AN ADAPTIVE "ADALINE" NEURON USING CHEMICAL "MEMISTORS"

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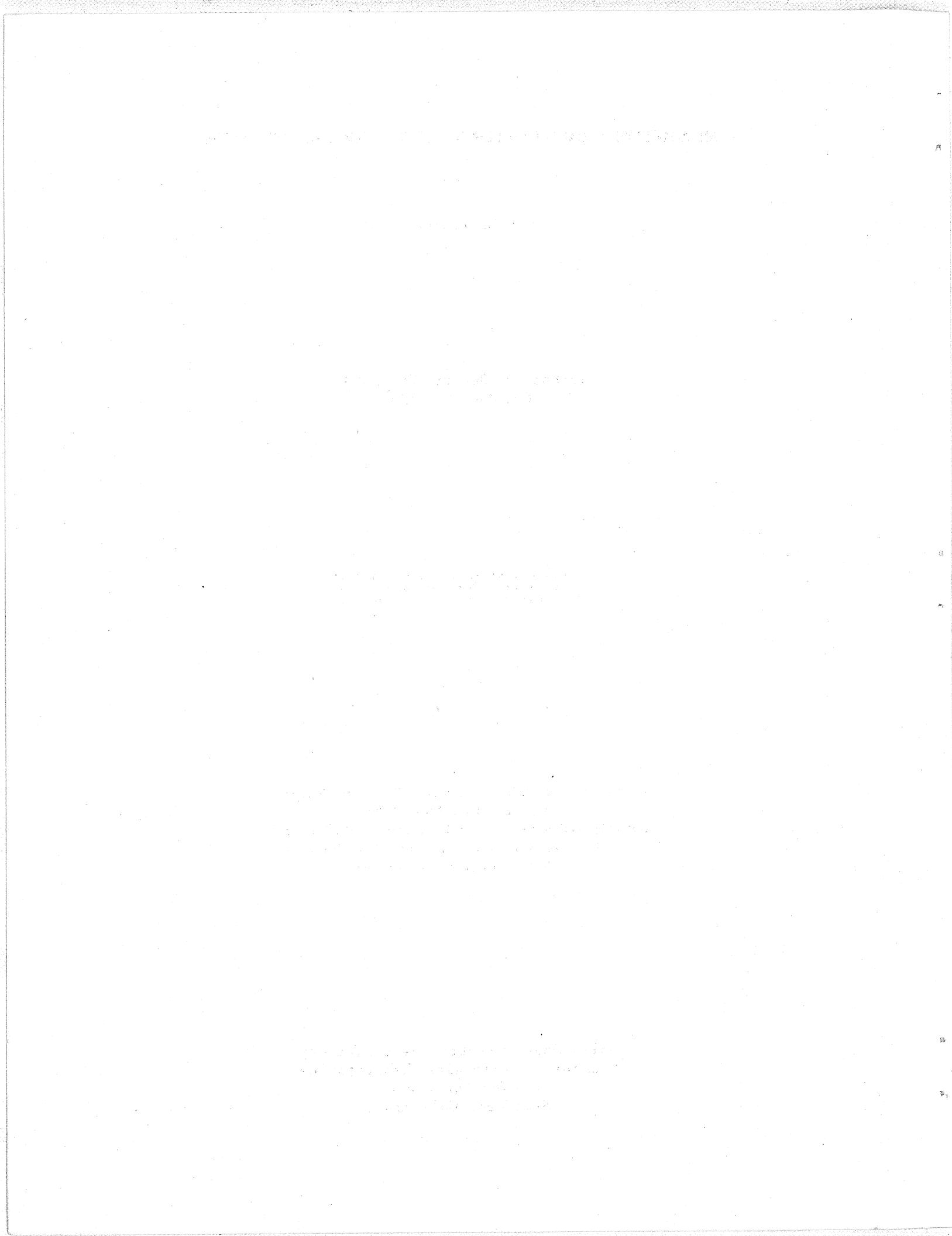
B. Widrow

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Solid-State Electronics Laboratory
Stanford Electronics Laboratories
Stanford University
Stanford, California

SUMMARY

A new circuit element called a "memistor" (a resistor with memory) has been devised that will have general use in adaptive circuits. With such an element it is possible to get an electronically variable gain control along with the memory required for storage of the system's experiences or training. Experiences are stored in their most compact form, and in a form that is directly usable from the standpoint of system functioning. The element consists of a resistive graphite substrate immersed in a plating bath. The resistance is reversibly controlled by electroplating.

The memistor element has been applied to the realization of adaptive neurons. Memistor circuits for the "Adaline" neuron, which incorporate its simple adaption procedure, have been developed. It has been possible to train these neurons so that this training will remain effective for weeks. Steps have been taken toward the miniaturization of the memistor element. The memistor promises to be a cheap, reliable, mass-producible, adaptive-system element.

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I. INTRODUCTION

An adaptive or "learning" system can automatically modify its own structure to optimize performance based on past experience. The system designer is more of an executive here. Instead of seeing to all details of system design, he "teaches" by showing the system examples of input signals or patterns and, simultaneously, what he would like the output to be for each input. The system in turn has the job of organizing itself to comply as well as possible with the wishes of the designer.

A means of constructing and analyzing simple logical and switching systems that are capable of being designed by teaching has been described by this author and M. E. Hoff in a report[1] and a paper,[2] both entitled "Adaptive Switching Circuits". The core of the schemes described therein consists of an adaptive logical element which has been named the "Adaline" neron (called Adaline, for adaptive linear).. The system design procedure is adaptive, and is based upon an iterative search process. Performance feedback is used in achieving automatic system synthesis, i.e., the selection of the "best" logical function from a restricted but useful. class of possibilities.

II. THE ADALINE NEURON ELEMENT

In Fig. 1, a combinatorial logical circuit is shown which is a typical element in the adaptive switching circuits to be considered. This element bears some resemblance to a neuron model introduced by von Neumann,[3] whence the name.

The binary input signals on the individual lines have values of +1 or -1, rather than the usual values of 1 or 0. Within the neuron, a linear combination of the input signals is formed. The weights are the gains a_1, a_2, ..., which could have both positive and negative values. The output signal is +1 if this weighted sum is greater than a certain threshold, and -1 otherwise. The threshold level is determined by the setting of a_0, whose input is permanently connected to a +1 source.

[1] Superscript numerals refer to list of references at end of report.
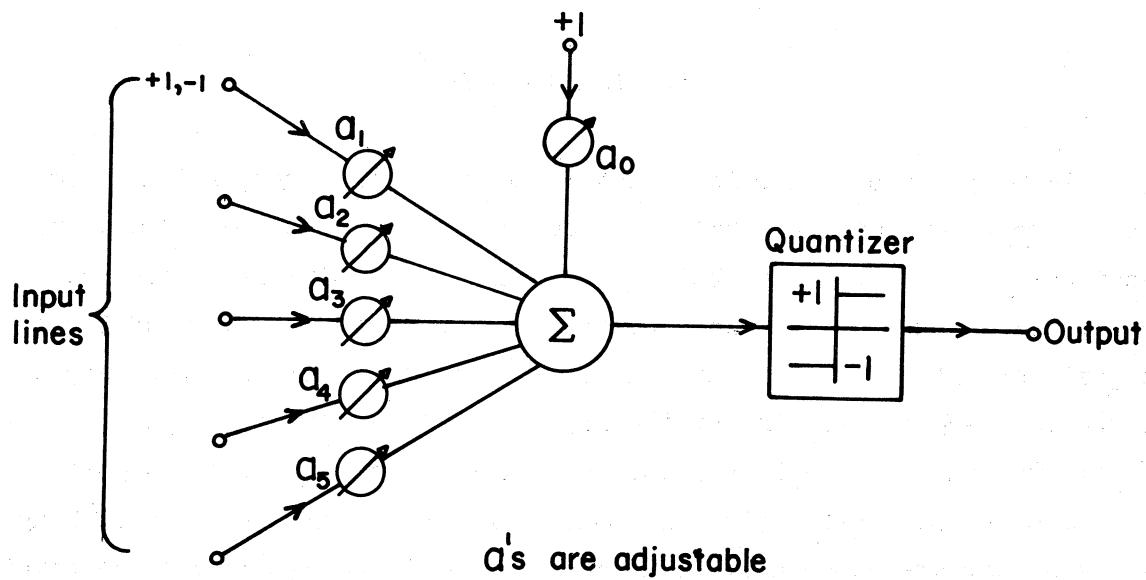
FIG. 1.--AN ADJUSTABLE NEURON.

