A Survey of Analog Memory Devices*

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Summary—**Widespread and persistent interest in the implementation of multilevel logic, conditional probability computers, learning machines, and brain models has created a need for an inexpensive analog or quasi-digital storage element. A number of possible approaches to this problem, ranging from the slow and reliable electromechanical systems to the many forms of charge and flux integration, are reviewed, and the suitability of each device for various fields of application is briefly discussed.**

INTRODUCTION

RECENT WORK on complex data-processing systems with large numbers of simultaneous inputs has spurred interest in a type of adaptive structure known as a nerve net. Adaptive nerve nets generally incorporate a number of variable weighted connections, whose levels must be set during the course of a training routine to correspond to the probability density functions characterizing the input or the system structure. The object of this paper is to provide a review of several kinds of memory elements which may be useful in implementing the information storage system of such nets.

The striking feature common to all these nets, be they part of a conditional probability computer, a pattern recognition device designed to classify bubble chamber photographs, or a model of the cat's visual cortex, is that the degree of interest and usefulness of the performance displayed increases with the number of variable strength links embodied in the system. Consequently, low unit cost is often the over-riding consideration in choosing a storage device for a particular machine.

Fortunately, the logical design of most nerve nets does not impose too stringent requirements on the performance of individual memory cells. As a rule, the outputs of a large number of weighted connections are added, and the correct classification of the input signal depends on whether the algebraic sum is greater or less than a given threshold (threshold logic), or greater or less than other similarly constituted sums (majority logic).

If only a coarse level setting arrangement is available, or if only a finite number of levels may be obtained, a well designed system will still converge to a solution, (achieve correct classification of a set of test stimuli), although a longer training sequence (adaptive period) or more adaptive links may be necessary. For a system comprising a fixed number of adaptive links, the number of levels required in a single memory cell will depend, in general, on both the signal-to-noise ratio of the input patterns, and on the resolution of the final comparator unit. Typical figures derived from computer simulation range from 30 to 300 levels.[1–3]

While it may be desirable to increment or decrement the value one level at a time, it is not necessary to be able to reproduce a given level exactly, as it would be if the machine were to perform arithmetic operations. A way of resetting the value to some arbitrary zero level would also be desirable in order to erase traces of previous learning before starting on a new problem.

The required speed of operation is more closely dependent on the particular application in view. For example, in a constantly updated radar monitor a fast reinforcement rate would be more advantageous than in a character recognition device which would be retrained comparatively rarely. A speech processor operating in real time would likely have to be faster than the visual models built to date. Sophisticated configurations incorporating feedback, reverberating loops and built-in decay[2] would be able to take advantage of higher rates than a series-coupled system paced by the speed of the input equipment. Furthermore, one attempt at least has already been made to directly couple a parallel device of the nerve net type to a conventional sequential digital computer.[3]

The degree of permanence required may also vary from a few hours in a laboratory machine designed to check system performance to several months in an automatic page reader which would normally be left alone as long as radical changes in the type present in its input did not occur.

This completes the list of features which may be relevant in selecting a memory component. Let us now see where we may hope to find a device satisfying our rather modest demands.

STATE OF THE ART

Electromechanical Memory Elements

As had been the case with both digital and analog computers, the first large scale parallel-pattern recognition machine made extensive use of electromechanical elements. The Mark I perceptron, built at the Cornell Aeronautical Laboratory, includes 512 gear-head direct-

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[1] A. E. Brain, H. S. Crafts, G. E. Forsen, D. J. Hall, and J. W. Machanik, "Graphical Data Processing Research Study and Experimental Investigation," Stanford Research Institute, Menlo Park, Calif., Rept. No. 10; December, 1962.

[2] F. Rosenblatt, "The Principles of Neurodynamics," Cornell Aeronautical Lab., Buffalo, N. Y., Rept. No. VG-1196-G-8; March, 1961.

[3] B. Widrow and C. H. Mays, Project No. 1557-26 in Solid State Electronics Research, Stanford Electronics Labs., Stanford University, Calif., Consolidated Quarterly Rept. No. 14; 1962.

current motors to actuate the potentiometers representing the values of its weighted connections.[4] While in a larger system cost and space requirements could be cut down considerably by mounting a number of potentiometers—possibly as many as forty or fifty—on a common shaft, and clamping appropriate ratio arms to the rotating shaft by means of a magnetic clutch arrangement,[5] on the whole, electromechanical elements are obsolete for parallel storage.

