A Survey of Digital Computer Memory Systems

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Classic Paper

Many types of storage and memory systems have been proposed for use in digital computing systems. This survey paper discusses only the various systems whose reaction time is faster than human reaction time, employing a historical approach to the subject. Criteria for evaluation are discussed, and comparisons given among the different systems as to general applicability, ease of construction and use, speed of operation, latency time, memory span, and economy.

I. Introduction

The history of the development of calculating devices includes in its scope the development of the many memory systems which have been considered, tested, used, held in abeyance, or discarded.

The concept of memory includes all forms of temporary and permanent storage of information for use in and by the computing device. A memory is a means for displacing in time various events which depend upon the same information. It is also a mediating device, a means for matching various speeds of operation to each other for the maximum efficiency of the computer components.

In the first instance the memory is much like the scratch pad used by a human being working a problem at a desk. It provides a place to put intermediate or auxiliary results, or to retain the original data of a problem. The center of concentration is focused one calculation at a time. In the second instance storage facilities such as punched cards, magnetic tape, punched paper tape, and other media can be used for matching the high, internal operating speeds of an output printer, or of a typist at some input device. The principal focus of this paper is the internal storage memory, the scratch pad of the computer data-processing circuits.

Upon looking into the systems which have been proposed for digital computers alone, one cannot help being struck by their wide variety and surprisingly large number. Many of these were, and may still be, impractical; yet there is no reason to believe that they must remain so, or that systems other than those already proposed may not be added to the list in the future.

Because there is such an abundance of examples, the better picture of the evolution of memories is probably given by a historical approach to the subject. Regardless of the approach, however, there are certain characteristics which inhere in any system of memory, and by means of which each may be evaluated.

One of the most important of these is the speed of operation, the rate at which reading-in and reading-out are accomplished. This is an especially important criterion in considering memories for high-speed computers.

The manner in which data are stored once inserted into the memory is another characteristic by means of which the various systems can be classified.

Additionally, speed of operation must be considered in terms of cost. The ratio is not a direct one: generally it is unwise to pay twice as much for doubling the speed. As a matter of fact, an increase of greater than 20% in cost for doubling the speed of operation is usually considered unwise.

Furthermore, the balance of speed in all parts of a computer is important. It is foolish to have processing circuits—arithmetic circuits, and so forth–operating so fast that they must sit idle half the time waiting for other circuits to catch up. Thus the speed of a memory system will be strongly influenced by the cost of achieving that speed, and by the requirements of the other circuits.

To reduce the scope of this topic for the purposes of this paper, an arbitrary limit has been set on the speeds of the devices discussed so as to include only those systems whose access time or operation time is somewhat better than human reaction time. This lower limit ranges somewhere between one-tenth and one-thirtieth of a second; any slower device has been excluded.

II. Early Digital Memories

Predating the electronic computer are a number of familiar memory devices which should be considered before attacking more recent developments. The punched card, for example, is one of the most common memory devices for computing equipment. Before it, however, was the Jacquard loom system, wherein cards controlled the design being woven on the loom.

Co-existent with these was the mechanical assembly, usually called the accumulator, used in desk calculators and in tabulating equipment. The original design for mechanical accumulators dates back to Pascal and Leibnitz in the 17th

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century. Modern machines are refinements of those early ideas.

As far as electrical devices are concerned, relays and stepping switches have long held a prominent position as memory devices. A combination of electrical and mechanical components is used in the Lake Adder and Lake Storage units, which are a part of so much IBM equipment. In these units one finds a magnetic release followed by mechanical operation.

Among thermionic devices one of the earliest truly digital ones was the ring counter made with thyratrons by Wynne–Williams in England. The thyratrons were capable of firing rapidly, but tended to turn off slowly. This characteristic was tolerable in a ring circuit, since the slow die-out time was not a severe limitation as long as the next stage triggered rapidly. A development of Wynne–Williams' work was the cold cathode ring built out of OA4G's. The first such ring was built by Mauchly at Ursinus College some time in 1938.

The classical Eccles–Jordan trigger circuit, or flip-flop, another early device, was the first hard-tube counter. Its uses since its origin have been legion. At MIT, an efficient cascade of these trigger circuits was developed as a ring counter.

Since each stage of this type of circuit requires two tubes, a decimal-type counter involves 20 tubes—perhaps ten envelopes. With some improvements, this basic circuit was used in the ENIAC. The improvements included careful consideration of all the tolerances, and cathode-coupling the circuits so that no two stages could come on at one time.

Another counter called a Lewis ring was developed from the Eccles–Jordan circuits. In the Lewis ring a single tube was used for each stage, and each tube was connected through a resistor to every other tube in the circuit. Lewis also developed the biquinary counter, requiring only seven tubes (compared to the 20 of the Eccles-Jordan-MIT ring) for a count of ten. Although the biquinary Lewis counter was known at the time of the construction of the ENIAC, it was not used because it required stable resistors, which were then much more expensive than they are now.

RCA, Remington Rand, and Bell Telephone Laboratories all have developed biquinary counters, the latter organization using relays. In the Lewis counter the quinary counter was stepped at each pulse, while the "bi" stage indicated whether the quinary was going through its first or second trip. The RCA biquinary system operated in the opposite way, with the "bi" stage stepped by each pulse. This is a better method since the binary counter, which has the simpler tolerance problems, is made the fast counter. In the Remington Rand 409-2 calculator, an ingenious method of pulsing both stages at the same time has been used.

A cascade of four binary counters or flip-flops provides another approach to the problem of a decimal counter. Potter at GE and Grossdoff at RCA both worked on this approach. The circuit is in wide use (in IBM 604 calculators, for example). There are probably more tube sockets now devoted to this type of circuit than to any developed thus far. This type of counter requires regenerative or jamming

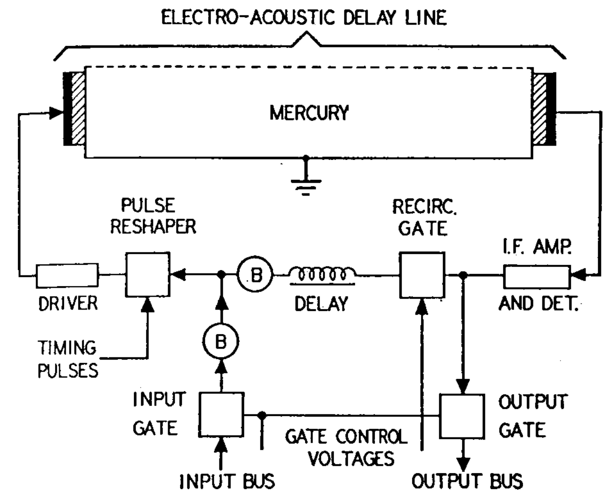

Fig. 1. Block diagram of UNIVAC acoustic memory.

connections which force the 16 possible states to become, in effect, only ten. An important step in the development of this system was regenerating or jamming at two different points in the ten-count, so that one counter stage would not be loaded with a regenerating connection to two other stages.

Probably the first example of what might generally be termed regenerative memory was developed earlier than 1942 by Atanasoff in Iowa. He used a drum with many capacitors mounted on it, and with a commutative method of connecting the capacitors with brushes for reading-in, reading-out and regenerating. The principal feature of the capacitor memory was the use of cheap, reusable elements. The capacitors could be charged, discharged and recharged as often as desired, and they were common and readily available components. The characteristics of small initial expense and almost unlimited reusability have guided the development of memory systems since, and remain two important criteria of the merit of any system at any time. There may have been similar systems prior to Atanasoff's but none was as inexpensive to construct. Unfortunately his development was interrupted by the war and never completed.

Another early reference to practical and relatively inexpensive large memory systems is given in a thesis written by Crawford at MIT in 1942. This thesis discussed certain fire-control computing apparatus in which the various functions representing firing table data were to be stored in the form of magnetic recording on discs. Out of this thesis grew the magnetic-drum and magnetic-disc memory system.

