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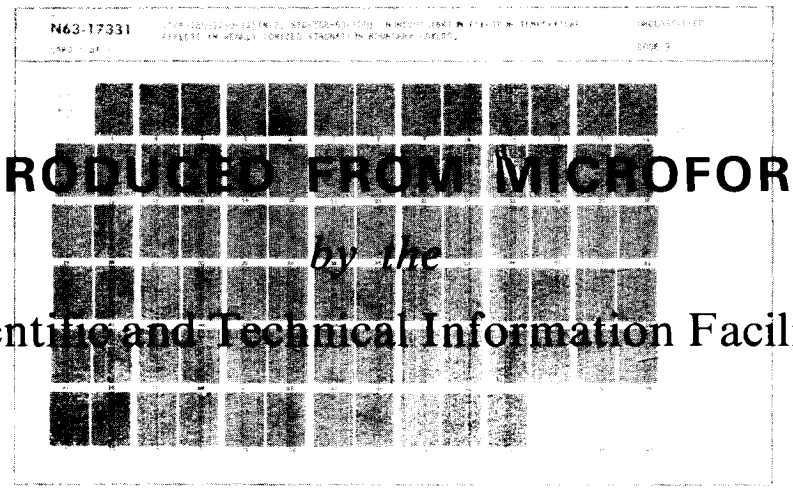

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ARTIFICIAL INTELLIGENCE: A SUMMARY OF CURRENT RESEARCH AND DEVELOPMENT

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ABSTRACT

Current research and development in the field of artificial intelligence was reviewed by examining existing physical, mathematical, and logical models of brain functions at the installations and facilities engaged in this research. Relevant literature also was reviewed to update the literature searches previously performed by the Jet Propulsion Laboratory. The findings are summarized under the general headings of neurological considerations, special purpose computer models and general computer program models. A bibliography of 1,123 supplementary specific references and 67 general sources (proceedings of symposia and conferences, anthologies and relevant bibliographies) is presented. A systematic review of the field is presented with special emphasis on evaluating the potentiality of theory and devices in providing a basis for the development of equipment to be used in space systems.

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I. INTRODUCTION

A. Problem

Recent developments have suggested that automatic devices can be constructed to simulate many of man's complex intellectual functions. However there is still a great deal of controversy with respect to the worth and capabilities of these devices. Some believe that these "mechanical brains" can "think" and that in due time may overwhelm man if not controlled. Others claim that the machines themselves cannot think but can do only what they are programmed to do by man. Recent research indicates that, in fact, neither of these points of view is entirely correct. Machines have been designed which play games, sometimes defeating their designers. Others are capable of distinguishing patterns, both visual and auditory. Computer programs have been written which simulate with remarkable accuracy the decision-making behavior of human subjects, and "self-organizing" and "adaptive" systems are being designed which will be able to adapt to changing and partially unknown environments. But no machine has yet been designed which is capable of duplicating man's tremendous flexibility, adaptability, and versatility in meeting new situations.

Much of the earlier literature is highly speculative and over-optimistic. Further, the early work seems mostly an uncontrolled, enthusiastic attack on various aspects of the problems of simulating human behavior by investigators from a variety of disciplines. However, more recently, there has been a trend toward an interdisciplinary approach in developing systems, programs, or machines that will accomplish well-defined and specific goals. Two "Bionics" symposia have been held in an attempt to unify and coordinate many of the facets of this new and rapidly growing discipline. Today's literature is made up of more sophisticated mathematical and logical formulations and more emphasis on specific, well-defined problems. Though much of the literature is still speculative and often redundant, the trend towards a more unified and specific approach is a healthy one.

This rapidly growing, young discipline has been given a number of names, the two most widely used being "Bionics" and "Artificial Intelligence." Bionics refers to the application of the knowledge of biology and of biological properties to the design of electronic devices and systems. Artificial

intelligence is a more inclusive term, encompassing work on intelligent devices which are not based on biological properties, as well as those which are. The latter term is used throughout this report.