Varying a_0 varies a constant added to the linear combination of input signals.

For fixed gain settings, each of the 2^5 possible input combinations would cause either a +1 or a -1 output. Thus, all possible inputs are classified into two categories. The input-output relationship is de-termined by choice of the gains $a_0, \ldots a_5$. In the adaptive neuron, these gains are set during the "training" procedure.

In general, there are 2^{2^5} different input-output relationships or truth functions by which the five input variables can be mapped into the single output variable. Only a subset of these, <u>the linearly separated truth functions</u>,[4] can be realized by all possible choices of the gains of the neuron of Fig. 1. Although this subset is not all-inclusive[*], it is a useful subset, and it is "searchable", i.e., the "best" function in many practical cases can be found iteratively without trying all functions within the subset.

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[*] It becomes a vanishingly small fraction of all possible switching functions as the number of inputs gets large.

Application of this neuron in adaptive pattern classifiers was first made by Mattson.[5,6] He has shown that complete generality in choice of switching function can be had by combining these neurons. He devised an iterative digital computer routine for finding the best set of a's for the classification of noisy geometric patterns. An iterative procedure having similar objectives has been devised by Widrow and Hoff and is described below. The latter procedure is quite simple to implement, and can be analyzed by statistical methods that have already been developed for the analysis of adaptive sampled data systems.[1,2,7,8]

An adaptive pattern classification machine (called "Adaline") has been constructed for the purpose of illustrating adaptive behavior and artificial learning. A photograph of this machine, which is about the size of a lunch pail, is shown in Fig. 2.

During a training phase, crude geometric patterns are fed to the machine by setting the toggle switches in the 4 x 4 input switch array. Setting another toggle switch (the reference switch) tells the machine whether the desired output for the particular input pattern is +1 or -1. The system learns a little from each pattern and accordingly experiences a design change. The machine's total experience is stored in the values of the weights $a_0 \cdots a_{16}$. The machine can be trained on undistorted noise-free patterns by repeating them over and over until the iterative search process converges, or it can be trained on a sequence of noisy patterns on a one-pass basis such that the iterative process converges statistically. Combinations of these methods can be accomodated simultaneously. After training, the machine can be used to classify the original patterns and noisy or distorted versions of these patterns.

A block schematic of Adaline is shown in Fig. 3. In the actual machine, the quantizer is not built in as a device but is accomplished by the operator in viewing the output meter. Different quantizers (2-level, 3-level, 4-level) are realized by using the appropriate meter scales (see Fig. 2). Adaline can be used to classify patterns into several categories by using multi-level quantizers and by following exactly the same adapting procedure.
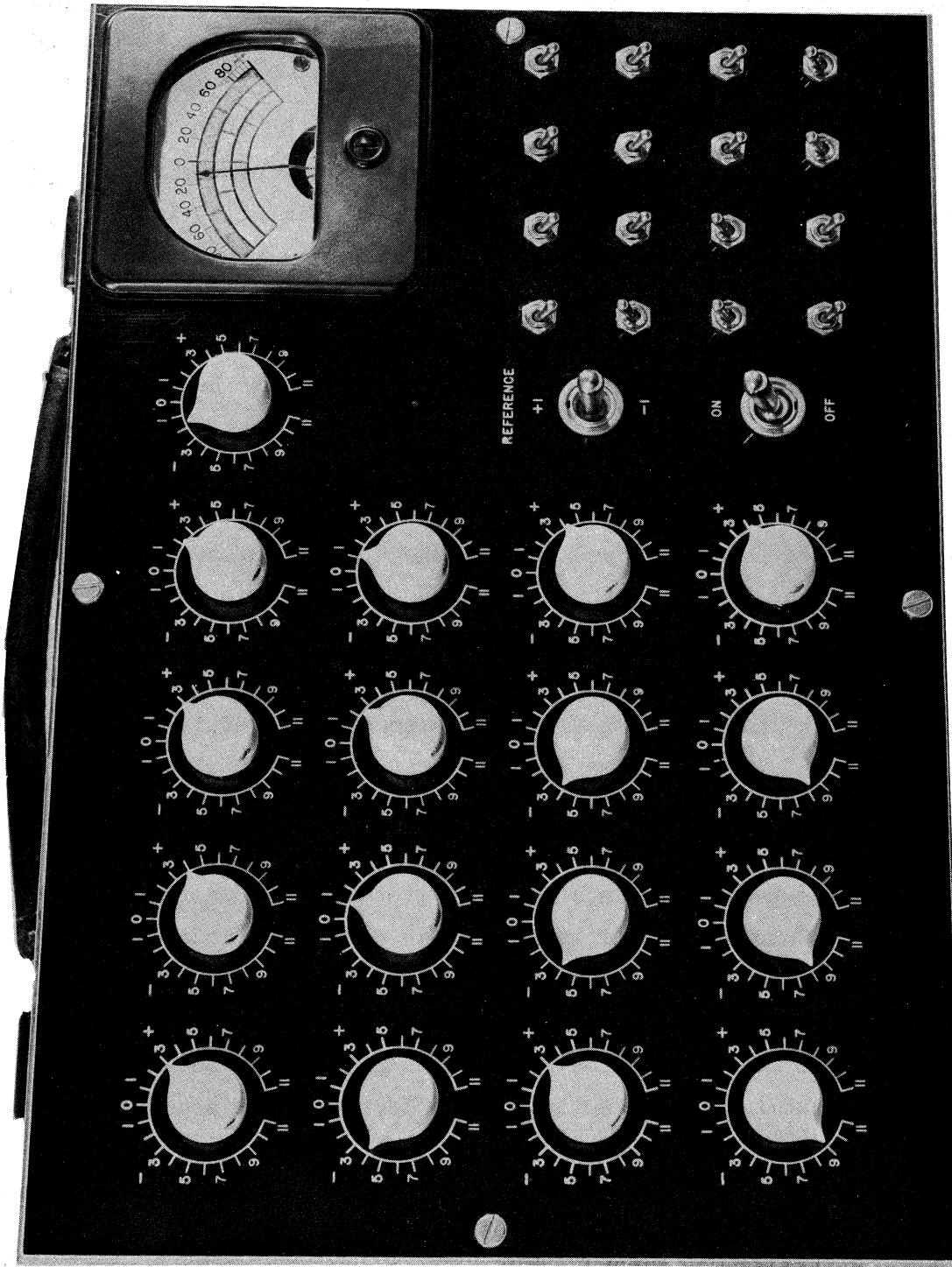
FIG. 2.--ADALINE.

The following is a description of the iterative searching routine.
A pattern is fed to the machine, and the reference switch is set to
correspond to the desired output. The error (see Fig. 3) is then read
(by switching the reference switch; the error voltage appears on the
meter, rather than the neuron output voltage). All gains including the
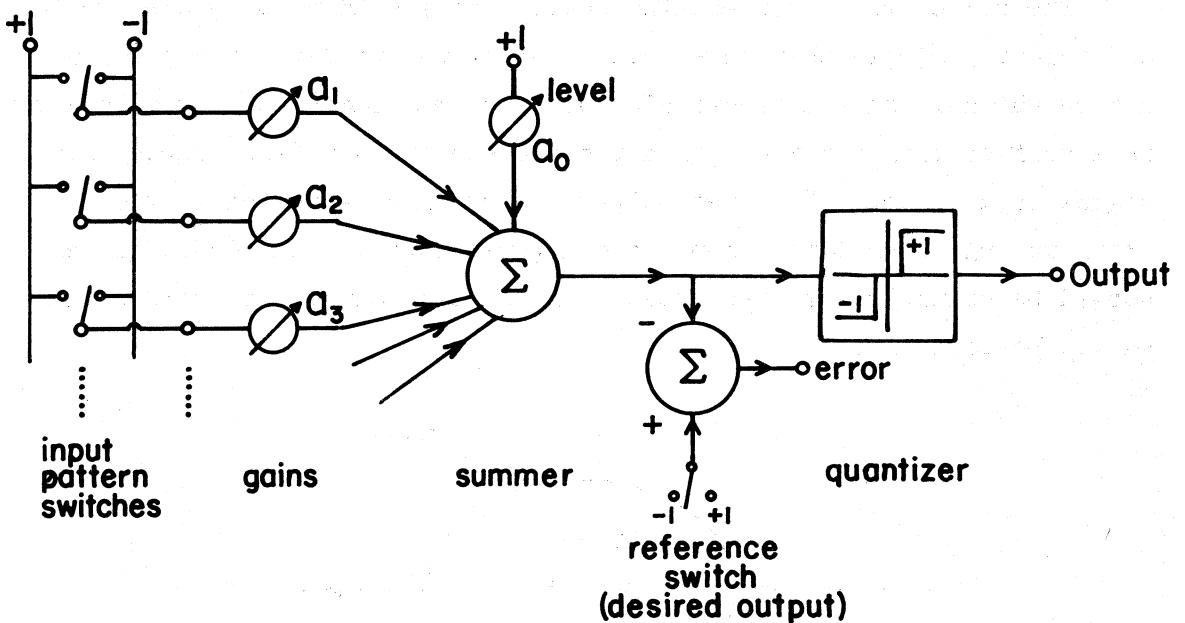
FIG. 3.--SCHEMATIC OF ADALINE.