In 1944 the author submitted to the Moore School of Electrical Engineering at the University of Pennsylvania a memorandum which recommended the use of drums or discs for the general storage of all data required by a computer—not only the numbers being processed, but also instructions, functions required for the computation, timing channel signals, and so forth. This memorandum became the basis for the design of the EDVAC memory. The EDVAC design was subsequently switched from magnetic discs and drums to mercury tanks, principally for the reason

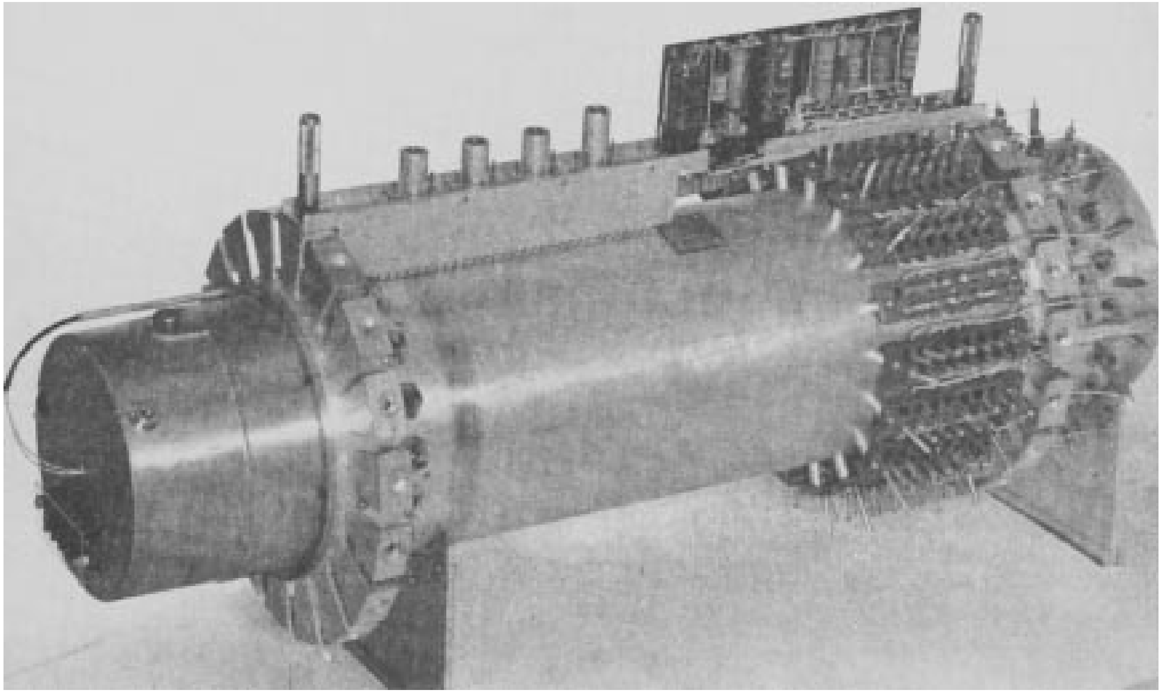

Fig. 2. Photograph of mercury tank used in UNIVAC.

that the mercury tank was a faster system at that time. Furthermore the engineers who worked on EDVAC were familiar with the use of mercury tanks, having previously developed a mercury-delay tank at the Moore School for some radar problems.

III. Delay-Line Memories

The basic concept of a delay-line memory is simple: an information pattern is inserted into a path containing a delay element. From the end of the delay element the pattern may be fed back to the beginning through amplifying and timing circuits, thus forming a closed loop for recirculation. In simplest terms, a delay-line memory is equivalent to the short-range human device of repeating a phone number to oneself from the time it is located in the phone book until it has been dialed. The delay medium should slow the propagation rate of the information sufficiently that the physical size of the storage equipment for a large number of pulses will be within reason.

A large variety of media has been suggested for use in delay-line memories. Some of these transmit the information pattern acoustically, some electromagnetically. In the acoustic field mercury has probably received the widest use so far. The BINAC, built by the Eckert–Mauchly Computer Corporation for Northrop Aircraft, included a mercury tank memory of 18 channels, each of which could hold 32 words of 36 bits each. Today the UNIVAC uses a similar mercury memory of 100 channels, each of which holds ten 91-bit words. Both the BINAC and UNIVAC memories hold approximately 1000 pulses per channel.

The block diagram of the UNIVAC memory channel is given in Fig. 1. At each end of the mercury column is a transducing crystal, backed by a special metal alloy mounting piece is shaped and designed to absorb reflections. The loop is closed through the recirculation amplifier, which contains not only the amplifying, timing and reshaping circuits, but also the gates through which data are read out and in, and by means of which the tank is cleared entirely. Fig. 2 shows a complete tank with one of the 18 recirculation chasses mounted on the shell.

The mercury tank requires rather precise temperature control since the velocity of an acoustic wave varies directly as the density of the propagating medium, which is a function of its temperature. The requirements are not so excessive as to have presented insurmountable problems, however.

One possible solution to the problem is to maintain no control of temperature, and to vary the master oscillator so that the delay through the tank is constant relative to frequency. On the other hand, an equally feasible solution is to use a crystal-controlled master-oscillator frequency as an absolute standard, and control the temperature to maintain a precise delay. The latter method has the advantage that electric delay lines can be used in the associated circuitry without additional compensation.

There are, in each of the seven mercury tanks in UNIVAC, a coarse and a fine temperature control. The coarse control operates from the expansion and contraction of the mercury. An expansion bellows at the end of the mercury column operates a microswitch, which applies power to a set of heating coils on a purely on-or-off basis. The signal for modulating the current through the heating coils of the fine temperature-control system comes from one of the 18 memory channels specifically reserved for the purpose of controlling temperature. A standard signal circulates through this channel, and its time of arrival at the end of the

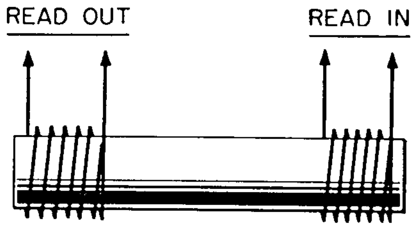

Fig. 3. Magnetostrictive delay line.

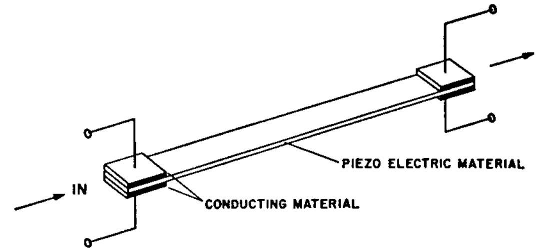

Fig. 4. Piezoelectric delay line.

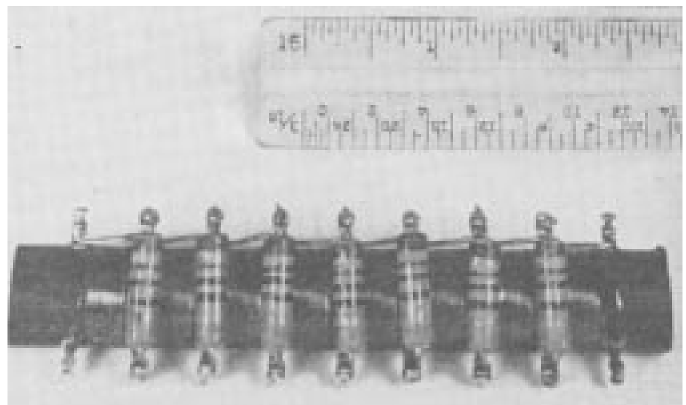

Fig. 5. Photograph of a lumped-parameter delay line.

delay line is compared with the timing of a control signal from the master oscillator. The results of this comparison adjust the heating-coil current.

Short mercury tanks are used in UNIVAC for the storage of 91 pulses (one word) in the small registers associated with the data-processing circuits. The same general design can also be used for the storage of two words, or half a word. In these small tanks the problem of temperature control is less severe, and a simple on-off control has been found adequate.

Other media have been proposed and tested for acoustic propagation systems. Quartz was tested at MIT and was used by the Japanese during World War II. The Japanese used a special powdered-glass coating on the outer surface of the quartz to suppress certain undesirable modes of wave transmission. Magnesium bell-metal was used by the Raytheon Corporation, while steel, lead, and glass were tried at the Moore School. MIT also experimented with glass. The Naval Research Laboratories have worked with thin steel rods wound in a helix with transducing crystals at each end. The crystals are without backing, and the lines are only useful to a fraction of a megacycle.

The choice of media for the UNIVAC memory fell heavily in favor of mercury. It is a stable liquid which can readily be matched to transducers such as quartz crystals; being a liquid, it will not support any waves except longitudinal-compression and surface waves, and the latter are suppressed when the mercury is enclosed in a tank; it has uniform characteristics achieved through careful distillation, and it has no localized strains to cause spurious patterns. Solids generally support shear waves, and usually present problems in coupling to suitable transducers.

Another type of delay line is one in which essentially acoustic patterns are propagated through a medium as a result of either magnetostrictive or piezoelectric effects. The Hazeltine Electronics Corporation first developed a nickel-ribbon magnetostriction system, and later a method using nickel wire. Elliott Brothers in England have also worked on nickel wire. Fig. 3 shows a magnetostrictive memory using ferrite as a medium. The read-in coil, when pulsed, produces a longitudinal-compression wave in the ferrite. This wave travels down the line and induces a current in the readout coil. This current can be detected and put through a regenerating circuit to make a continuous loop.