B. Method

It was the purpose of this study to review relevant literature in order to determine the state of the art of this new field and to investigate the feasibility of developing automatic devices to be used in space vehicles. The work was carried out in two phases: (1) Conducting a supplementary literature search to update the surveys previously performed by the contractor, and (2) visiting installations and facilities involved in research in the field in order to examine existing physical, mathematical, and logical models of brain function.

The first step in the literature survey was to review the documents prepared by the contractor. These were: Swanson, Dorothy I. Biological and artificial intelligence. Pasadena, California: Jet Propulsion Laboratory, December 1960 (Literature Search No. [illegible]) and May 1961 (Supplement to Literature Search No. [illegible]). These two documents contained 1,976 references classified under 11 major headings. The classification structure was revised and was reorganized into the following [illegible] categories: (1) Feasibility of simulating thought processes by machine; (2) Mathematical machines, automata, and logic; (3) Neurophysiological [illegible] function research; (4) Neurophysiological models: simulated [illegible], neural nets, and organisms; (5) Pattern recognition [illegible]; (6) Theory and models of learning, general thinking, [illegible]; (7) Heuristics, problem-solving, and games; (8) [illegible]; (9) Language processing; and (10) Man-computer symbiosis. Following review of the JPL documents, relevant literature was obtained and reviewed in the 10 categories listed above.

The second phase was conducted concurrently with the first throughout most of the project. At each research facility investigators were interviewed, pertinent documents were obtained, and in many instances hardware models and experiments were observed. Among the research projects studied in this manner were: (1) Perception and spinal cord studies at the National Institute of Neurological Diseases and Blindness and at the University of Michigan; (2) Studies in chess and checker playing and mathematical theorem

proving at IBM; (3) Speech and pattern recognition devices and programs at the University of Illinois, Bell Telephone Laboratories, Air Force Cambridge Research Laboratory, Lincoln Laboratories, the University of Michigan, Stanford Research Institute, IBM and Burroughs Corporation; (4) Computer program models of human intellectual behavior at the University of California at Berkeley, RAND, the University of Michigan, and the System Development Corporation; and (5) Neuron and neuron net models at the Stanford Research Institute (Perceptrons, Neuristors), Adaptronics, Inc. (Artron), Raytheon (Cybertron), Bell Telephone Laboratories (neuron model), and the Burroughs Corporation (Albert I, a perceptron). Information was also obtained about the state of the art through such noted persons in the field as Ashby and von Foerster at the University of Illinois, McCulloch and Minsky at MIT, Steele at WADC and Yovits of ONR.

C. Scope and Limitations

This report summarizes current research and development under the general headings of neurological considerations, special purpose computer models, and general computer program models. Under each of these topics, the more relevant research for the purposes of this project is briefly reviewed and the applicability to space systems evaluated. No effort has been made to present a completely exhaustive survey of the literature in the body of the report, although the appended bibliography is believed to provide adequate sampling of the ten subject categories, when pooled with the two JPL bibliographies.

D. Organization of the Report

The programs, devices, models, and approaches which were reviewed were divided for convenience into two groups. They are described in sections III and IV, Special Purpose Computer Models and General Computer Program Models. The neurological implications of these models are discussed in some detail in Section II under the subheadings neuron simulation, mathematical and logical model building, net or system development, heuristic programming, and study of biological systems. In Section V, some tentative conclusions are presented concerning these specific devices as well as the need for redefinition of the use of automatic devices in space missions.

The bibliography, indexed to ten major subject categories, is presented in Section VII. It includes a list of 1,129 specific references which are

supplementary to the AFIL literature searches and 67 general sources such as proceedings of symposia and conferences, anthologies, and relevant bibliographies.

A glossary of terms is presented in Section VI in the hope that it will help reduce some of the confusion that has resulted from the intermingling of so many different scientific disciplines. Also included in the report is a list of investigators who are currently participating in relevant research (Appendix A).