level are to be changed by the same absolute magnitude, such that the
error is brought to zero. This is accomplished by changing each gain
(which could be positive or negative) in the direction which will diminish
the error by an amount which reduces the error magnitude by 1/17. The 17
gains may be changed in any sequence, and after all changes are made, the
error for the present input pattern is zero. Switching the reference
back, the meter reads exactly the desired output. The next pattern,
and its desired output, is presented and the error is read. The same
adjustment routine is followed and the error is brought to zero. If the
first pattern were reapplied at this point, the error would be small but
not necessarily zero. More patterns are inserted in like manner.

Convergence is indicated by small errors (before adaption), with small fluctuations about a stable root-mean-square value. The gain values automatically stabilize about their optimum values. The iterative routine is purely mechanical, and requires no thought on the part of the operator. Electronic automation of this procedure is the subject of this report.

The structure of the Adaline neuron and its adaption procedure is sufficiently simple that an effort is under way to develop a physical device which is an all-electronic fully automatic Adaline. The objective is a self-contained device, like the one sketched in Fig. 4, that has a signal input line, a "desired output" input line (actuated during training only), an output line, and a power supply. The device itself should be suitable for mass production, should contain few parts, and should be reliable.
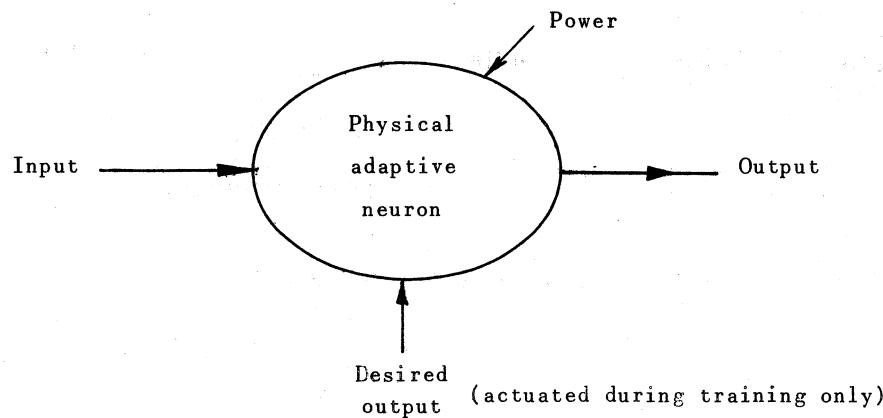

FIG. 4.   ELECTRONIC AUTOMATICALLY-ADAPTED NEURON.

To have such an adaptive neuron, it is necessary to be able to store the gain values, which could be positive or negative, in such manner that these values could be changed electronically.

III. THE MEMISTOR

A variable gain effect could be achieved physically by using a
variable resistance, capacitance, inductance, or combinations of these.
The use of a variable resistance device, and characteristics of such a
device, will be discussed in this report.

A variable resistor called a memistor (a resistor with memory) has
been devised which uses the phenomenon of electroplating to control re-
sistance by depositing metal on a resistive substrate. The first
successful attemp at making a memistor involved electroplating copper
from a copper sulfate-sulfuric acid bath upon an ordinary pencil lead.

The circuit-diagram symbol for the simplest configuration of
memistor is shown in Fig. 5. The substrate structure is the variable
resistance, while the source is the control element. The substrate
resistance is sensed with ac current while the plating thickness is
controlled with dc current. This device is like a three-terminal
transistor, except that the resistance between two of the terminals is
controlled not by instantaneous control current in the third, but by
the time integral of this current.
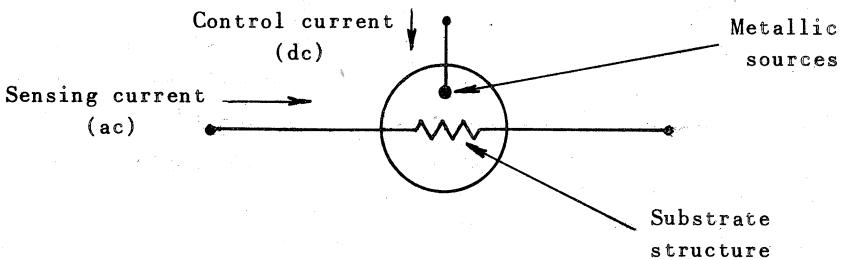
FIG. 5.   SYMBOL OF MEMISTOR.

An ideal memistor would have the following electrical character-
istic: the conductance would vary linearly with total plating charge.
Achieving this characteristic requires that the plating process be
reversible, that the memistor resistance stay put indefinitely when
plating current is zero, that the conductance vary smoothly with
plating current, and that there be no hysteresis associated with change
in direction of plating. The first pencil-lead memistors have been

made to exhibit approximations to such characteristics over the dynamic
resistance range from 5 ohms down to 1/2 ohm. The conductance versus
plating charge with an ordinary copper sulfate-sulfuric acid plating
bath is shown in Fig. 6 (a). The hysteresis effect is believed to be
caused by large copper crystals. Addition of a "brightener" to the bath
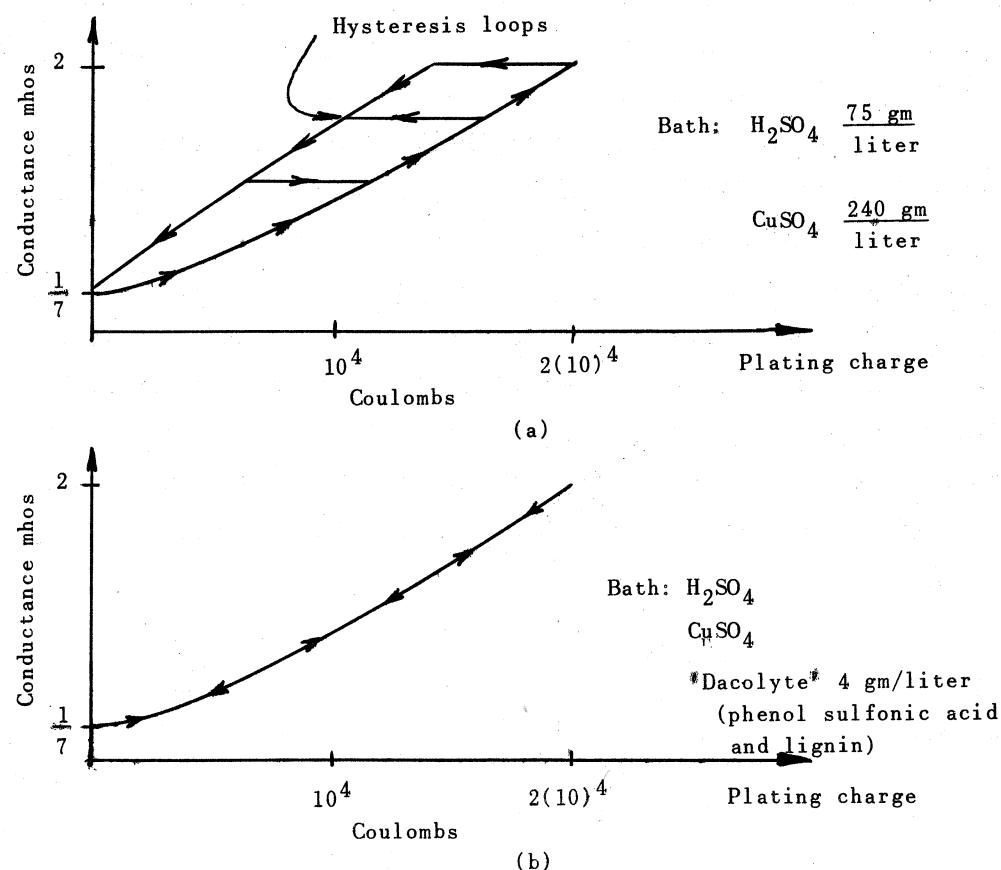