In the piezoelectric delay line illustrated in Fig. 4 a pair of conducting plates are supplied with a voltage pulse which produces a double-shear wave in the piezoelectric material. This wave travels along the line to the output plates where a voltage pulse is generated.

A third form of dynamic storage, which has seen wide acceptance, is the electric delay line. There are two types of these: distributed parameter and lumped-parameter lines. Fig. 5 is a photograph of a lumped-parameter line.

Both types of lines were thought of by Pupin sometime in the late 19th century. More recently, MIT and Bell Labs worked with distributed-parameter lines with lumped-parameter phase correction networks at the end. Kallman, at MIT, worked with distributed-parameter lines, placing semi-lumped phase correctors consisting of tinfoil at uniform intervals along the line. Experiments performed at the Moore School by the author produced some distributed-parameter lines with metal-ribbon phase correction windings. Maximum surface-to-surface apposition of the metal ribbon resulted in large interwinding capacitance. Double-layer wire windings were used, with the same aim.

The General Electric Company developed a system in which the line was sprayed with aluminum paint to provide continuous phase correction. A distributed-parameter delay line made by Millen is used by the Bureau of Standards in the SEAC. At frequencies under a megacycle such a line is economically useful with proper circuits up to about eight pulses. The continuous-parameter line tends to become comparatively less efficient than the lumped-parameter line for more than eight or so pulses. Neither type is as efficient spacewise as the acoustic line since each type requires greater space for a given amount of memory, and both electric types are expensive except for a small number of pulses. Wherever lumped-parameter lines are used in UNIVAC, the signal is regenerated after every seven-pulse delay (although 30 pulses were stored in an electric delay line with only one regeneration station in the

BINAC). Electric lines cause comparatively large signal attenuation in any event, but lose almost nothing in the input or output coupling; signals passing through acoustic lines, on the other hand, suffer little attenuation in the medium, but are severely attenuated in the transducers at each end.

The use of any delay-line memory usually makes time-sharing of the recirculation circuits impractical. Other disadvantages of the delay line are the awkward amount of access time (the maximum access time being the length of the delay) and the amount of terminal equipment involved. Making longer channels amortizes the terminal equipment over more memory, but increases the access time and presents a greater problem in temperature control.

IV. Electrostatic Systems

Under the general heading of electrostatic memory systems are many different examples, some of which differ only slightly from others. Basically there are four types, referred to as the surface-redistribution, holding-beam, barrier-grid and sticking-potential types. The surface-redistribution type is sometimes called the interfering-periphery type.

Although the basic phenomenon of electrostatic storage was illustrated in the earliest iconoscopes, such a recording was continuous in nature. Some of the first experiments with the electrostatic principles aimed directly at the digital problem were inducted at the Moore School by Sharpless and the author. Prior to this, McConnell at MIT did some work recording radar signals. Other early experiments with this type of system were performed by Forbes at MIT and Williams in England. The latter system has been quite widely and successfully used in various digital computers.

There are some characteristics of electrostatic systems, and criteria for their evaluation, which differ markedly from the characteristics of delay line. The retentivity ratio—the ratio of the retention time to the read-write time—is one of these. In a delay line the two are identical, and the ratio is one. A complete cycle of the delay line is required for reading in or out; this is also the retention span of the line. (Obviously a system with a ratio less than one is infeasible, since the read-in or readout time exceeds the memory span, and the second cycling would override part of the first.) The retention time is usually larger than necessary in an electrostatic storage tube.

Another important characteristic of electrostatic systems is the redistribution, or “read-around” time. This is the maximum time during which a spot may be read without destroying the spots in the vicinity. This characteristic determines when the adjacent spots must be regenerated in terms of the total time the reading beam has spent on a selected spot. The ratio of read-write time to redistribution time is an excellent indication of the requirements of the regeneration system. For example, with redistribution time measured in milliseconds and read-write time measured in microseconds, this ratio would be on the order of 10^3. If, in such a circumstance, there were 10^3 spots on a tube, then regardless of the absolute rate, regeneration should occupy half of the time, allowing reading and writing to occur during the other half. Improvements in the redistribution characteristic could improve this situation, by permitting either less frequent regeneration or increased spot densities.

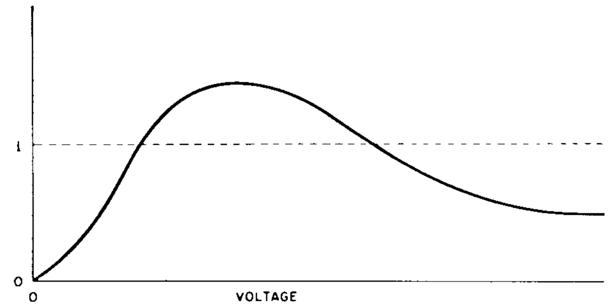

Fig. 6. Ratio of primary to secondary electrons versus voltage.

A. Surface Redistribution System

An interfering-periphery, or surface redistribution, storage system developed at the Eckert–Mauchly Laboratories is similar in concept to most of this type of store. It will be used as a model in this discussion.

Most such storage systems depend on the secondary-emission phenomenon. Fig. 6 shows the relationship of primary and secondary emission as voltage increases. The region wherein the secondary emission exceeds the primary is the important area of this graph. When this ration exceeds one, the potential of the spot on the screen goes positive.

This alone, however, is not enough to allow storage of the binary digits or two-level signals required by the usual digital computers. In order to achieve two-level storage two different patterns must be stored on the face of the tube, one of which is used as a reading pattern. If the reading pattern is the same as the stored pattern, there will be little change in the charge on the face of the tube when reading occurs. If the reading pattern is different, the stored pattern will be destroyed and changed to the reading pattern. It is this change from one pattern to another which produces a total change of charge on the face of the tube. A fine wire mesh may be placed over the outside face of the tube to detect this change by capacitor action.

Numerous charge patterns have been devised and tested, some of which are illustrated in Fig. 7. It is desirable to choose two patterns whose peripheral interference is large. Our experiments have been concerned mostly with the dot-circle and focus-defocus patterns shown on lines D and C of the illustrations. More widely used, however, is the dot-line (or dot-dash) of line A and an adjacent-dot system similar to line F. The original dot-line system was developed by Williams in England.[1] The signals at the right of Fig. 7 are suggestive in shape only of the typical output signals obtained when the smaller-periphery shapes are read by superimposing the larger patterns.

The block diagram of the surface-redistribution system is given in Fig. 8. The blanking circuit cuts off the beam while

[1] Comparison and discussion of these systems, as well as Fig. 7, appear in [7].

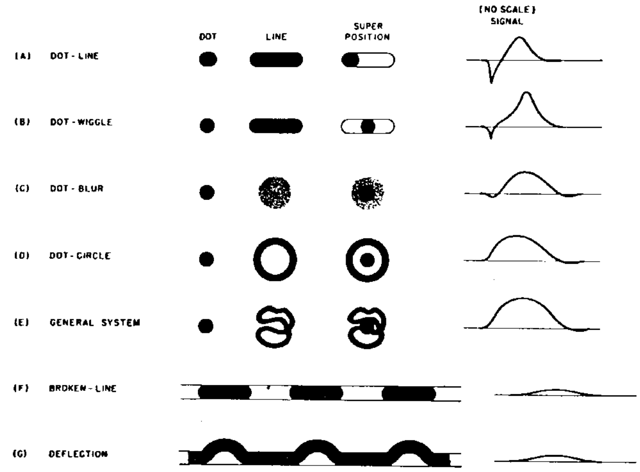

Fig. 7. Electrostatic storage patterns.

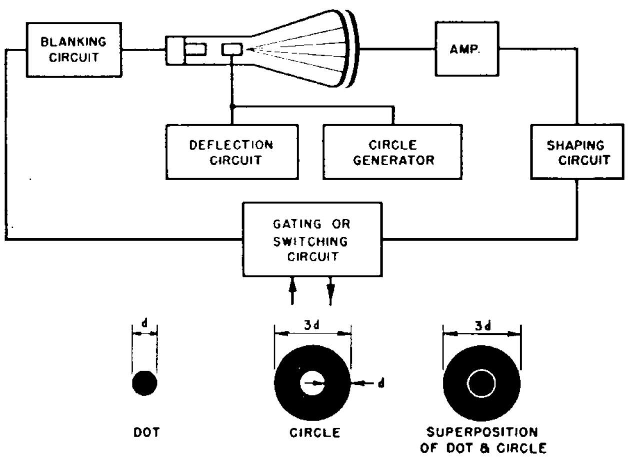

Fig. 8. Block diagram of electrostatic [circle-dot] storage.