II. NEUROLOGICAL CONSIDERATIONS

A. Overview

This section presents a summary of major trends in the field from a neurological point of view. No attempt is made to give a complete description of all the current research or conceptual developments of a neurophysiological nature. Rather, the approach is aimed at giving an overview of current events, together with their neurophysiological implications, and this is followed by a critique of these findings. However, the rationale for this approach is not aimed primarily at criticism for its own sake. It is felt that, in addition to providing an exhaustive survey, the major purpose of this document is to highlight requirements for further research and development. In this direction, therefore, a systematic and selective orientation has been adopted rather than an eclectic and purely expository one.

B. Resume of Current Work

The early work of Turing (1263) was virtually unnoticed by American investigators until the introduction of cybernetics by Wiener (1271). Wiener's work unquestionably influenced further speculation on life-like automata by Ashby (1197), Grey-Walter (1269), and others and brought Turing's machines into general consideration. From a neurological viewpoint, however, these efforts were largely general and speculative. It remained for McCulloch and Pitts (1237) and, more recently, von Neumann (1167) to suggest rather cogently the logical and digital basis of functioning in the central nervous system. The work of these latter authors serves as the cornerstone of almost all of the neurological model building that is taking place today. In fact, the "statistical neuron" of McCulloch and Pitts is the one that is typically simulated by analog techniques. This practice will be commented upon further in this section.

For purposes of convenience, current work in the field of artificial intelligence has been grouped into five subheadings. Neurophysiological aspects of each of these technical areas are discussed below.

1. Neuron Simulation

This type of effort, together with theoretical model building, appears to make up the most active area in the entire field. Neuron analogs already have been developed by the Rockefeller Institute, Bell Telephone

Laboratories (439, 1045), Stanford Research Institute (205, 206, 207, 208), Applied Physics Laboratory (1274), General Electric Company (1206), University of Illinois (1059), Aeronutronic Division of Ford Motor Company (448, 449, 642), Lockheed Electronics (637), RCA (645, 830, 1234), MIT (103, 104), and Litton Industries (1260). In addition, similar undertakings are currently underway at Melpar, Inc. (151, 152, 153), and Raytheon (1224). The basic approach in all these cases is simply that of simulating a neuron by electronic techniques and then investigating response (output) characteristics of the neuron following stimulation (input) under varying conditions. The objective of most of these efforts seems to be primarily that of demonstrating that the electrical characteristics of the neuron itself can be simulated and incorporated into an electronic model. The model, subsequently, is capable of functioning in terms of straightforward electronic characteristics. In summary, it can be said that these devices can be built merely by incorporating parameters in the model reflecting some combination of typically no more than six of the general neurophysiological principles which have been found applicable to neuron functioning. The principles that have been applied are:

a. Inhibition. A particular input connection to a neuron, while energized, can inhibit firing of the neuron by other inputs.

b. Excitation. Other input connections to a neuron, if sufficiently energized, will always fire the neuron if certain conditions are met.

c. Threshold. A neuron may be fired if the triggering energy supplied to it exceeds a certain threshold value within a time limit. There are input pulses which have insufficient amplitude to cause firing no matter how long they last. This threshold is variable, being a function of the previous history of firing of the neuron.

d. Refractory period. Immediately after firing, the neuron's threshold rises effectively to infinity for a period on the order of a few milliseconds. During this period, no input can fire the neuron again. This absolute refractory period is followed by a relative refractory period. During the latter phase, a decreasing threshold is observed, approaching the pre-firing threshold and then reaching it after a few tens of milliseconds.

e. Summation. Two or more input pulses, each of insufficient energy to excite a neuron, can be integrated by a cell so that firing does occur. To be successful, this summation must occur within a maximum time period typically on the order of a millisecond or so. Since these inputs may arrive over different pathways, provisions must be made for spatial as well as temporal summation.

f. Output. The output of a neuron is "all or none." If firing occurs, a pulse of standard amplitude and direction is produced. While there are some exceptions, the energy per output pulse may be considered constant.