FIG. 6.   CHARACTERISTICS OF TYPICAL PENCIL-LEAD MEMISTOR.
(a) WITHOUT BRIGHTENER; (b) WITH BRIGHTENER.

which causes the deposit to consist of smaller copper crystals, has been
very effective in eliminating hysteresis and causing this characteristic
to be as shown in Fig. 6.(b).

A photograph of the pencil-lead memistor and the containing test
tube is shown in Fig. 7. The "lead" used is a 2 3/4 in. Fineline type
H, medium hard. The ends are plated first so that the connections can
be soldered. The end connections are insulated by painting. The
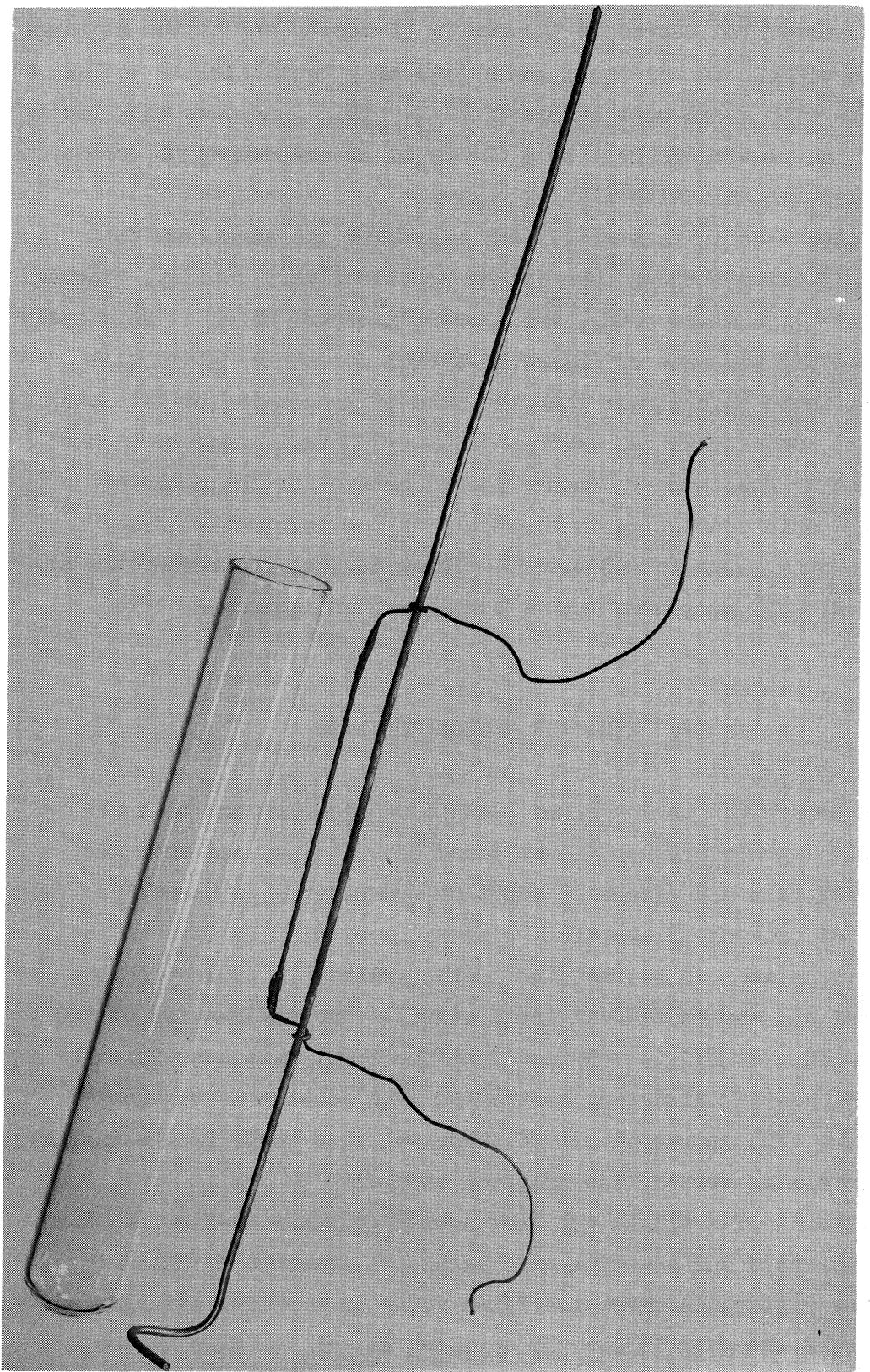
FIG. 7.   PENCIL-LEAD MEMISTOR ELEMENT.

supporting copper rod serves as the source of copper and as the plating-current electrode. It was found to be extremely beneficial to polish the graphite with steel wool before plating. This increases the effectiveness of the plating current by a factor of 3, and causes the conductance to vary smoothly with plating charge.

Memistors made in this or similar ways have the advantage that information flowing through them can be processed very rapidly, flowing in a metallic conduction path. The plating process, which is relatively slow, determines the rate of change of system structure, which will always want to be much slower than the rate of processing or filtering information. Other chemical devices or ideas [9,10] that might be used to perform similar functions to those claimed herein for the memistor depend upon ionic conduction in electrolytes for information flow, rather than upon metallic conduction. These devices and mechanisms are inherently slower, more temperature sensitive, and generally less reliable.

IV. MEMISTOR NEURON CIRCUITS

The neuron circuits described in this section presume that the neuron input signals are applied by means of switches, and that the over-all direction and extent of adaption are controlled manually. The individual directions of adaption (plating on or plating off) of the memistors is determined by the sign of the arithmetic product of the error signal and the individual input signal. The information on the individual input signal is obtained from the input switch position by having final plating direction controlled by a section of the gauged input switch. The source to all of these switches comes from a manually operated reversing switch, the adaption control.