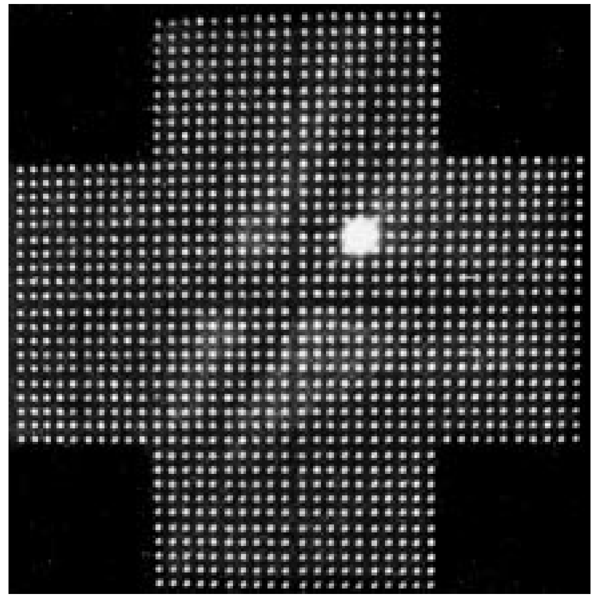

Fig. 9. Photograph of face of electrostatic storage tube.

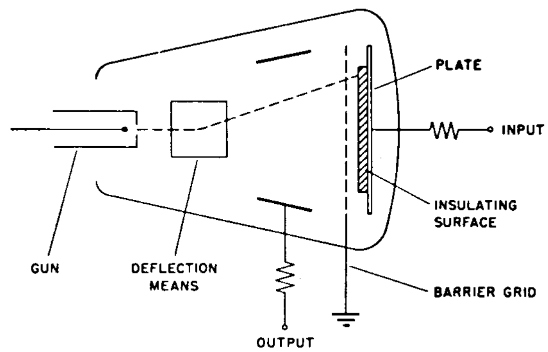

Fig. 10. Barrier-grid memory.

the deflection circuits are assuming the correct potentials for the chosen spot. The circle generator is gated in and out of the circuit, depending on the pattern desired. The wire mesh over the face of the tube is shown connected to an amplifier. The amplifier output is shaped and fed to a switching circuit, which is controlled from the computer's sequencing and control circuits.

In this system the circle is always used as the reading pattern. If a circle has been previously stored in a given area, and a circle superimposed on it for reading, there will be no appreciable output signal. If, however, a dot has been stored, the circle will destroy the dot and in so doing develop a significant output pulse. Typical dimensional relation of dot and circle, giving reasonable peripheral interference, is shown in the lower part of Fig. 8.

The operation of such a tube within a computer depends on the systematic interlacing of the regeneration operation and the reading and writing operations. During one part of each memory cycle, one spot is regenerated, first being read off the screen and then being replaced through the recirculation loop. The second part of the cycle can then be used as required by the computer for reading or writing. When a spot is read for transferal to the data-processing circuits, no significant information is left on the face of the tube. In the write operation the previous pattern is of no importance, since the new pattern will override and destroy the old in any event.

Fig. 9 shows the face of an electrostatic storage tube with the pattern of dots and circles. At the time the photograph was made the same spot was being read each cycle, while every other spot was being regenerated in sequential order during successive cycles. Since there are 1200 separate spots on the tube, the one selected spot in this worst of all possible conditions is being read 1201 times to only once for each other spot; hence it appears as a much more intense image than the others.

B. Barrier-Grid System

Another electrostatic storage system, operating in a manner similar to the surface-redistribution type, is the barrier-grid type. An example of this is the Radicon tube produced by RCA and intended for use as a digital storage tube. A cross section of this type of memory is shown in Fig. 10.

The capacitance between the inside surface of the insulating plate and the conducting back plate reacts as many elementary capacitors. In operation each of these

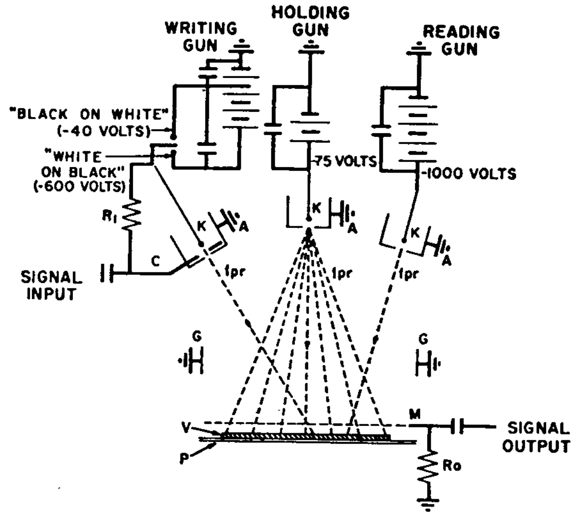

Fig. 11. Holding-beam memory tube.

elementary capacitors is charged by the beam through the barrier-grid to a potential determined by the potential at which the input conducting plate is held. The deflection means may be any one of the familiar types. The purpose of the barrier grid is to reduce the number of secondary electrons which would otherwise fall back on the surrounding area of the tube face. Because of the grid mesh most of the secondaries are directed toward the output collector plate; what few do fall back land near the spot made by the beam.

A variation of this system is the Krawinkel tube, which is really a barrier-grid system without a barrier grid. In both systems the potential on the plate in front of the tube determines the potential stored during the writing process; this is the essential difference between these two and the redistribution system. In the reading operation the beam is directed at the proper spot while a standard reading potential is maintained on the plate behind the storing surface. If the stored potential differs from the reading potential, current will flow in the input or output resistor, and from there can be read to other circuits.

C. Holding-Beam Systems

A third type of electrostatic storage is commonly called the holding-beam system. In this type of memory, developed by Haeff and others, areas on the inside face of the tube are charged to one of two levels. Long-term memory of either of these levels is accomplished by spraying the entire target area with a defocused beam from a separate holding gun.

Fig. 11 illustrates the holding-beam method. The cathode potential of the holding gun is established at such a value that the equilibrium of all points on the target will be maintained, regardless of whether they are charged to the higher or lower potential. For example, if the collector is grounded, and the holding gun cathode potential is -75 V, the writing gun could have a potential of -40 V. Under these conditions, the entire face of the tube is set initially at the collector potential. The action of the writing beam combined with that of the holding beam would shift the potential of the selected area to that of the holding-beam cathode. (The choice of potentials depends on the target material.) The various areas of the target, therefore, would be at either collector or holding-gun potential.

To read the information it is necessary to scan the selected area with a reading beam whose cathode is so much more negative that the secondary emission ratio is greater than one. If an area is nearly at collector potential, the collector grid placed between the target and the guns will receive a capacitor discharge current of a given magnitude. If an area is at holding-gun potential, the action of the reading beam produces a capacitor discharge of greater magnitude.

A single gun can be used for both reading and writing provided that the potential of its cathode is shifted from one value to the other for the two operations. One advantage of using separate guns, however, is that writing and reading can be separated from those generated by the reading action. One method of achieving this is modulating the reading beam with a high-frequency alternating signal, and separating the signals in the output with IF and detector circuits.

Erasure of all information means bringing the entire target area to a common potential. This can be accomplished by raising the holding-gun cathode potential to 40 V and then flooding the tube face with the holding beam.

The holding-beam system requires a specially constructed tube. An additional disadvantage is that adjacent areas charged to different potentials may bleed into each other if left under the influence of the holding beam alone for long periods of time. The spillover can be overcome by constructing the tube face in the form of a mosaic, in which the elementary areas are of nonconducting material and the mosaic itself is of conducting material. With such a construction the system is quite stable, and external regeneration is not required. Furthermore, the information is not destroyed on read out.

The holding-beam type of memory, like the interfering periphery and barrier-grid types, possesses an inherent parallelism in that a common deflecting circuit can position the reading or writing beams in several tubes at a time, each of which can deliver one binary component of an element of data. For a given output rate this reduces the response requirements of the deflecting system.

The selectron is a specialized tube operating on the principles of a holding-beam tube and built as a digital data store. The geometry of the electrodes is the most important factor in the construction of the tube, due to the fact that the lattice-like arrangement of selecting bars entirely controls the registering of the data and its subsequent readout.

The geometry of the elements is shown in Fig. 12. The actual storage elements are the metallic eyelets near the top of the drawing, which are insulated from all surrounding construction. The cathodes continuously emit electrons toward the storing eyelets, just as the holding gun does. There is a small hole in the center of each eyelet. The beam is focused on the eyelets by the horizontal and vertical selector bars and through the collector plate. The selector bars permit precise selection of any eyelet.