It is true that there have been many successful neuron simulations based on these principles, in the sense that electrical circuits have been designed which operate either singly or in combination much as real neurons appear to do. However, what is demonstrated by these analogs, beyond the point that the electrical characteristics of neural tissue may be replicated by inanimate techniques, is not clear. An assumption that the complexities of human intellectual behavior could be duplicated by a device simply because it is made up of such elements would be at best naive. And surely, only the most meager start has been made on simulating all of the parameters which have been investigated by electrophysiological methods such as those used by Coles (1616). Consider, for example, the following treatment of principles which are well established and which most certainly must bear significantly upon the underlying capabilities of nervous system function.

a. The set of processes following neural firing are far more complex than the absolute and relative refractory periods which have been involved in current simulation. There are also negative and positive recovery periods which are accompanied by associated increases and decreases in the threshold sensitivity.

b. Spontaneous firing of living neural nets is a known condition which always occurs. The relevance of this phenomenon for simulation efforts is that input events probably never are received by dormant circuits. In the nervous system, they are typically superimposed on processes which are already active, and--if Hebb is correct--active in a directed rather than random fashion.

c. Conduction rates in nerve fibers vary as a function of diameter, myelinization, and metabolic condition. Whether this fact makes a difference is not known, but the point is that it seems to be generally ignored and will not be answered except on logical grounds. That is, it is not being investigated in simulation efforts.

d. There may be interaction effects of other nervous system cells (such as the myelin sheath and neuroglial cells) with the electrical characteristics of neurons and synapses. This possible interaction is completely ignored in simulation studies.

e. Only synaptic, or end-to-end connections are being explored. The possibility of ephaptic, or side-by-side, connections is not even admitted in simulation efforts.

f. All simulation has been limited to the characteristics of somatic nervous system tissues which have yielded clear-cut and measurable electrical effects. Since autonomic nervous tissue has never been studied with the same success little is known of its electrical properties. To show interest only in those aspects of behavior that are attributable to somatic nervous system function is inadequate, for in the brain (and even in the cord) there are many mutual centers, interconnections, and overlap of apparent functions.

g. Finally, but perhaps most importantly, despite the long standing controversy in neurophysiology concerning electrical or chemical transmission, there have been no chemical simulation studies. Transmission is tacitly designed as an electrical affair. Of course, electrical transmission is itself contingent upon chemical changes, but the transmitter agents in the nervous system have been found to be acetylcholine (ach) and the adrenergic compounds. Therefore, questions concerning the fidelity of electrical models certainly are appropriate.

Briefly, it can be pointed out that these comments indicate at least the oversimplification that is taking place in neuron simulation efforts. In itself, this does not constitute a blanket condemnation, for virtually all scientific inquiry requires some simplification if progress is to be made. It is certainly a limiting factor, however, and becomes of

paramount importance when viewed against claims that a particular device is capable of human performance merely because its active organs show some similarity to the properties of neural organs.

2. Mathematical and Logical Model Building

Perhaps the largest area of effort, especially at universities, is concerned with the development of mathematical and logical models. Work at MIT (394, 395), Lincoln Laboratories (1210, 1218), National Biomedical Research Foundation (R. S. Ledley), Stanford Research Institute (1247), and Syracuse University (65, 66, 67, 359) is directed toward this end. Such work is characterized by mathematical and logical analysis of the possible functions of neurons in processing information. These efforts do not deal with the functions or properties of neurons directly, except in terms of treating them as active organs in a computer or data handling system. As such, the major effort is to attempt to derive mathematical theories for their data processing functions. Model development of this sort is discussed elsewhere in this report and will not be elaborated in this section.