The circuit of a simple memistor neuron is shown in Fig. 8. The effect of positive and negative gain values is obtained by balancing the memistor resistance against a fixed value in a bridge arrangement. The sensing of the gain is done by applying an ac voltage to the memistor, and another ac voltage with a 180-degree phase difference to the fixed reference resistor; the currents are proportional to the
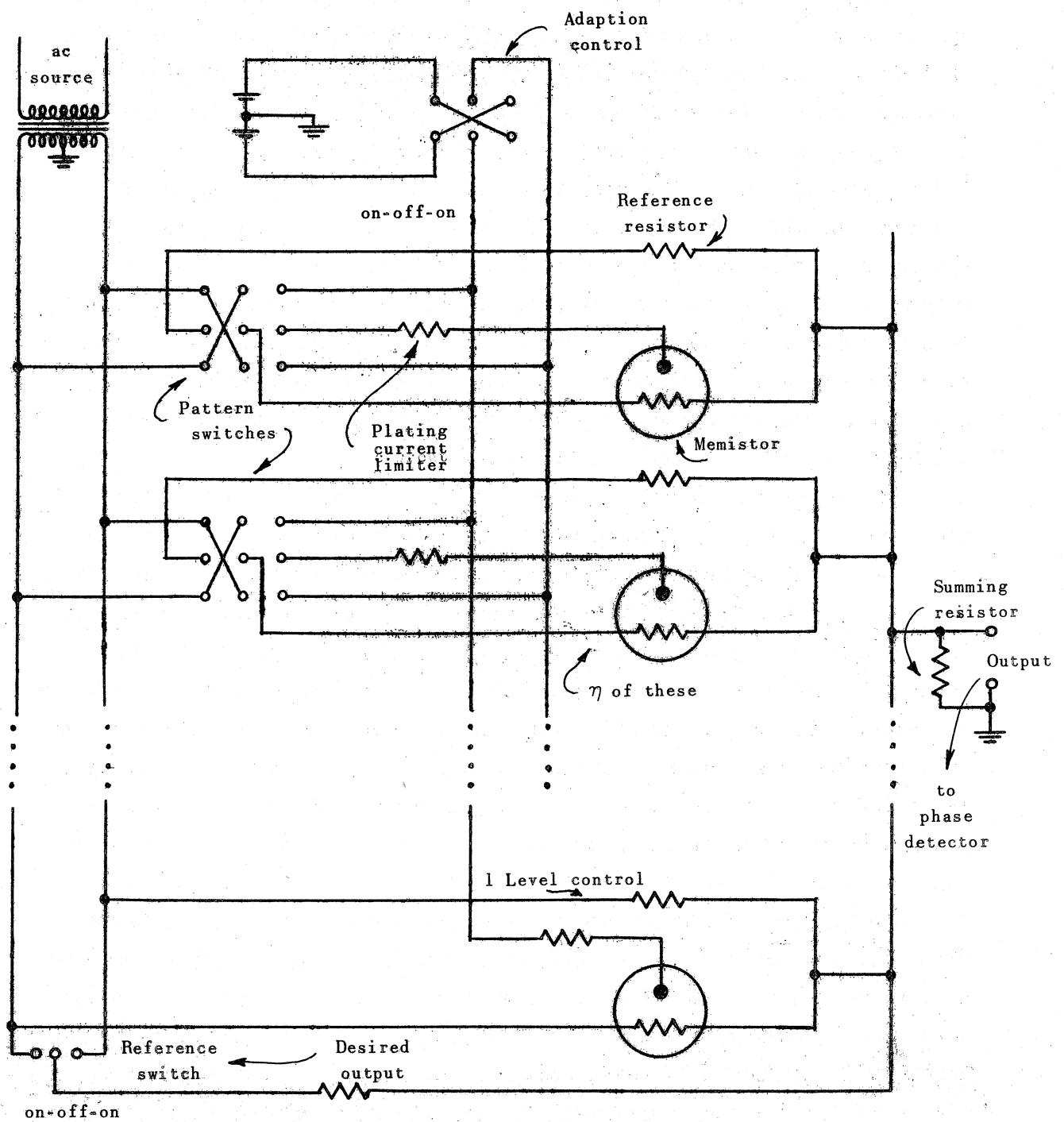
FIG. 8. A SIMPLE MEMISTOR ADALINE CIRCUIT.

conductances, and are summed. The gain is zero when the conductances are equal. The smoothest control of gain is achieved when the full dynamic range of conductance values of the memistors is utilized. With this criterion, the optimum value of conductance for the reference resistor is the average of the extremes of the memistor conductances.

During the training phase, input patterns are applied by setting the pattern switches. The desired output is applied by setting the reference switch. The adaption control is actuated in the proper direction as long as necessary to bring the output signal to zero. The reference switch is then returned to "off", whereupon the output signal is a measure of the neuron sum (see Fig. 1). The phase of this sum is either the same as that of the ac source, or 180 degrees different from this. The phase indicates the sign of the sum which dictates whether the neuron output is +1 or -1.

Another neuron circuit is shown in Fig. 9, which is the dual of the circuit of Fig. 8. The memistors and the reference resistors are driven by equal and opposite ac current sources. Their voltages are summed here. A gain of zero corresponds to equal resistances. Utilization of the full dynamic range of memistor resistance can be had by making the reference resistance be the average of the memistor resistance extremes. Electroplating will naturally tend to make conductance rather than resistance a linear function of plating charge. For small changes in resistance, the resistance will vary approximately linearly with plating charge. The training procedure of the system of Fig. 8 is identical with that of Fig. 8.

The circuit of Fig. 10 uses a somewhat different kind of memistor element. Two memistors are immersed in the same bath with equal amounts of plating, initially. There is no source-of-copper electrode. Change in bridge balancing is accomplished by plating from one substrate to the other by applying equal and opposite dc voltage components along with the usual ac sensing voltages. The advantage to this circuit is its simplicity. The main disadvantage lies in the difficulty in stabilizing the memistor resistance values with no fixed reference resistors for comparison. It should be noted however that the equivalent gain associated with a given double-memistor will come to a stable value as a consequence of the nature of the adaption procedure. The gain value is proportional to the difference in the conductances.
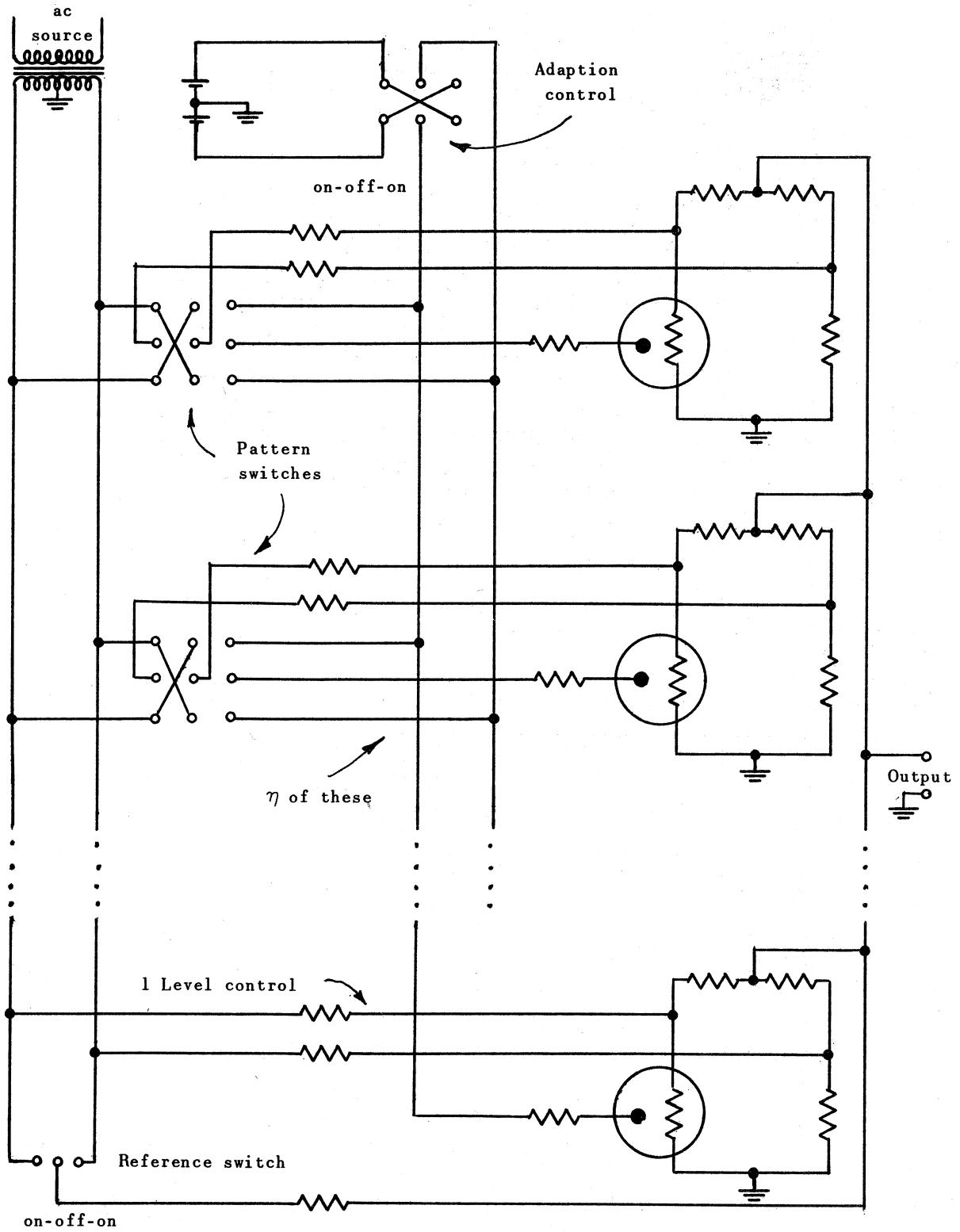
FIG. 9.   CURRENT-SOURCE DRIVEN MEMISTOR NEURON CIRCUIT.