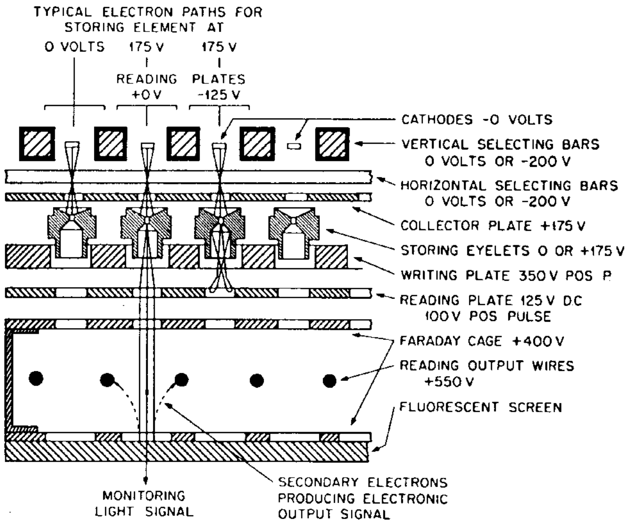

Fig. 12. Selectron.

The eyelets can sit at either of two stable potentials, one slightly below cathode potential (which is near ground) and the other slightly below collector potential. The current-voltage characteristic of the storing element has an unstable crossover point between these two extremes. If all the selector bars but one horizontal and one vertical are pulsed negatively at the same time, only one square or gate will remain at the bias cathode potential. All others will be driven to the more negative collector potential. In this fashion a selective gating arrangement is obtained for either reading or writing.

Reading and writing can be done only after the selection has been made. In the write operation the writing plate is pulsed positively as the selector bars reach their maximum negative potential. The writing plate is capacitively coupled to each of the storage elements. If the element is at collector potential, it will be raised to nearly twice this potential by the writing pulse. If it is originally at cathode potential, the pulse on the writing plate will bring it nearly to collector potential. Either positive or negative registry of the information may be made. If positive registry is desired, the writing pulse is made to decay slowly enough to keep the displacement current to the element small. For negative registry, the writing pulse is kept at its maximum value long enough for the primary electrons to bring back to the collector potential those elements whose potential was doubled. The writing pulse then drops sharply; the resulting negative displacement of current overrides the holding current, and brings the storage element to cathode potential, where it remains locked.

Erasure as a separate operation is not necessary. Regardless of the previous condition, the act of writing will bring the element to either of the possible levels. It is the pulse applied to the writing plate which determines which of the two levels is to be stored in the eyelet.

The hole in the center of the eyelet is used for reading. Some of the electrons focused on the eyelet from the cathode pass through this 0.02-in hole to the reading assembly. When an eyelet is positive, that is, near the collector potential, the beam passes through the hole by virtue of its own inertia. When the eyelet is near cathode potential, however, it exercises gate action, repelling the beam and preventing it from passing through the storage element.

The presence or absence of the beam on the lower side of the eyelet determines the potential state of the eyelet. The selector bars pick out whichever eyelet is to be read. A positive pulse then applied to the reading plate allows any current through the selected element to proceed through to the output electrodes. If a beam passes into the Faraday cage, it strikes a coating on the plate on the other side. The secondary emissions which result are collected by the output wires and read to the external circuitry.

Except for its complex constructional details, and its cost, there is much to recommend the selectron as a memory system: It does not require regeneration; the access time is reasonable; there is no destruction on readout; the locating system does not drift since it is mechanical in character and fixed in relation to the storage element; and there is no resolution problem since the storage elements are isolated from one another. Somewhat like other electrostatic systems, the selectron is not subject to loss of memory in the event of a short power failure. A long power failure, however, will cause loss of memory.

D. Sticking-Potential System

The fourth variety of electrostatic storage utilizes the sticking potential of the material on the tube face. The face material will not allow more than a certain potential-difference to exist between it and the gun. This is the potential at which the secondary emission ratio becomes one again at the high-potential end.

If the sticking potential is (for the sake of discussion) 10 000 V, then setting the gun potential at $-11\ 000$ V will cause the area under the beam to be charged to 1000 V. If the gun potential is made to be $-12\ 000$ V, the area will assume a charge of 2000 V. It is possible to operate the system using more than two stable states if that is desired. Reading can be done by holding both the gun and the target plate at a standard potential while observing the current through a resistor connecting the target plate to the external circuits.

The principle disadvantage of this type of memory is that none of the currently available face materials exhibits a sufficiently stable or uniform sticking potential for reliable operation. This, of course, does not gainsay the possibility that a reliable material may be found and the system may become a practical one.

The main advantages of all electrostatic memory and storage systems are the low latency time, which is a microsecond or less per binary digit, and the economy of being able to share regeneration circuits and deflection circuits among tubes. The characteristic of destruction on readout, although it could be avoided by using smaller reading current, is not too damaging anyway. Computer applications frequently require that the inspected area be cleared; furthermore, the facilities for reading in are avail-

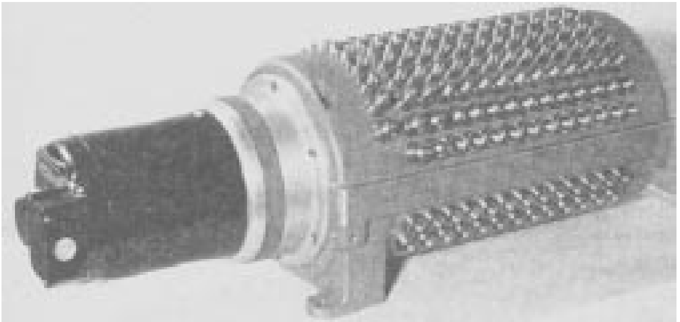

Fig. 13. Photograph of an ERA magnetic drum.

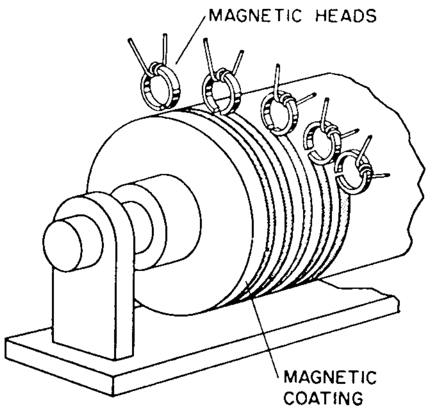

Fig. 14. The magnetic-drum system.

able for fuller use in recirculating the readout data back into the memory.

V. Magnetic Drums

Another storage system for digital computers is the magnetic drum. Engineering Research Associates have pioneered in the construction of practical magnetic-drum memories. A photograph of one of these drums is shown in Fig. 13. Many different examples have been built since then and are in wide use in many presently operating computing systems.

In this system, illustrated in Fig. 14, a cylindrical surface treated with a magnetically-sensitive material is rotated at a fixed speed under a row of heads. These heads, which are usually staggered around the drum, can serve for both reading and recording. External switching circuits select the proper head and the specific operation. The information stored takes the form of magnetized regions on the surface of the drum.

The schemes for writing on the drum can be either in a return-to-zero or a nonreturn-to-zero system. Manchester's computer in England uses a nonreturn-to-zero system which avoids a dc component yet produces a pulse for each bit by virtue of a probing pulse system. The return-to-zero method, used more commonly, can either pulse positively from a zero reference level for a one and pulse negatively for a zero, or it can use one polarity continuously for zero and pulse fully positive for ones.

In some of the earlier schemes for magnetic drums a writing amplifier was supplied for each head, unless the speed of the system was sufficiently slow as to tolerate relay operating speeds. Circuits are now appearing which allow "power switching" at electronic speeds, allowing a few writing amplifiers to be time-shared by a large number of writing heads via high-speed switching circuits.

The timing problem—the problem of determining where on the cylinder a particular piece of information is located—is akin to the similar problem in a mercury-tank memory. Instead of depending on temperature, however, it depends on the speed of rotation of the drum. The resolution problem includes such factors as the spacing of the heads so that cross-talk is eliminated; the pulse densities used; and the accuracy with which the drum can be machined. This last aspect is critical because of the variations in signal strength which are caused by a change in distance between the head and the recording medium. If the drum has any sizeable variations in diameter, the variations in output signal may become intolerable. With fixed heads such as the illustration shows, the principal requirement is that the drum be circular under any head; the actual diameter of the drum may vary slightly from one end to the other. This variation may be compensated for in the initial setting of the heads.

One would at first think that currently achievable rates of rotation would make for long latency time of a mercury tank. However, by means of interlacing and minimum latency coding much can be done to improve this situation. Further improvements are possible with increased drum speeds. Laboratory models have been operated in excess of 75 000 rpm.