3. Net or System Development

The most extensive and comprehensive program that has been conducted in this area is the perceptron program at Cornell Aeronautical Laboratories (889, 1252, 1253). In essence, the aim or purpose has been the simulation of certain portions of the neural nervous system by analog technique. Neural components have been developed by means of electronic analogs. These circuits have been coupled together in terms of a spatial or anatomical arrangement. The anatomical basis for the circuit design of the perceptron was Hebb's (1227) speculations on the anatomical distribution of fibers occuring in the striate cortex, that is, Brodmann's areas 17, 18, and 19. Essentially, Hebb's hypothesis on the interconnections of fibers in these three areas was that, since there were so many fibers found in the areas and since the interconnections in most of them were so numerous, it could be assumed on probability grounds that any fiber was interconnected to any other fiber. The probability distribution would be determined by the number of fibers occuring in both areas. Moreover, it was asserted that the interconnections among fibers in these three areas occurred on a random, normally distributed basis. Although

the perceptron started out as a [illegible] a significant portion of the brain and its functions, it evol[illegible] a simulation of the pattern recognition capabilities of the visual [illegible] (including the cortical projection area). Work on [illegible] has continued in connection with the perceptron [illegible] and has led to the development of other programs in which neuro[illegible] of nerves are simulated in connection with the problem of pattern recognition.

As models of the central nervous system, it must be pointed out that what has been a[illegible] far must be considered to be extremely simple work on [illegible] and very limited aspects of the mammalian brain, much less the human brain. This point would not be worth making if the primary goal of the work were merely to develop physical analogs of the nervous system for the purpose of furthering scientific understanding of that system itself. For example, much useful and provocative research and theorizing was stimulated by the famous "iron wire" model of Lillie. But, in a very important sense, the objective of much of the nervous system modeling taking place today does not stop here. When even partial success is realized in a given model, the trend seems to be to search immediately for possible device applications and to make as many loose and global claims about its capacity to simulate human functions as possible. An excellent example of this tendency is illustrated by the perceptron program. What began as a very exciting demonstration that certain physical characteristics of the brain and its associated complex functions were amenable to analog simulation seems to have ended in a frenzied search for novel hardware applications of its limited capabilities. The entire program seems to have contributed not one whit to the understanding of brain functions. This, undoubtedly, has contributed to the lack of ongoing theoretical development such a program requires for its continued success.

The sterility of contribution to anatomical and neurological information is not peculiar to the perceptron efforts, however. None of the research in the field of artificial intelligence has added to knowledge of either the anatomical relationships of the human brain or its physiological processes. The highly speculative and imprecise description of the neurophysiology and functions of the visual projection system given

by Hebb in 1949 still serves as the cornerstone of the physical model builders, even though a considerable amount of direct research on the anatomy and physiology of the higher mammalian brain has occurred since then. Virtually ignored are research showing subtle interactions between higher cortical centers and low brain centers via the reticular formation, and studies such as those of Penfield in which highly specific memory stores are located in the temporal lobes. A possible exception to this criticism is the work of McCulloch and Pitts and their associates at MIT (105, 200, 201, 394, 395). But their work is aimed at developing a fundamental logic and mathematics for the nervous system, and they have always worked with hypothetical and abstract definitions of the nervous system and its neurons. For their purposes, it is not crucial that the "neuron" they define as a mathematical construct be a counterpart of reality. Rather, it must be a logical convenience within the mathematical model which may or may not suggest physical characteristics in common with actual neurons. Whether future research will disclose that their neuron was in fact a better guess about the true physical state of affairs than current observation had revealed to that time will be of interest and importance, but it is not necessary for validity in their efforts. On the other hand, even complete success on their part does not imply that the structure and function of the nervous system is indeed described by their mathematical model. Only further substantive research would permit that conclusion.