ac
source

Reference switch

on-off-on

η of these

Output

1 Level control

Chokes

on-off-on

Adaption control
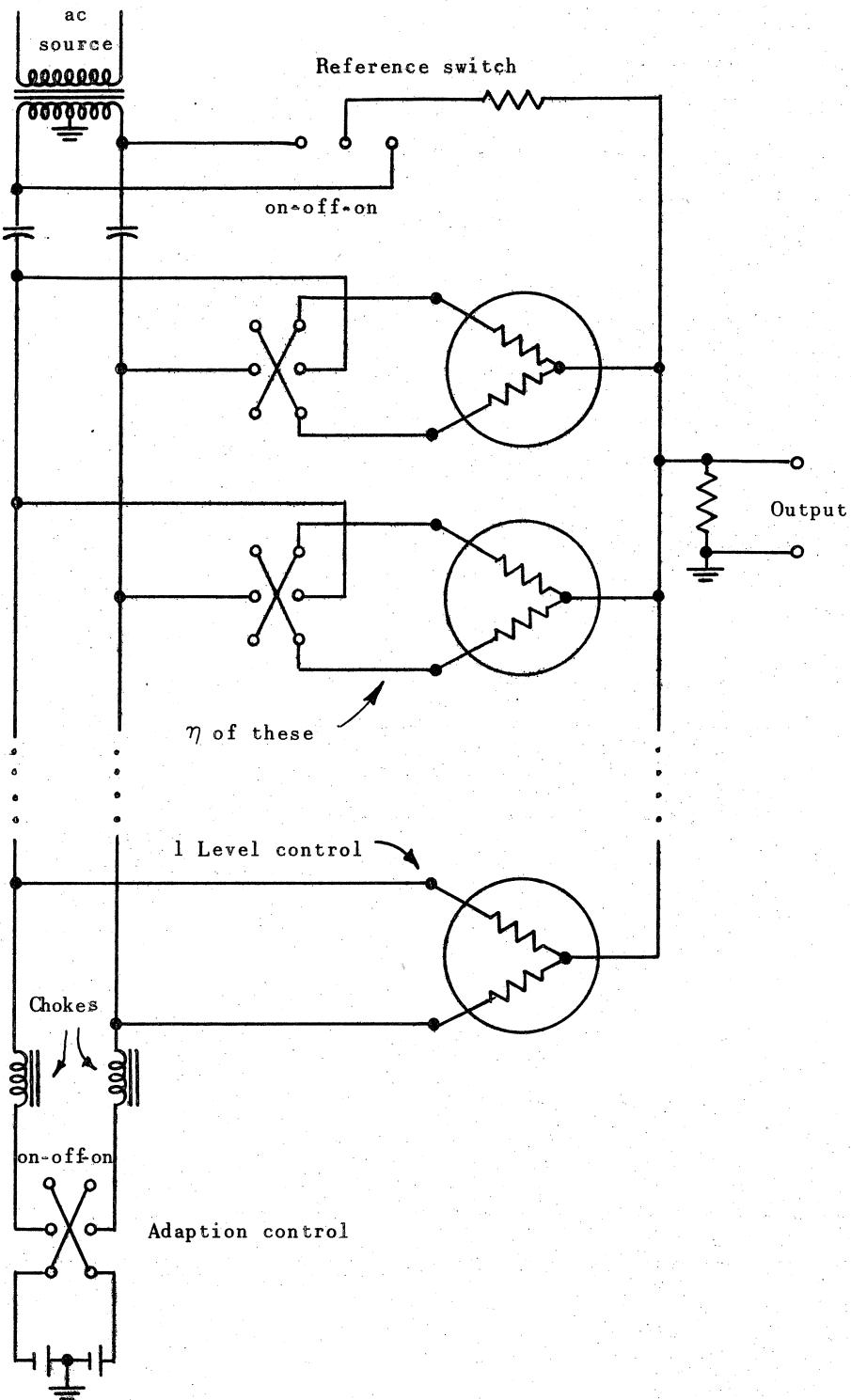
FIG. 10.   A DOUBLE-MEMISTOR ADALINE NEURON.

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V. A 3 X 3 MEMISTOR ADALINE

A 3 x 3 neuron has been constructed to illustrate the memistor operating principles. A photograph of the apparatus is shown in Fig. 11.

This apparatus is an implementation of the circuit of Fig. 8. The memistors are the pencil-lead type described in Section II. The 60-cycle ac supply to the neuron has a voltage from center tap to one side of 0.5 volts. The reference resistors have values of 2.7 ohms. The dc plating supply has 6 volts from center tap to each terminal, and the plating current limiting resistors have values of 49 ohms. These give plating currents of approximately 100 ma. The summing resistor was found to be unnecessary and has been eliminated.

Output wave forms are shown in Fig. 12 which resulted from the indicated training experiment. It is clear that the seven different patterns and the associated desired outputs comprise a linearly separable set and are resolved by the single neuron. This is a demanding test for the neuron, however, as can be seen by comparing the "J" whose desired output is -1 with the horizontal "C" whose desired output is +1.

The speed of convergence (measured in terms of number of data reiterations) of the adapting processes appeared to be somewhat greater for the memistor Adaline than for the manual Adaline of Fig. 2. The reason for this lies in the fact that the gain changes in the memistor circuit are smooth rather than discrete. Quantization noises in the adjustment transients give these transients the appearance of being longer-lived.

The memistors used in the 3 x 3 neuron were not individually tested. The plating-current-limiting resistors and the reference resistors had 5 % tolerances. The performance feedback process was able to make operation of the neuron insensitive to variations in characteristic of the individual gain elements.

