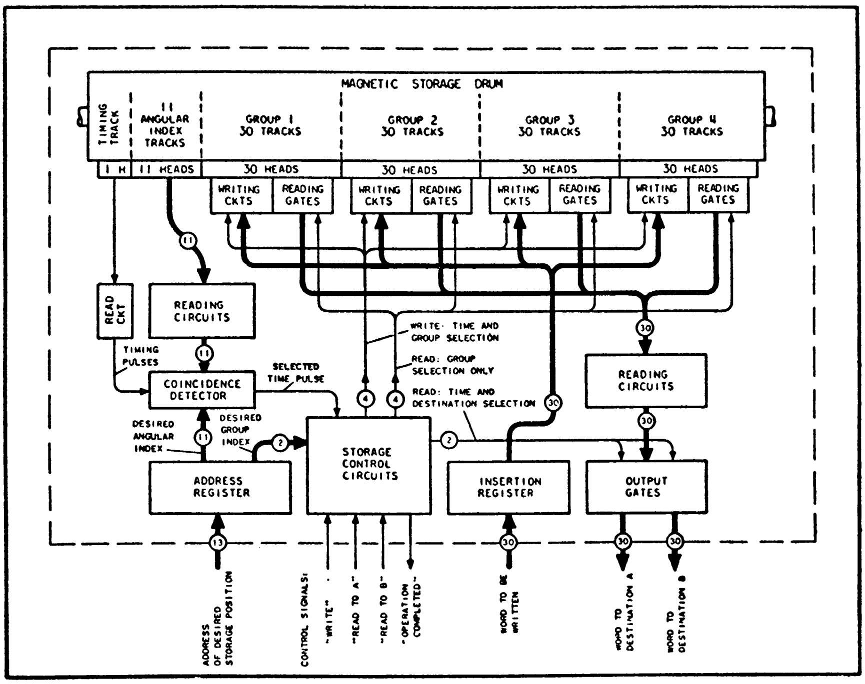

FIG. 1. Functional Block Diagram of Magnetic Drum Storage System.

The table contains information as to the number of magnetic heads and the number of electron tubes required for each example. It will be noted that the number of tubes is essentially constant for a given word size and drum length. Under these conditions the access time and storage capacity are both directly proportional to drum diameter.

Circuit cost per unit storage capacity may be expressed in terms of the number of tubes per thousand binary digits. This quantity is seen to be a decreasing function of access time and storage capacity, each considered independently, and a moderately increasing function of word size.

An idea of the space occupied by a given storage system may be gained from the tabulated data. The size of each drum is given in the table. The size of the cabinets needed to contain the electronic circuits may be estimated by allowing about one cubic foot for every 30 tubes.

Loading of Drum.—The contents of storage undergo numerous changes during the course of operation of an IPS. The entering of initial contents and the introduction of new data at occasional intervals is a function of the input section of the IPS. The choice of the input medium is governed largely by the application. Input data may be on magnetic tape or wire, punched cards, punched paper tape, or perhaps even introduced manually from a keyboard. The present storage system is capable of accepting successive items at rates up to about 500 *words* per second.

An input system using punched paper tape as the medium has been developed for use with a storage system similar to the example of Figure 1. The tape is scanned by a photoelectric reading device at a nominal speed of 75 feet per minute, corresponding to a storage insertion rate of 1800 30-digit words per minute. Even if it should be desired to load the entire drum, it would take only about five minutes to fill the 8192 storage positions. The magnetic drum rotates continuously at its normal speed during the loading operation. The tape feed need not be synchronized with drum rotation. Simple means are provided for loading sequences of data into any desired storage positions, in any order.

Some Possible Variations.—The described function table type of magnetic drum storage system embodies only the simplest and most straightforward features. Departures from these properties may be desirable to suit the needs of certain applications.

For example, it is possible to shorten the access time in a system of given capacity by assigning two or more magnetic heads to each track in place of one. Another way to shorten access time, but at the expense of storage capacity, is to repeat the stored information in several equal sectors about the drum. This method is useful only if reading is a more frequent operation than writing.

It is possible to add considerable flexibility to the manner in which stored items are located for reading out. If suitable coincidence detectors are provided, items written into storage in the standard way may subsequently be located on the basis of certain sets of digits *within* the stored words.

Although communication within the storage section is on a parallel-channel basis, the described system may readily be made part of an IPS operating serially, i.e., one in which the several digits of a word are transmitted sequentially over a single channel. This requires that the Address Register and the Insertion Register be endowed with the property of shifting. The incoming word then arrives digit by digit at one end of the receiving register. The register shifts its contents by one place upon arrival of each digit, until the complete word is assembled. Shifting registers must also be provided for transmitting words out of the storage section in serial fashion.

Status.—The developmental status of the magnetic drum storage technique at the time of this writing (May 1949) may be summarized as follows. A complete pilot model of the described function table type of system is undergoing final tests. Although this model is scaled down in capacity and word size, the standardized values of the physical parameters are used, and every basic system function is included. Tests of every operating function under every expected condition have been performed with a repeated reliability which confirms the adequacy of the selected design standards. Reliability of the basic circuits and of the magnetic and mechanical components has been further established in an extensive laboratory program of component research and in the development of other types of magnetic drum storage systems during the past two years.

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DISCUSSIONS

Notes on Modern Numerical Analysis—I

EDITORIAL NOTE: There is a general feeling that, once the problems of construction and maintenance of automatic digital computing machines are solved, the remaining problems will be relatively simple. This may be the case if attention is confined to standard classical problems; however, if an attempt is made to use these machines fully, one is likely to encounter formidable mathematical difficulties. It is expected that these difficulties will be discussed in the current mathematical journals; but there are also smaller, more technical problems which may cause trouble. It is believed that a discussion of these smaller problems will prove beneficial in avoiding a great many difficulties which are expected to arise when the machines are in actual operation; and we should like to urge interested persons to submit technical notes of this nature for future publication in the Automatic Computing Machinery Section of *MTAC*. These notes could be by-products of or preliminaries to more constructive investigations. It would be a great advantage, for expository purposes, if the authors, even at the expense of a choice of an extravagant example, could exhibit the troubles under discussion on a manual scale.

Solution of Differential Equations by Recurrence Relations

1.1. In general the most satisfactory method for the numerical solution of ordinary differential equations is one of the "extrapolation" methods.[1] These methods have proven very efficient in the hands of a practiced computer. There is little doubt that some of the experience he uses could be codified and adapted for use on automatic digital computing machines. Nevertheless, the use of some direct recursive process is very attractive and worth investigation.

Let us consider the solution by such methods of the equation

$$y'' = -y, \tag{1}$$

with the boundary conditions $y(0) = 0$, $y'(0) = 1$, by use of the well-known formula [2]

$$h^2y'' = (\delta^2 - \tfrac{1}{12}\delta^4 + \tfrac{1}{90}\delta^6 - \cdots)y. \tag{2}$$

1.2. First let $h = 1$, using only the first term on the right-hand side of (2). If the condition $y'(0) = 1$ is replaced by $y(1) = 1$ the following recurrence relation is obtained

$$y(n+2) = y(n+1) - y(n) \tag{3}$$