Thermistors

The currents which flow through a thermistor raise its temperature through ohmic dissipation, and the temperature characteristics of the device are such that its conductance is thereby increased. Thus, thermistors are ideally suited for the type of training required in certain four-layer and cross-coupled systems:[6] only links originating at "active" signal generating units carry current, and are consequently reinforced. Unfortunately, reinforcement is strictly monopolar. A further drawback is the short "half-memory" of thermistors: it is only of the order of three or four minutes.[7]

Photochromic Storage Devices

The characteristic curves of the photochromic or phototropic film[8] on which these devices are based are displayed in Fig. 1. The unique property of this film is that its transmittance near the center of the visible spectrum may be reversibly altered by exposure to high intensity radiation in the borderline regions. Curve A shows the transmittance of the film after it has been exposed to a flash of light of the spectral composition indicated by curve C (yellow filter), while curve B shows transmittance after an "erase" pulse through blue filter D. Curve E describes the "read" filter which has been found to interfere least with the condition of the film. Reading is, of course, performed at relatively much lower intensities than reinforcement; the over-all transmissivity varies from about 0.3 to 0.8. The material is not too unstable; at room temperature it decays towards an equilibrium point with a time constant of several hours.

A rather elegant photochromic device, designed by Scott H. Cameron,[9] consists of a modified automatic slide projector. The input patterns, in the form of transparencies, are introduced into a collimator in front of the photochromic film. A photoresistor behind the film measures the total amount of light transmitted during a "read" cycle. If the intensity exceeds a preset threshold and the input pattern is to be classified in the positive class, a flash of "blue" light is triggered. If the input is to be classified negative, and the intensity fails to reach threshold level, the film is flooded with "yellow" light. It may be shown that iteration of this procedure will enable the machine to form dichotomies among a broad class of patterns; in fact, the machine is designed to run through its magazine of slides until it stops making mistakes.

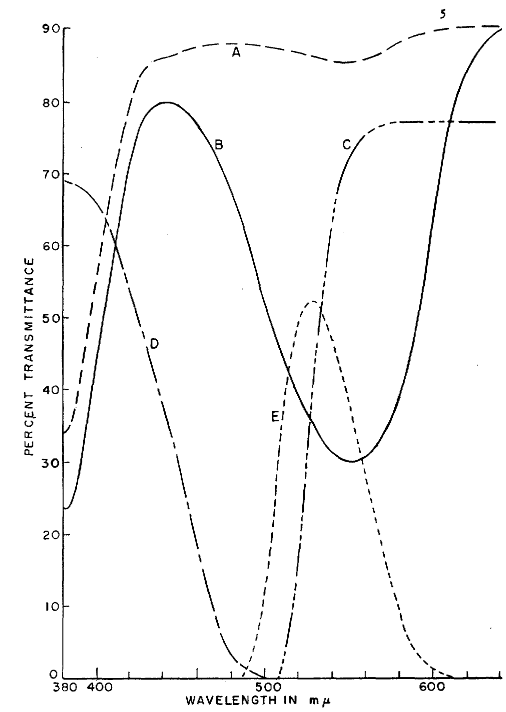

Fig. 1—Photochromic characteristics.

Photochromic devices are proving their usefulness in the two-layer processing of visual data, but there appears to be no simple way of adapting them to more complicated topologies.

Charge Integration

The engineer's concept of a circuit with a memory generally involves one or more charged capacitors, so it is reasonable to investigate whether these hold out any promise for present nerve net applications. Charge integration in capacitors presents the problem that for linear operation a constant current source, implying in practice a large series resistance, is required. This in turn renders incrementation intolerably slow, since for reasonable storage times large capacitance values are necessary. The sensing of the charge offers a further problem.

These difficulties are largely overcome by Bab-

[4] J. C. Hay, F. C. Martin, and C. W. Wightman, "The Mark I Perceptron, Design and Performance," 1960 IRE International Convention Record, pt 2.