After training, the neuron structure has been able to remain essentially unchanged for days. Slight changes in output waveforms have been noticeable one day after fresh training, but almost no change takes place after that. In one test, the patterns shown in Fig. 12 were "socked in", and four days later, with no further training, output
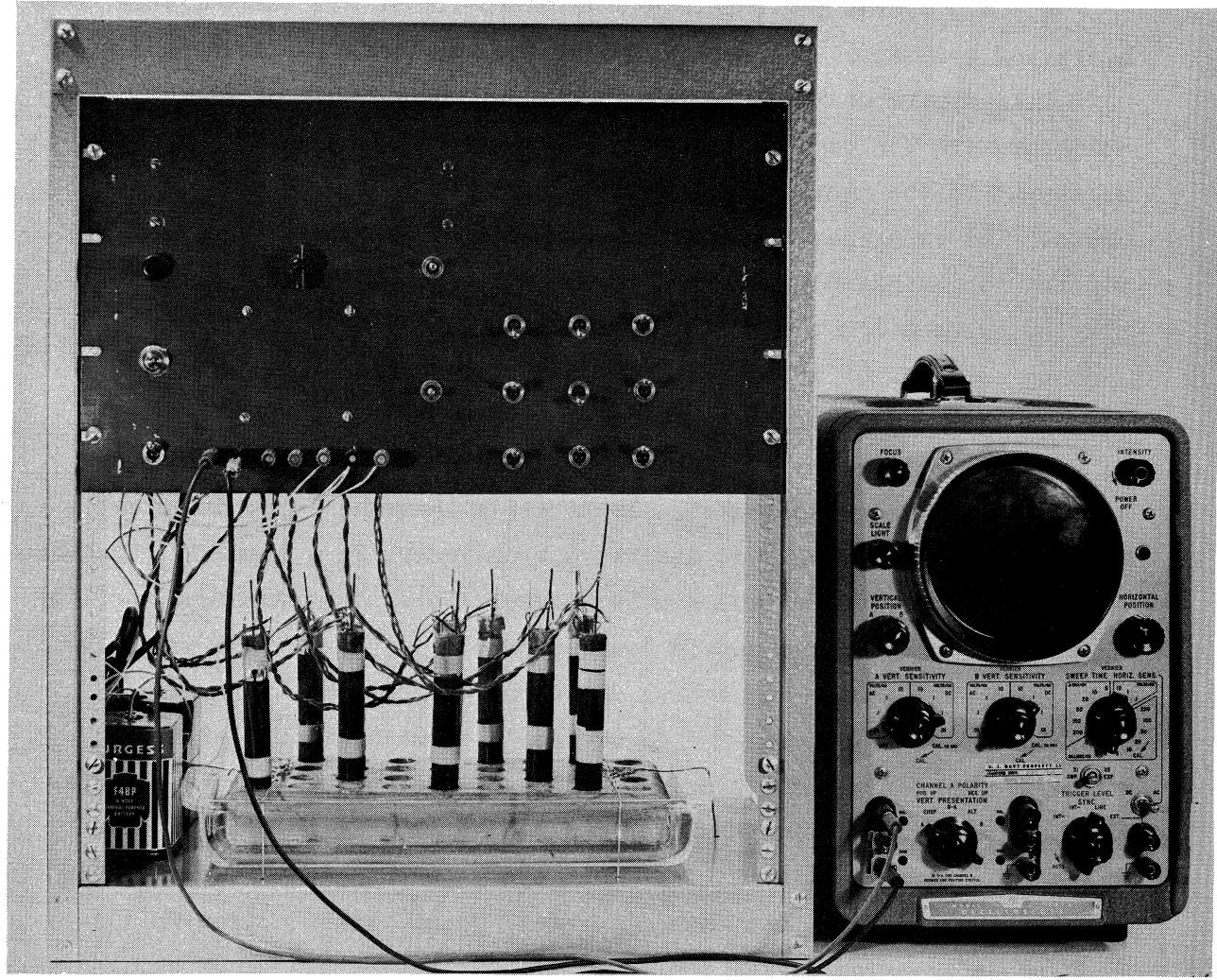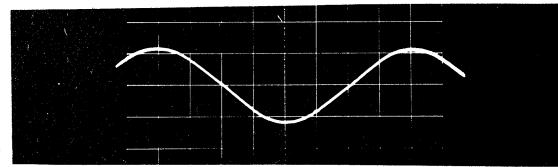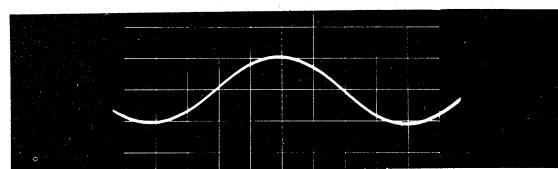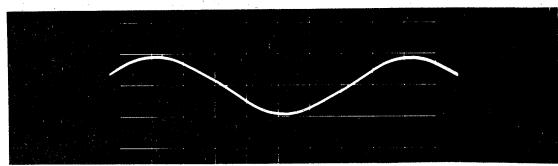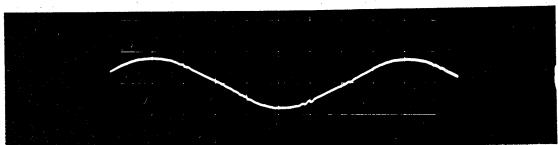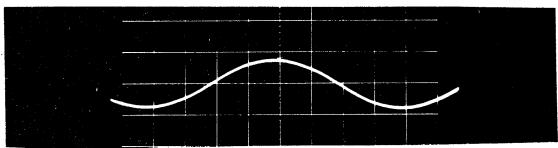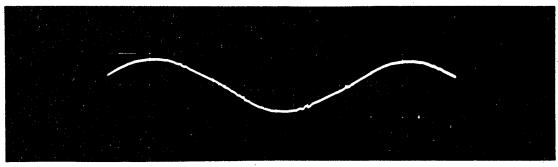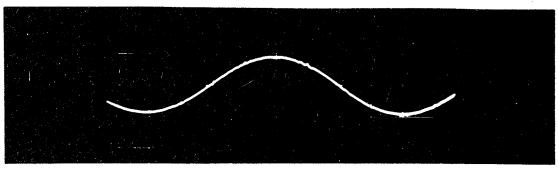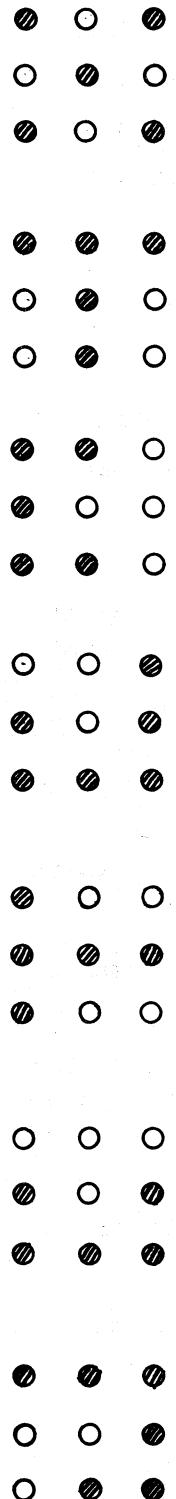
FIG. 11.   A 3 x 3 MEMISTOR NEURON MODEL.

60 ~ sine waves; vertical scale is 0.1 volts/cm

FIG. 12.   WAVE-FORMS OF A MEMISTOR NEURON AFTER A
TRAINING EXPERIMENT.

wave-forms were observed to be almost unchanged when the original input patterns were re-applied. The permanence of the storage of plating depends upon the plating bath being rich in copper sulphate. The acid tends to dissolve such thin platings. The brightener helps greatly in ensuring the permanence of the plating.

VI. FUTURE DIRECTIONS

The following is a list of objectives that, when realized, will bring memistor neuron circuits to a far more flexible and useful state of development.

(a) Adaption processes should be fully automatic, and there should be extremely simple circuitry and components involved in this.

(b) Input signals are to be supplied directly, not by switch settings. Control of direction of adaption must come from the input-signal phase information.

(c) The neurons should be interconnectible for use in neural networks. Impedance levels and signals at inputs and outputs should be compatible.

(d) The neurons should be smaller, faster in plating, and take less plating current.

(e) The geometry of the electrodes, nature of the electrolyte, and configuration of the associated circuitry should be such as to permit the use of a common electrolyte bath or single cell for all the memistors.

(f) Dry paste electrolytes should be used, or plating or other phenomena in solids should be used to get memistor action.

(g) Structures and materials should be such that memistors and neurons could be mass produced by thin-film or other microelectronic building techniques.

The circuit shown in Fig.13 represents a highly speculative step toward realization of objectives (a), (b), and (c). The intention here is that adaption be automatic, and that the direction of each gain change be determined by the phase of the error signal and the phase of the individual input signal. The input signals are shown, for the sake of