The magnetic drum does not have a limited memory span and will retain its information if the power fails. The locating system does not drift, since it is fixed by the geometry of the head placement. Read-out does not destroy the record, and there is no regeneration problem. Since the drum has proven to be an inexpensive device per bit of information, the development of minimum latency and interlacing techniques and of higher-speed drive systems places it in the foreground as a contender of some importance in the computer field.

VI. Other Systems

In any rapidly developing field there is a natural tendency to make the best use of those systems which appear the most likely to respond successfully to a given amount of engineering research. Once these avenues have been traveled and the immediate needs are satisfied, time can be taken to evaluate and experiment with other, initially less promising, systems. Moreover, experience provides an additional criterion with which to evaluate other ideas.

A. Magnetic Cells

Of the more speculative and experimental memory systems, the most promising are those utilizing materials whose magnetic properties are characterized by square

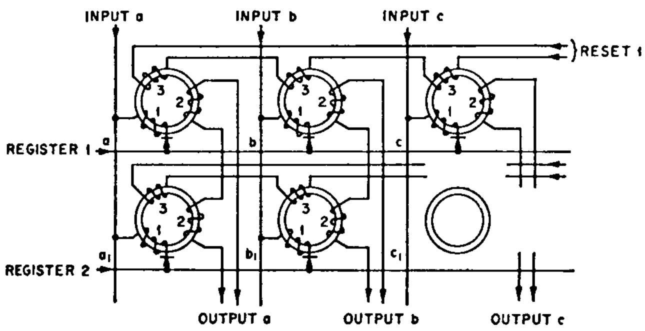

Fig. 15. Magnetic cell with diode.

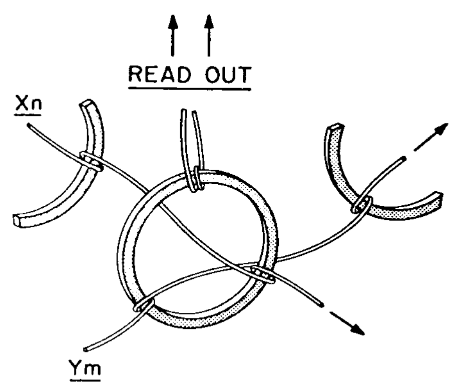

Fig. 16. Square-loop ferromagnetic cell.

hysteresis loops. Work on magnetic cells was done at the Moore School in 1945 by Chu and the author. Fig. 15 illustrates an early magnetic-cell system which used diodes. The magnetic material used here did not have the square hysteresis characteristic now demanded for similar systems. The square characteristic enables the cell to perform both memory and selection functions; in the illustrated system, the diode performs the selection while only the memory function inheres in the material. In the horizontal direction of this array are registers one, two, and so forth. Vertically there are inputs a, b, c. For reading into the memory, the input lines are energized with the voltage levels representing the digit to be stored, and the selected register line is pulsed. This causes current to flow through the write coil (marked 1) and the diode. Reading-out of a register is accomplished by pulsing the reset line. This clears all the cells to the standard polarity of magnetization, and causes current to flow in the outputs of those cells which had previously been set at other than standard polarity.

Experimentation has recently been focused on materials having a more nearly square hysteresis characteristic. Fig. 16 is a diagram of a memory cell which uses these materials. In this system, the cells are arrayed with a matrix of wires crossing the X and Y directions. Exciting an X-wire and a Y-wire with current in the same direction will cause the cell to which the two wires are common to flip from one polarity to the other. The current in a single wire is not sufficient to cause the cells to flip.

The third coil in the drawing is the readout coil, which listens for a magnetic shift in the core. In actual practice it may be possible to do away with the third coil if a current-sensitive device is attached to the two wires leading to the cell. This device could determine whether or not a coil had flipped by sensing the magnitude of the current in the line. These coincident current memories improve on the earlier type described above through use of rectangular hysteresis materials, and the elimination of the diode and soldered joints.

The magnetic-core "shifting register" type of memory, in which magnetic cores with square hysteresis characteristics are arrayed much as the elements of a lumped-parameter delay line, is a feasible type for small amounts of storage. Pulse trains can be read in and out either in series or in parallel. For serial operation diodes switch the pulses down the line as new pulses come in. The system is more expensive per bit of information than the magnetic-cell matrix type, but might be valuable in situations requiring both serial-to-parallel conversion and nonvolatility. The earliest version of this type memory operated at 25 kilocycles and was constructed at Harvard by An Wang and Way Dong Woo. Numerous laboratories have built examples since, working at higher frequencies up to 100 kilocycles.

Such magnetic systems are nonvolatile; there is no loss of memory on power failure. It requires little power for reading or writing, and none for regeneration. There is no resolution problem, nor any possibility of drift in the locating system. There is destruction on readout, but this is not too serious, since most computers possess equipment for reentering the data directly. Also, Buck of MIT is now speaking about nondestructive readout for this type of memory.

B. Ferroelectric Cell

Operating on a somewhat similar principle is the ferroelectric cell, in which a ferroelectric material is sandwiched between two plates. The construction is similar to that of a capacitor. Unlike an ordinary dielectric, however, the ferroelectric material possesses a square, hysteresis-like characteristic, instead of a linear relationship of voltage and charge. This curve is identical with the curve for the magnetic phenomenon, but with D and E as variables instead of B and H. Once the voltage across the cell has been brought to a maximum and reduced to zero, a charge remains in the material. As the voltage across the cell is reduced to a negative maximum and brought back to zero, a similar charge of opposite polarity is left.

A typical circuit for reading a ferroelectric memory is shown in Fig. 17. If a pulse of the same polarity as that stored in the cell is applied across the circuit, there will be little current through the resistor and a negligible output signal. If, however, the applied pulse is of the opposite polarity a larger current will flow and develop an output signal across the resistor.

The ferroelectric cell memory requires adjustment of polarity and amplitude of voltage, instead of the adjustments effected on current in the magnetic cell system. The construction is also somewhat different, as shown in Fig. 18. Here a plate of ferroelectric material such as

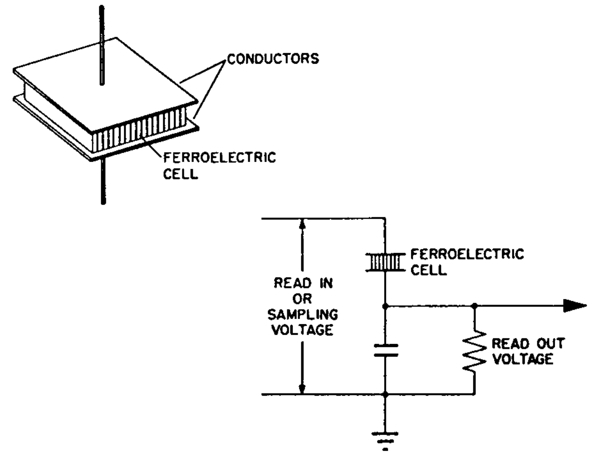

Fig. 17. Ferroelectric cell.

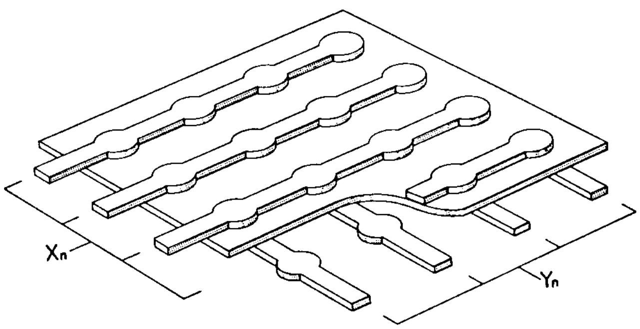

Fig. 18. Constructional detail of ferroelectric cell.

barium titanate is sandwiched between strips of conducting material. The arrangement of the sets of strips at right angles to each other results in a matrix of individual memory cells. To select a particular cell it is necessary only to energize an X-bar and a Y-bar in a manner similar to that employed in magnetic cell systems.

(In connection with the selection process in either ferroelectric or ferromagnetic cell memories, one should realize that there is a choice in the selection of the energizing voltages or currents. For example, the system could use a $+1$ value on one side of the matrix and a -1 value on the other. These could be applied to the selected line on each side, and all other lines kept at zero. No more than ± 1 is applied across any cell except the cell at the junction of the two lines. This cell, which is the "selected" cell, responds to a potential difference of 2. On the other hand, the normal for one side may be 0, and the energizing signal, 2; while $+1$ is applied as normal to the other side and -1 used for energizing the selected line. The junction of the $+1$ and -1 lines would then be the "selected" cell, while all other cells would have only a unit signal in one or the other direction—$+2$, $+1$, or 0, -1. This arrangement provides a 3 : 1 distinction between selected and nonselected cells, as compared with 2 : 1 in the first situation. The signals must be applied in the right order, however, with the $+1$ and -1 occurring first and the 2 signal afterward.)