[5] M. Minsky, "Neural-Analog Networks and the Brain Model Problem," M.S. Thesis. Princeton University, Princeton, N. J.; 1954.

[6] H. D. Block, B. W. Knight, and F. Rosenblatt, "Analysis of four-layer series coupled perceptron," *Rev. Mod. Phys.*, vol. 34, pp. 135–142; February, 1962.

[7] A. Arking and H. Y. Chiu, "Proposal for Construction of a Thermistor Perceptron," Laboratory of Nuclear Studies, Cornell University, Ithaca, N. Y., 1959.

[8] B. K. Green, E. Berman, B. Katchen, L. Schleicher, and J. J. Stansbury, "Chemical Switches," *Proc. Internat. Symp. on Theory of Switching*, Harvard University Press, Cambridge, Mass.; 1957.

[9] S. H. Cameron, "Self Organizing Networks," Armour Research Foundation of Illinois Institute of Technology, Chicago, Ill., Annual Rept., Project No. E154; 1962.

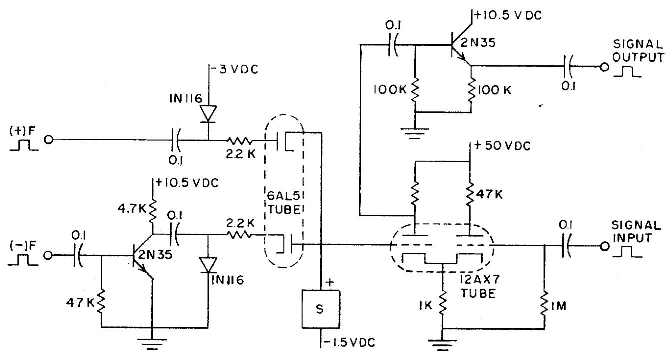

Fig. 2—Babcock's "refined facilitator."

cock's "Facilitator,"[10] shown in Fig. 2. The facilitator simulates biological neuron properties such as temporal and spatial summation, latency, inhibition and refractive period. It is rather too expensive to use in conventional pattern recognition machines, and should be of interest chiefly to specialists in complex neuron interactions.

Solions

Solions is the generic name of a family of amplifying devices which function by controlling and monitoring a reversible electrochemical reaction.[11]

The reaction utilized in solions is a so-called "redox" reaction in which oxidation and reduction take place in turn. In the solion tetrode four inert electrodes are immersed in an electrolyte containing both the oxidized and the reduced species of an ion, and by controlling the charge transferred between the two input electrodes, a change in conductivity proportional to the input current may be obtained between the output electrodes.

Fig. 3 is a simplified diagram of a solion tetrode connected as an integrator. The electrolyte used is an aqueous solution containing a small amount of iodine and a comparatively larger amount of potassium iodide. The amount of tri-iodide (resulting from the dissociation of the iodine in the presence of the potassium iodide) transferred from the reservoir to the integral compartment by the input current is, by Faraday's Law, proportional to its integral with respect to time. The output current is proportional to the concentration of tri-iodide in the integral compartment, and hence to the integral of the input current. The polarized shield merely serves to reduce the tri-iodide concentration near it to the point where diffusion through the small perforations of the electrode is negligible.

Because of the concentration potential resulting from the difference in ion concentration in the vicinity of the two input electrodes, the input impedance of the solion tetrode varies by a ratio of 5:1 in the operating range of the device. An even more serious drawback is the low output impedance of the device, which causes units connected together for the purpose of summing operations to discharge through one another. These difficulties are similar to those encountered with capacitors, though the time constant is greatly magnified in solions by the use of a liquid medium.

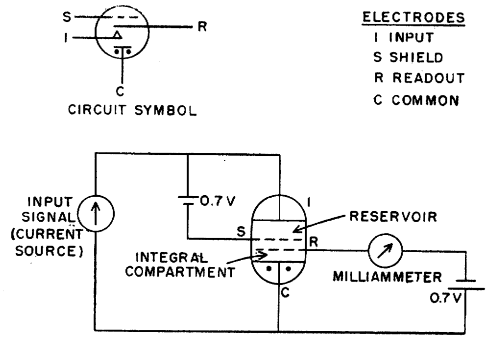

Fig. 3—Solion tetrode connected as an integrator.