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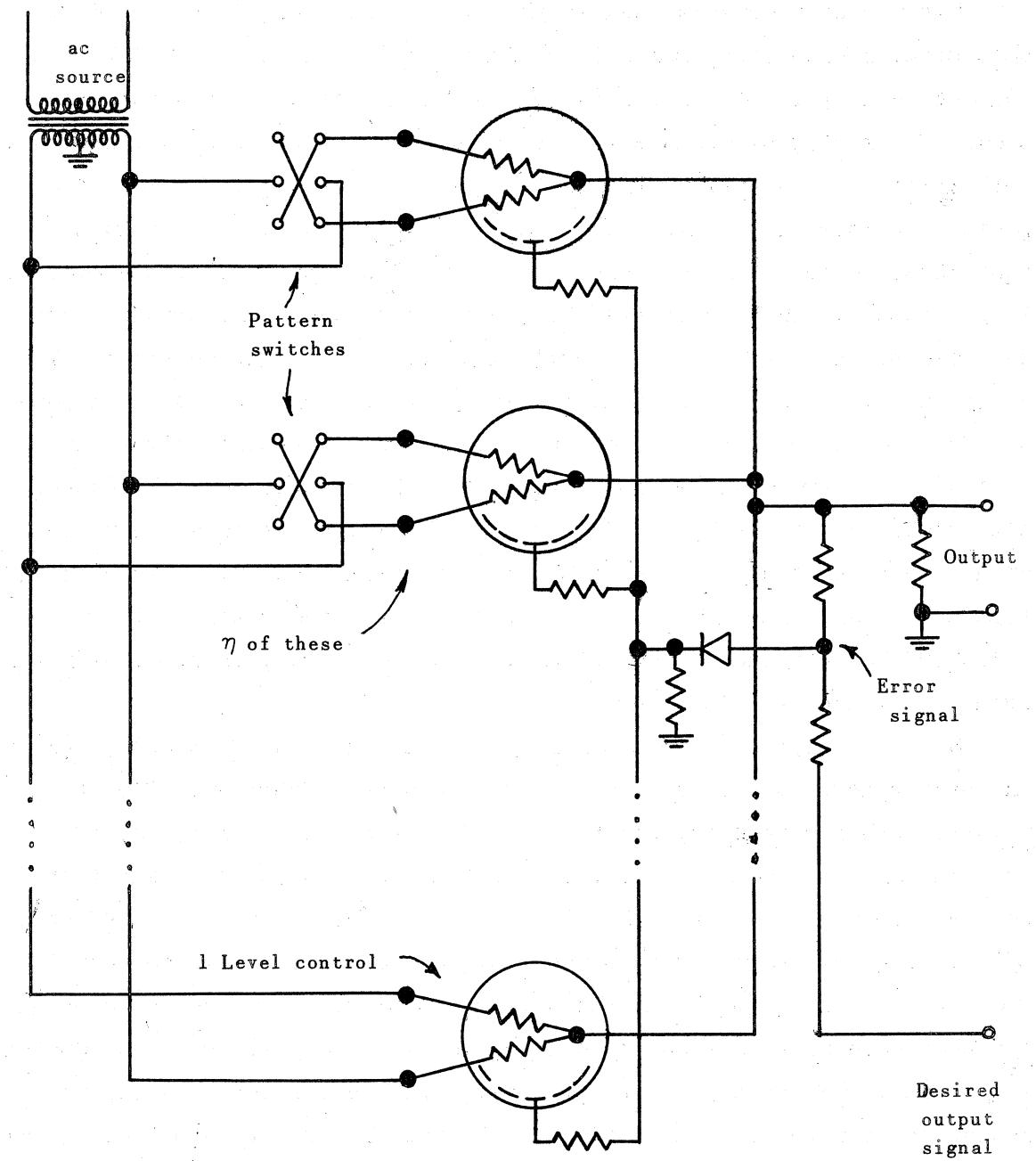
FIG. 13. A SPECULATIVE FULLY AUTOMATIC MEMISTOR NEURON.
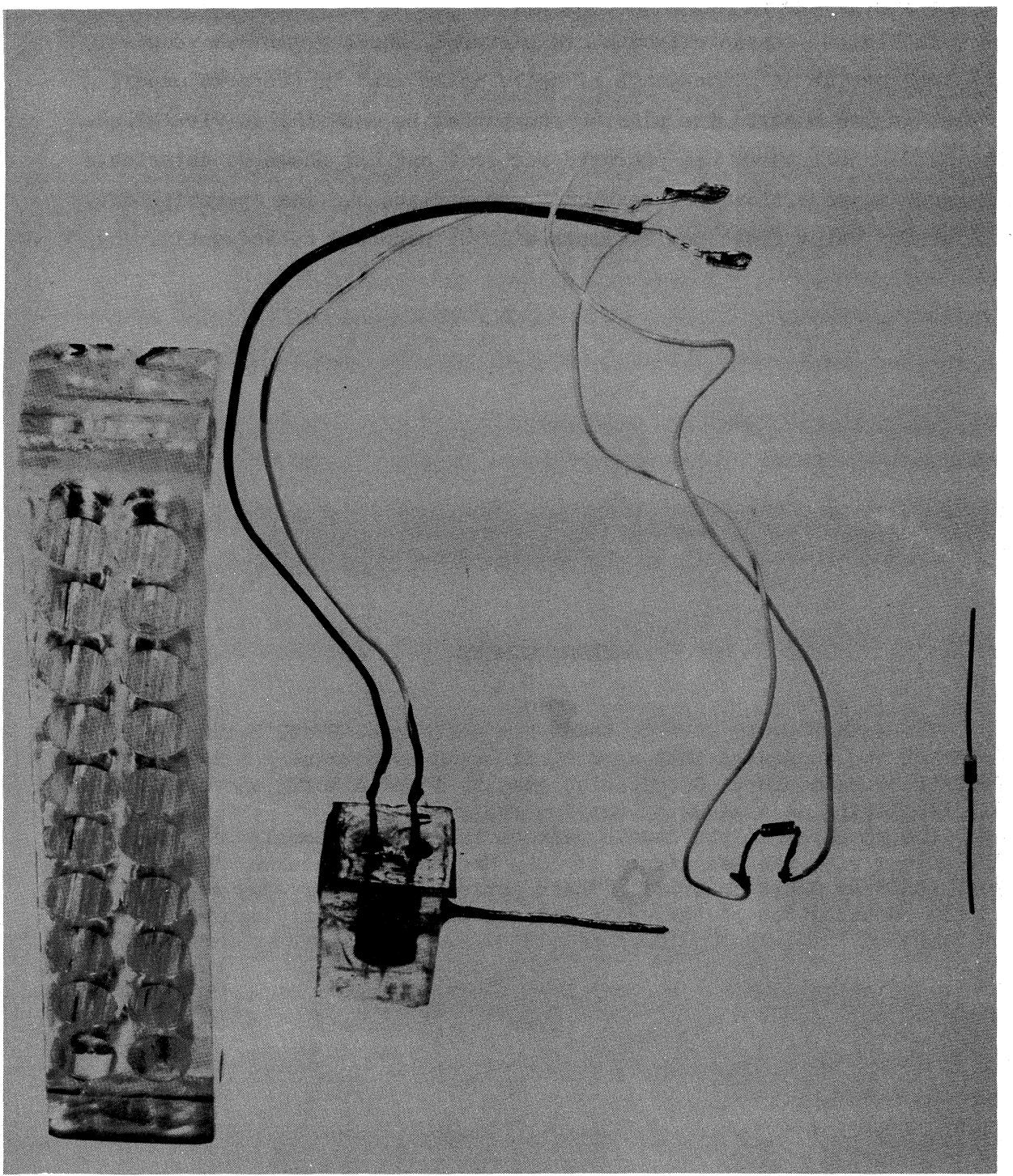
clarity, as arising from input switches. They could just as well come from other neurons or from other signal sources.

The memistor devices used in the circuit of Fig. 13 are unusual, consisting of double elements in a single bath with an electrical connection to the bath itself by means of a graphite or platinum electrode of large area. This electrode could be the casing or shell of the cell. The error signal in the circuit is rectified, and the resulting positive pulses are applied to all the casing electrodes. The normal equilibrium exchange of alternate plating and stripping from one element to the other would be disturbed by the error pulses. The plating onto the element that has a negative voltage during the positive error pulse would receive an amount of plating deposit that would exceed the deposit on the other element on the next half-cycle when the error signal is rectified to zero. There should be no plating deposited on the casing electrode. The tendency is the reverse of this, hence this electrode should be made of a material that will not go into solution, such as platinum or graphite. The total amount of deposited metal on the memistor elements should be constant. Adaption merely shifts this metal from one element to the other.

Certain steps have been taken toward realization of objective (d). The next generation of memistor elements has been fabricated from tiny $\frac{1}{10}$-watt carbon resistors, which are used in transistor circuits. By grinding and polishing, it is possible to have a smooth flat substrate to plate upon which is parallel to the cylindrical axis of the resistor. By grinding down part way into the resistor leads, metallic contact is made between these leads and the surface plating. A successful element has been made in this fashion that begins (with no plating) with 100 ohms resistance. In about 1 minute of plating with a current of 3 ma, the resistance can be taken down to about 1 ohm. The relation between plating charge and conductance is smooth and instantly reversible.

This new element compares with the pencil-lead element in the following way: It has 10 times as great a resistance ratio, it requires 1/30 of the plating current, it covers the resistance range several times faster, it is about 10 times smaller in linear dimension, it has a more favorable resistance range (about 10 times as high an impedance level

FIG. 14. HONEYCOMB OF MEMISTORS.

as the pencil lead).

In Fig. 14 , these elements are pictured, showing various stages in the fabrication of a honeycomb of cells to be used in the next experimental neuron model. The plastic encapsulating material is Plexiglass. The single cell shown has operated for days and has shown no detectable changes in properties as a result of encapsulation. The operation of the neuron using these new elements will be reported subsequently.

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