The ferroelectric cell has a memory span as great as magnetic cells with similar hysteresis characteristics. Most

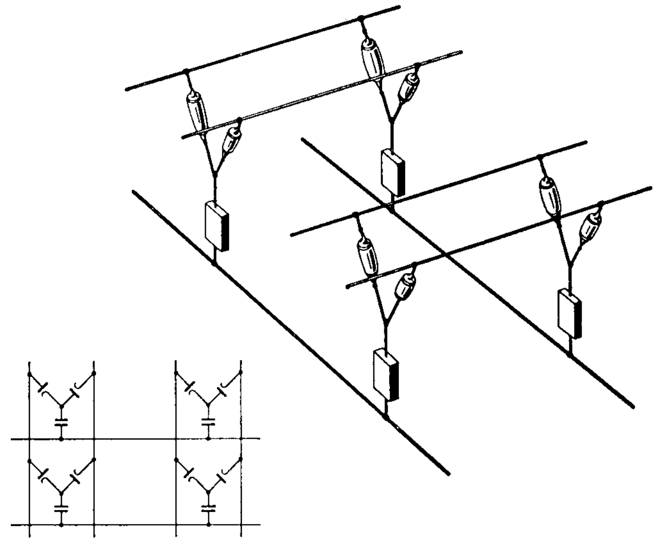

Fig. 19. Capacitor-diode memory.

of the advantages and disadvantages of magnetic cells, as regards small-power requirements, resolution, lack of drift in selection and location, no regeneration, and destruction on readout, also apply to the ferroelectric cell system.

C. Capacitor-Diode

A memory using capacitors as storage elements is feasible if capacitors could be developed which are capable of storing a charge sufficiently long. Fig. 19 shows a circuit developed by the Bureau of Standards and used by that agency in a number of experiments. This capacitor-diode memory has no particular virtue as far as cost is concerned, since it requires two diodes and there are systems which require only one. The system requires regeneration to compensate for leakage over long periods of time within both capacitors and diodes.

D. Neon-Resistor

Another matrix-type system has been considered which uses neons and resistors in series at the junction points of the matrix. The principal requirement of such a system is that the firing potential of the neon must be well above the extinguishing potential. The system has a number of possible advantages, including that it would not be necessary to destroy on readout: a small pulse put in on one coordinate of the matrix would appear on lines in the other coordinate only through the conducting neons.

E. Neon-Capacitor

Still another matrix-type system, conceived by Mauchly about six years ago, utilizes a capacitor and a neon bulb in series at each junction point. This system depends upon the capacitor to hold a charge for relatively long times, using the neon when not fired as a switching device. In operation the potential difference between the selected matrix lines would be increased until the neon fired. The neon will fire in a few microseconds and assume a low impedance; the capacitor is charged to a substantial voltage through the neon. As the potential between the lines is reduced, the neon is extinguished, becoming an extremely high impedance, and leaving a charge on the capacitor. To read from the memory, a smaller potential can be applied across the two lines in the opposite sense. If the capacitor is charged, the neon will fire and draw current, if the capacitor is not charged, the potential difference will not be enough to fire the neon. The destruction readout current is sensed and used as a means of detecting the condition of the memory after which any necessary regeneration takes place.

F. Phosphor Drums

A system utilizing drums coated with a phosphor has been considered at Harvard, but is not yet beyond the experimental stage. This memory system makes use of the property of phosphors that enables them to be excited into phosphorescence by ultraviolet light, and extinguished by infrared light. In the latter case the phosphor emits a bright flare of visible light.

In this system two cathode-ray tubes are used, one for reading and the other for writing. The writing tube emits ultraviolet light to ignite the phosphor in an area selected by the tube's deflection circuits. To read the same area the deflection circuits of the reading tube focus infrared light on the selected band. A recorded spot will flare brightly and then die out; the bright flare of light is detected by a photocell and read out to external circuits. A nonrecorded spot will emit no light under infrared bombardment.

G. Mellon Optical

Another system utilizing light is the Mellon optical system developed at the Mellon Institute in Pittsburgh. Fig. 20 illustrates the Mellon memory. The elementary cell in the upper left-hand corner consists of two materials, one of which is photoemissive, and the other, phosphorescent. A high dc potential is placed across the two. When light strikes the photoemissive material, electrons pass toward phosphorescent material. This, in turn, emits photons which pass back to the photoemissive material. A continuous cycle of operation is set up once light has struck the photoemissive layer.

A typical array of cells is shown in the drawing. A cathode-ray tube and lens arrangement is used to select particular cells in order to ignite them. A convenient property of the system is that light focused on an already excited cell overloads and paralyzes the cell. Overloading or paralysis clears the cell. The change in total light can at any time be detected by the photocell, which is the output pickup of the system.

H. Krawinkel Tube

There are many other systems which have been suggested and which may yet be developed to a useful state. There is a variation of the electrostatic store suggested by Krawinkel. In this variation, the target is covered with a photoelectric layer upon which is superimposed a mosaic of insulating

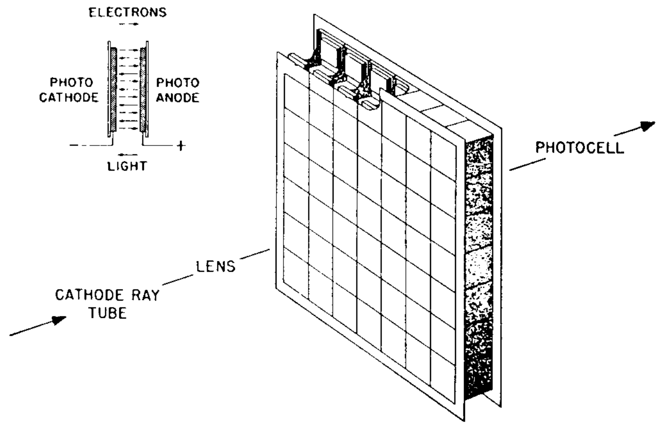

Fig. 20. Mellon optical memory system.

particles. Writing is done by the electron gun, but the output is obtained by shining light on the target from an external source. The backplate is made negative, and the charge areas consequently cause a phosphor screen to glow by photoemission.

I. Gas Triodes

Another promising matrix type of storage utilizes gas triodes. Typically, a thyratron whose striker is connected by a resistance divider to the two input lines can be fired when both input lines are sufficiently elevated. The output is read at the anodes. A variation on this system has one input fed to the grid and the other to the cathode of the gas tube. In either case, both inputs are required to fire a given tube, which then retains the single bit of information until cleared or until the power goes off. This system requires one tube for each bit of information.

J. Temperature-Sensitive Pigment

Another interesting optical storage system uses a temperature-sensitive pigment that exhibits what is known as color hysteresis in the temperature range between 0° and 100°C. Under thermal stimulus the material changes color, remaining in the changed state at ambient temperatures and until an "opposite polarity" of heat is applied. Both heat and electrical discharge can be used to write, and no additional input is required beyond the energizing pulse. Readout from these optical systems requires lenses and image tubes.

K. Electrolytic Diodes

Electrolytic diodes, which can be packaged with as many as 1000 diodes per cubic inch, may lend themselves to the construction of small diode-matrix type memories. The active (columbium or tantalum) and inert (gold or silver) electrodes are immersed in a hygroscopic electrolyte, and the gases produced by the chemical reaction are catalytically recombined in a space above the cells. The electrolyte reabsorbs the vapor and thus maintains its chemical equilibrium. The back resistance of the electrolytic diode, due to the passive character of the inert electrode, is extremely high—ten to 20 megohms, compared to a typical forward resistance of ten ohms—except when the anodizing voltage is exceeded. The rather high interelectrode capacitances, of 500 mmf and more, render these diodes infeasible for high-frequency work.

L. Coherers

Certain metallic powders act as insulators under weak electrical stimulus, but as conductors under the influence of stronger fields. A cell composed of a pair of electrodes immersed in one of these voltage-sensitive powders is called a coherer. When the potential difference between electrodes reaches the critical crossover point, the resistance falls quite suddenly from a value of about 10^9 ohms to about 100 ohms. To effect decoherence—to restore the high-resistance condition—it is necessary merely to tap the cell mechanically (Marconi, who used a coherer to detect the first transatlantic wireless message, used the impact of a bell-clapper). The energy required to recohere a cell varies directly with the physical energy applied in the decohering. The disadvantage to the coherer system is, of course, the comparatively long time required to clear (decohere) the cell. Attempts to use supersonic or magnetic stimuli to clear the cell have not met with success. There have, however, been successful experiments in which thin layers of the voltage-sensitive powder immersed in a liquid (such as mineral oil) were decohered by electrical discharge across the electrodes, although this is believed to be a low-frequency electromechanical phenomenon.