At constant temperature the stability of isolated solions is reported to be excellent, with drifts of only a fraction of 1 per cent over periods of several days. Reasonably high packing densities may already be achieved —the volume of a tetrode now on the market is approximately 0.2 cubic in—but prices are still rather high. If solions are to be seriously considered for embodiment in large nerve nets, considerable redesigning is required with the emphasis shifted from precision to ease of mass production.

Electrolytic Integrators

Yet another form of charge integration is exhibited in the "electrolytic integrator." The basic principle behind it is so simple that it had occurred to practically every investigator in need of a cheap and reversible memory device, but the first really workable device was developed by B. Widrow using high precision electrochemical techniques and, it is said, a number of incantations devised originally in connection with the touch-stone research program.[12]

The electrolytic integrator, in its basic form, consists of two electrodes immersed in an electrolyte (see Fig. 4) in such a way that it is possible to vary their resistance relative to each other by transferring metal in ionized form through the solution. In practice, one of the electrodes, the variable element, is a fairly high resistance conductor with two terminals accessible in order to detect resistance changes. The other electrode, the source, is simply a bar of metal.

The basic resistance of the variable element must lie in a relatively narrow range. If the basic resistance is too low compared to the resistance of the source metal, then in order to produce a detectable resistance change, very large amounts of the source metal must be deposited on

[10] M. L. Babcock, "Reorganization by Adaptive Automation," University of Illinois, Urbana, Ill., Nonr 1834(21) Tech. Rept. No. 1; January, 1960.

[11] "An Introduction to Solions," Texas Research and Electronic Corp., Dallas, Tex.; June, 1961.

[12] B. Widrow, "An Adaptive 'Adaline' Neuron Using Chemical 'Memistors'," Stanford University, Calif., Solid State Electronics Laboratory Tech. Report No. 1553-2; October, 1960.

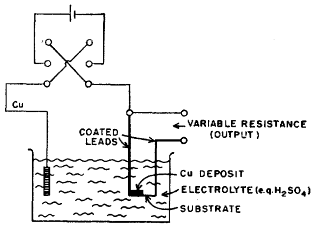

Fig. 4—Schematic of electrolytic integrator.

the surface of the variable element. Since the maximum permissible plating current is limited by the need for even plating action, low basic resistance entails inadmissibly slow integrating action. If, on the other hand, the basic resistance is high compared to that of the solution, then the resistance change measured at the terminals of the variable element will again be small, due to the constant low resistance of the solution which is essentially in parallel with it.

Commonly used substrates include metallic oxide films deposited on glass, graphite and thin resistance wires. The electrolyte is usually a solution of copper sulphate in water, with various chemical agents added to regulate the ph factor and insure even plating characteristics. Currents of the order of a milliampere and time constants of a few seconds are typical of the small airtight integrator capsules now available.

A slight variation on the electrode resistance integrator, investigated by H. Y. Chiu and others, deserves mention.[13] Chiu advocates the use of cells where the resistance between the electrodes, rather than that of one of the electrodes, is changed as the result of copper transfer. For example, the cathode of such a cell may be a cylinder of copper foil, while the anode would consist of a thin gold wire concentric with the cathode. The reversibility of a process based on such a geometry is questionable and the data obtained by Chiu are not encouraging.

The Optimistor is yet another version of the electrolytic integrator.[14] Here a very thin layer of metal is deposited on a transparent substrate and the thickness of the layer is sampled with a light beam. Because of the relatively large ratio of exposed surface to amount of material present, this arrangement is rather unstable.

Experiments have also been conducted on transferring silver ions through a thin film of silver bromide.[15] The nonlinearity of this process renders it suitable for coincidence mode selection of the points to be incremented in a memory matrix. The matrix consists simply of the points of intersection of thin silver wires electrolytically coated with a 10-micron tungsten bromide film. When

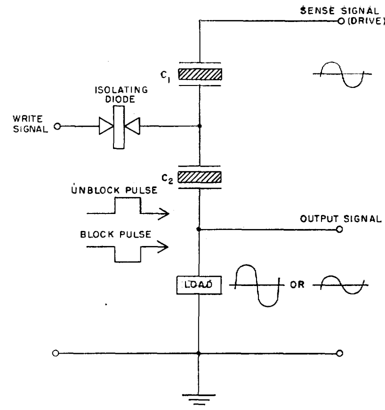

Fig. 5—Basic circuit of a transpolarizer.

current is passed through a point of intersection, silver ions are released from the wire acting as the anode, transported across the bromide film and deposited on the cathode wire. Eventually, a bridge of silver is built up between the wires, and the resistance between them changes from about 1 megohm to less than 10 ohms. Here again, reversibility is the chief problem. A program to investigate solid solutions with a view to electrolytic integrator applications is reported to be underway at the Cornell Aeronautical Laboratory.

The Transpolarizer

The transpolarizer, an electrostatic analog of the more widely known transfluxor, consists of two capacitors with a crystalline ferroelectric dielectric and a nearly rectangular hysteresis loop.[16] The basic circuit is shown in Fig. 5, and the mode of operation is as follows.

One of the capacitors, say C_1, is maintained in a polarized state by means of a dc bias. Then the transpolarizer is said to be in the unblocked state if C_2 is polarized in the same direction as C_1. In this case the two capacitors in series behave essentially as a single ferroelectric element, and present a low impedance to a small ac sensing signal. If, however, C_2 is polarized oppositely to C_1, then any attempt to switch C_1 would result in C_2 being driven further into saturation. Hence, no switching occurs and the transpolarizer is said to be in the blocked state. The combination acts as a small linear capacitor and therefore has a relatively high impedance at the driving frequency.

Making use of the partially blocked states of the transpolarizer, about thirty discrete and reproducible steps are attainable. The polarization is set to the desired level by 1-microsecond pulses of the appropriate polarity. With recently developed materials, such as tri-glycine sulfate (TGS) and tri-glycine fluoberyllate (TGFB), extremely stable operation may be expected, and sensing voltages several times as large as the coercive voltage may be safely applied.

[13] H. Y. Chiu, "An Investigation of the Possibility of Using Electrolytic Cells as A-Units in the Construction of a Perceptron," Laboratory for Nuclear Studies, Cornell University, Ithaca, N. Y.; 1959.

[14] M. E. Hoff, H. S. Crafts, and J. B. Angell, "Components for Trainable Systems," *Digest of Papers*, 1962 Internatl. Solid State Circuits Conference.

[15] H. J. Honerloh and H. Kraft, "Technische Verwirklichung der Lernmatrix," in "Lernende Automaten," H. Billing, Ed., R. Oldenbourg, Munich, Germany; 1962.

[16] P. Pulvari, "The transpolarizer: An electrostatistically controlled circuit impedance with stored setting," Proc. IRE, vol. 47, pp. 1117–1122; June, 1959.

Magnetic Flux Integration

Modelled on the core memories so widely used in digital computers, most flux integrators use the partial switching of the domains in a toroidal core under a current impulse as the basic increment. Differences between particular designs arise chiefly in the mode of nondestructive readout employed.

One popular approach to the readout problem makes use of quadrature fields. A weak "strobe" field is applied orthogonally to the "write" axis of magnetization; it causes the flux vector to rotate slightly, generating a voltage proportional to its rate of change (and hence its magnitude) in the read winding (which may be the same as the write winding). At the end of the strobe pulse, the flux vector springs back to its original preferred orientation by virtue of "domain elasticity." Fig. 6 shows a core which was used in a small perceptron utilizing this principle for information storage and modification.[17]

Another working analog storage device has been developed at the Stanford Research Institute by A. Brain,[18] using the multiaperture device (MAD) derived earlier from the transfluxor configuration by Bennion and Crane.[19] A schematic of the MAD ferrite, as used for analog storage, is shown in Fig. 7. The current through the bias winding holds the core material near the inside perimeter of the core in a saturated condition, thus "trapping" any flux which may be present around the small apertures. Pulses through the set winding vary the total amount of flux in the core with the amount of flux switched at each increment held constant by means of a "bucket" core.

A slightly different version of the toroidal flux integrator is now being patented by J. Divilbiss of the University of Illinois.[20] His device is shown in Fig. 8. The novel feature here is the variable resistance short circuited loop which controls the field available for flux switching.