M. Corona Discharge

In another type of memory system, a glass or other nonconducting disc rotates between pairs of probe-needle electrodes, or between a set of these electrodes on one side and a backplate on the other. Sufficiently high-voltage pulses applied to the writing electrodes leave coronas of electrostatic charge on the disc, which will remain for a few seconds. The corona discharge disc system, illustrated in Fig. 21, may contain a second set of electrodes for readout into external circuitry and for external regeneration; regeneration may also be provided through the principle of the Wimshurst machine. Erasing electrodes are charged to a high direct potential to destroy the corona. The system functions more efficiently in a partially evacuated chamber, or in one containing a readily ionizable gas such as neon or argon.

Still other systems make use of thixotropic liquids, crossed fields (magnetic, electric, or supersonic), and other phenomena. A form of memory is probably latent in the process of xerography. More sophisticated treatments of some of the systems already discussed here are possible: magnetic cells with multiple orientations or in multiple levels, for example.

VII. Conclusion

A comparison of some of the important characteristics of the systems discussed here is presented in Fig. 22. The points of comparison are: destruction 1) on readout, 2) in case of power failure, and 3) in the event of drifts in the locating system; the resolution problem; and the span of the memory, or its time existence. The yeses in the six starred cases under "Destruction by Power Failure" are conditional: power failures of short duration do not necessarily cause loss of memory, but longtime failures do. The conditional yes under resolution problem for the Mellon system is true only when the device lacks mechanical separation of cell areas.

An important consideration in the evaluation of a memory system is that not all systems are equally applicable or economical for all purposes. For example, a storage system of 10^5 cells would not necessarily be economical if built with only 10^3 cells, and vice versa. For a small memory of 1000 digits, a gas-tube arrangement might be best; the driving circuits are simple and cheap, and the price per cell is tolerable. An electrostatic memory, on the other hand, does not become economical until it includes at least 10^4 bits of information; the investment in switching and deflection circuits must be spread over a larger memory to be economical.

The favored memory system of this or that group becomes more blessed simply by being selected as the mem-

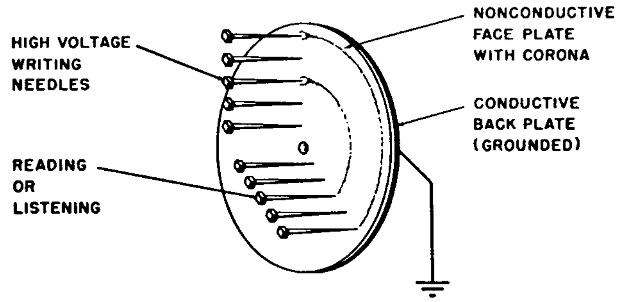

Fig. 21. Corona discharge disc memory.

	DESTRUCTION: READOUT	DESTRUCTION: POWER FAILURE	DESTRUCTION: LOCATING SYSTEM DRIFT	RESOLUTION PROBLEM	LIMITED TIME EXISTENCE
DELAY LINES	YES	YES	YES	YES	YES
ELECTROSTATIC INT PERIPHERY	YES	YES*	YES	YES	YES
HOLDING BEAM	NO	YES*	YES	YES	NO
SELECTRON	NO	YES*	NO	NO	NO
MAGNETIC DRUM	NO	NO	NO	YES	NO
FERROMAGNETIC CELL	YES*	NO	NO	NO	NO
FERROELECTRIC CELL	YES*	YES*	NO	NO	NO
DIODE – CAPACITOR	YES	YES*	NO	NO	YES
MELLON OPTICAL	YES	YES	YES	YES*	NO
PHOSPHORUS DRUMS	YES	YES*	YES	YES	YES

Fig. 22. Comparison and evaluation chart.

ory for a going computer. Thus, we can look with affection at delay lines and electrostatic stores, sometimes forgetting that our favorable feelings are due to our expenditure of work and our successful experience with them. Other systems, which have not received this attention, may possibly become as good as any of the present systems once someone has spent the effort on them.

It is also important to remember that there has been intensive effort in the computer field over a short period of time, and all the wood may not be hard. Had we been able to proceed more slowly, some of our decisions might have been different. We have not scratched the surface of the subject—not even thoroughly tested and evaluated the systems which have been suggested. The future undoubtedly will see the development of still more ideas, any one of which may become more nearly the ideal memory system than any which have been discussed here.

ACKNOWLEDGMENT

Credit is due the Radio Corporation of America for permission to reproduce Fig. 12, and John Wiley & Sons, Inc., New York, NY, publishers of *Storage Tubes and Their Basic Principles*, by M. Knoll and B. Kazan, for Fig. 11.

REFERENCES

[1] J. F. Adams, "The Krawinkel image-storing CR tube," *Fiat Final Rep. 1027*, Apr. 1947.
[2] A. A. Auerbach, J. P. Eckert, Jr., R. F. Shaw, J. R. Weiner, and L. D. Wilson, "The Binac," *Proc. IRE*, vol. 40, pp. 12–29; Jan. 1952.
[3] I. L. Auerbach, J. P. Eckert, Jr., R. F. Shaw, and C. B. Sheppard, "Mercury delay line memory using a pulse rate of several mega-cycles," *Proc. IRE*, vol. 37, pp. 855–861, Aug. 1949.
[4] P. R. Bell, G. D. Forbes, and E. F. MacNichols, Jr., "Storage tubes," in *Wave Forms*, Ch. 21, Radiation Laboratory Series #19. New York: McGraw-Hill, 1949.
[5] H. N. Beveridge and W. W. Keith, "Piezoelectric transducers for ultrasonic delay lines," *Proc. IRE*, vol. 40, pp. 828–835, July 1952.
[6] W. W. Davis, "The SEAC memory using Williams' storage," NBS Electronic Computer Lab. Rep. #12.3-7R; Apr. 20, 1951.
[7] J. P. Eckert, Jr., H. Lukoff, and G. Smoliar, "A dynamically regenerated electrostatic memory system," *Proc. IRE*, vol. 38, pp. 498–510, May 1950.
[8] J. D. Goodell and T. Lode, "Multistable magnetic memory techniques," *Radio Elec. Eng.*, pp. 3–5, Dec. 1951.
[9] A. V. Haeff, "A memory tube," *Electronics*, vol. 20, pp. 80–83, Sept. 1947.
[10] J. L. Hill, "Design features of a magnetic drum information storage system," *Proc. ACM*, Mar. 28, 1950.
[11] A. W. Holt, "An experimental rapid access memory using diodes and capacitors," NBS Electron. Computer Lab. Rep., pp. 133–141; 1953.
[12] M. Knoll and B. Kazan, *Storage Tubes and Their Basic Principles*. New York: Wiley, 1952, pp. 22, 44, and 85.
[13] A. J. Lephaskis, "An electrostatic tube storage system," *Proc. IRE*, vol. 39, pp. 1413–1415, Nov. 1951.
[14] R. A. McConnell, "Video storage by secondary emission from simple mosaics," *Proc. IRE*, vol. 35, pp. 1258–1264, Nov. 1947.
[15] *Mellon Institute of Industrial Research: Computer Component Fellowship #347*, Quart. Rep. no. 3 (Apr.–July 1951) Sec. I–VI; Quart. Rep. no. 5 (Oct.–Jan. 1952) Sec. I–V; Quart. Rep. no. 6 (Jan.–Apr. 1952) Sec. II, III, VI; Quart. Rep. no. 9 (Oct.–Jan. 1953) Section III.
[16] K. H. Olsen, "A magnetic matrix switch and its incorporation into a coincident current memory," Rep. R-211, Digital Comput. Lab., MIT, June 6, 1952.
[17] W. N. Papian, "A coincident current magnetic memory cell for the storage of digital information," *Proc. IRE*, vol. 40, pp. 475–478, Apr. 1952.
[18] C. V. Parker, "Charge storage in cathode-ray tubes," *Proc. IRE*, vol. 39, pp. 900–907, Aug. 1951.
[19] J. Rajchmann, "The selective electrostatic storage tube," *RCA Rev.*, vol. XII, pp. 53–97, Mar. 1951.
[20] D. G. Scorgie, "Lead networks utilizing a saturable core memory," Natl. Radiation Lab. Rep. 4006, July 16, 1952.
[21] A. Wang, "Magnetic delay line storage," *Proc. IRE*, vol. 39, pp. 401–407, Apr. 1951.
[22] F. C. Williams and T. Kilburn, "A storage system for use with binary-digital computing machines," *Proc. IEE* (London), vol. 96, Part II, pp. 183–202; and Part III, pp. 77–100, 1949; and vol. 97, Part IV, pp. 453–454, 1950.