A mode of readout first investigated by B. Widrow[21] has been recently perfected by H. J. Honerloh at the Technische Hochschule in Karlsruhe, Germany, and is about to be incorporated into an 8,000 element "Lernmatrix."[15] Here the readout signal is proportional to a difference frequency generated by core nonlinearity between two drive frequencies in the low broadcast range. The signal is very small but the summing operation

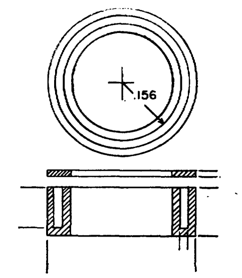

Fig. 6—Aeronautronic integrator core and steel cover.

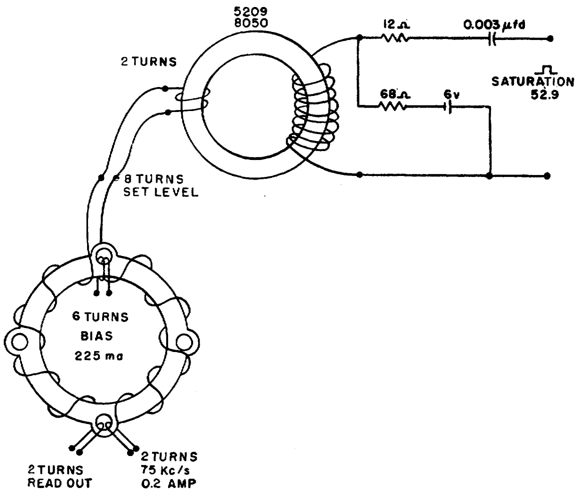

Fig. 7—MAD integrator.

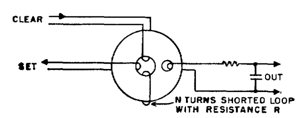

Fig. 8—Divilbiss' modified transfluxor.

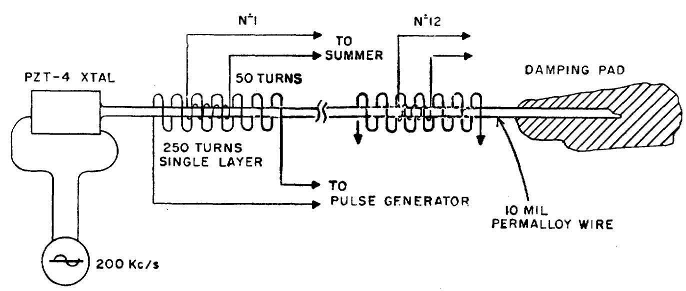

Fig. 9—Schematic diagram of magnetostrictive readout integrator.

characteristic of parallel-pattern recognition machines raises it above noise level. In the Lernmatrix the cores are simply threaded onto the read and write wires in the manner of conventional digital core memories and incrementation takes place by coincidence mode switching.

Reversible flux switching in a tape-wound toroidal core, which takes place at harmonic frequencies of a drive current due to core nonlinearity, has been successfully exploited for readout purposes by H. S. Crafts.[1,14] An early version of the so-called second-harmonic integrator consists of two cores wound in such a manner

[17] J. K. Hawkins, C. J. Mansey, and R. A. Stafford, "A Magnetic Integrator for the Perceptron Program," Newport Beach, Calif. Summary Report, Aeronutronic Res. Lab. Publication No. U-1405; 1961.

[18] A. E. Brain, A. B. Novikoff, and C. P. Bourne, "Graphical" Data Processing Research Study and Experimental Investigation, Stanford Research Institute, Menlo Park, Calif., Rept. No. 4, April, 1961.

[19] D. R. Bennion and H. D. Crane, "Design and analysis of MAD transfer circuitry," *Proc. W.J.C.C.*, pp. 21–36; March, 1959.

[20] J. Divilbiss, "A Magnetic Pulse Integrator, Disclosure of Invention and Letter of Transmittal; University of Illinois, Urbana, 1962.

[21] B. Widrow, "A radio-frequency non-destructive read-out for magnetic core memories," IRE TRANS. ON ELECTRONIC COMPUTERS, vol. EC-3, pp. 12–15; December, 1954.

TABLE I
CHARACTERISTICS OF ANALOG MEMORY ELEMENTS

Integrator	Number of Available Levels	Time Required for Reinforcement	Stability	Means of Reinforcement	Approximate Unit Cost
Electromechanical	500	0.1 second	infinite	2 amp dc	$40.00
Thermistors	continuous	5 seconds	5 minutes	40 ma dc	$ 0.50
Photochromic	2	—	6 hours	high energy flash	—
Transpolarizer	30–300	1 microsecond	infinite	electron beam	$15.00
Ferrite	20–200	3–80 microseconds	infinite	1 microsecond; 1 amp pulse	$ 3.00
Capacitor	continuous	1–1000 milliseconds	6 hours	1–1000 millisecond pulses	$ 1.00
Solions	continuous	1 second	30 days	50 μamp dc	$15.00
Electrolytic	200	10 milliseconds	6 months	10 millisecond; 1 ma pulse	$10.00
Magnetostrictive	50–100	0.1 microsecond	infinite	0.1 microsecond pulse	$ 1.00
2nd Harmonic	50–500	0.1–1.0 milliseconds	infinite	0.3 millisecond pulse	$ 1.00

that in the output winding the second-harmonic components, which are proportional to the flux level, add, while the fundamental cancels out. Because the high-level radio frequency drive effectively lowers the core coercivity, coincidence mode incrementation is readily practicable. Other features, such as relatively low cost, large number of levels available and the simplicity of the required auxiliary circuitry, contribute to make this device a strong contender for a leading position among practical integrators.

We shall conclude this sampling of flux integration techniques with an idea originated by C. Rosen of the Stanford Research Institute. When a magnetostrictive element is acoustically excited, an alternating flux wave is generated whose magnitude is proportional to the initial magnetization of the element. A device based on this principle is illustrated on Fig. 9. The flux carrying medium is the 10-mil permalloy wire, ultrasonically driven by a piezoelectric transducer. With this arrangement it is possible to obtain up to 80 discrete steps, using only a very modest amount of auxiliary circuitry. Further development work on this device is being carried on both at the Stanford Research Institute[1] and at Cornell University,[22] in conjunction with the construction of large scale visual and audio pattern recognition devices.

Conclusion

The list of analog memory devices presented in the preceding paragraphs does not pretend to be exhaustive. One may gain some idea of the staggering variety of processes which may be potentially harnessed to fulfill nerve net memory functions by considering the number of physical phenomena characterized by a first-order differential equation. Since the specifications for the simultaneous access storage in a pattern recognition computer are often rather loosely formulated, the choice between the various approaches available is not an easy one; a quantitative evaluation based on performance curves and cost would be a major research project in itself.

Table I summarizes available information on the devices reviewed in this paper.

Among the alternatives presented, the various magnetic flux integrating devices offer perhaps the most flexibility for many applications. The popularity of the toroidal cores for analog storage is bound to grow as improved fabricating methods and materials become available for thin film deposited cores and for the application of printed circuit techniques to provide the necessary windings. Coincidence mode incrementation will no doubt be employed on all large scale machines.

It is also possible that improvements in electron-optical machining techniques, now being developed by K. Shoulders in Palo Alto,[23] may obviate the necessity for analog storage. In principle, any pattern recognition machine using weighted connections may be simulated on a binary machine of sufficiently large capacity. With cryogenic storage elements it may be possible to build large, fairly general-purpose parallel computers, on which any specific connection scheme necessary for a given task may be established by external control.

Even the considerable improvements in components almost within reach are not likely to close the existing gap between proposed theoretical models and their hardware realization. As much as ever it will remain up to the individual designer to maximize the yield of machines severely handicapped by the lack of a really cheap, reliable and fast analog memory component.

Acknowledgment

The author gratefully acknowledges support of the Office of Naval Research.

[22] G. Nagy, "Analogue Memory Mechanisms for Neural Nets," Ph. D. Thesis, Cornell University, Ithaca, N. Y.; 1962.

[23] K. R. Shoulders, "Research in Microelectronics Using Electron-Beam Activated Machining Techniques," Stanford Research Institute, Menlo Park, Calif., 1960.