4. Heuristic Programming

This effort, strictly speaking, does not lead to the development of a model of the nervous system, since it is based on behavioral processes rather than neurological events. However, it is an effort which deserves special attention. It represents an allied, rather than an intrinsically related area of research. The techniques employed here stem largely from the work of Newell, Simon and Shaw (739, 740, 741) at RAND Corporation several years ago and subsequent work by Simon, Shaw and their students at Carnegie Tech. In this method, Newell, Simon and Shaw originally studied the behavioral processes and introspections of human subjects in problem-solving experiments and then attempted to write a computer program which would simulate these functions. The resulting computer program then was submitted to experimental tests in solving

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the problems. The results were a striking success in that the machine programs were able to solve new problems similarly to the human subjects from whose behavior the programs themselves had been developed. This technique has resulted only recently in the successful emulation of a bank executive's behavior in an investigation by Clarkson at Carnegie Tech. (181). Clarkson studied the decision-making behavior of the bank executive over a period of six months. Subsequently he was able to write a successful program in which the bank executive's decision-making behavior was simulated very closely in comparative runs on novel problem-solving situations. A similar approach is being taken by several investigators at the System Development Corporation (656, 950, 1035). In their studies, problem solving, language behavior and similar processes are being simulated by the development of programs which are eventually run on digital computers. It should be stated, again, that these techniques do not simulate neural events, nor are they derived from either known or speculated neural events. However, the results that have been obtained by these workers have been quite fruitful and the general approach seems worthy of considerable further support.

5. Study of Biological Systems

A number of investigations are aimed at the study of specialized biological systems in certain organisms in order to apply any knowledge of the systems to problems of computer or hardware system design. The studies of Lettvin and others at MIT (1153) in which the frog's eye has been analyzed in terms of motion sensors or detectors serve to illustrate this general type of study. At the University of Arizona, the antennae of moths are being studied as a model for potential electromagnetic antenna design. Communication behavior in fish is being analyzed at the American Museum of Natural History. At the University of Wisconsin, the orientation of aquatic animals, especially by olfactory processes, is under investigation. A more general study at the University of Minnesota concerns electrical characteristics of living tissues and related excitatory processes. The physiology and chemistry of biological clocks, as well as a more general attempt to study rhythmic internal devices of living organisms, is under investigation at Princeton University and the University of Arizona (908). Closely related work on rhythmic variations in metabolic rate are under study at Northwestern University.

The Commonwealth Research Institute is conducting studies of the intellectual capacities and capabilities of porpoises. Finally, the migratory behavior of pigeons is under investigation at Duke University. The explicit purpose of all of these studies is to derive more information about the biological systems under investigation. However, it is the implicit hope that in most of these studies new insights and information will be gathered which will lead to or perhaps suggest any devices, techniques, or approaches which can be lent to advance state-of-the-art in the electronic hardware area.

C. Critique of Present Efforts

The preceding review of current studies in the field discloses a number of limitations which must be overcome before a full and comprehensive program of effort will be realized. The following comments are raised in the hope of clarifying some of the major issues which must be considered in developing such a program.

In the area of neuron simulation it is significant to note that the Hodgkins-Huxley model of the neuron is the one which is used exclusively by neuron modelers. In this regard, it should be pointed out that the best description of the neuron and its physiological processes has been given by Eccles (1216). This work summarizes the results of his electrochemical investigations of somatic nerve cells of the central nervous system. There is no more comprehensive or detailed description of the electrochemistry of nerve cells available. Eccles' work seems to have been ignored by researchers in this field. His contributions to the neurophysiology of the nerve cell seem to be lacking in any existing simulated neurons. An approach to neuron simulation based on the findings of Eccles' work certainly should serve as the basis for major investigations.

Closely related to this observation is the fact that there are no chemical analogs under development. All efforts in the field are directed toward electronic simulation of the neuron in terms of its known electrical characteristics. Actually, in the neuron, the electrical effects are concomitants of the underlying chemical processes. For example, synaptic transmission is known to be produced by a transmitter agent, acetylcoline, though there is no doubt that the event is accompanied by a negative electrical discharge. While it may be argued that these phenomena are electrochemical in nature

and that it is not fruitful to separate them, it certainly seems reasonable to propose that an attempt to develop a biochemical analog be initiated and that the functions of such an analog be studied similarly to the fashion in which electronic analogs are being investigated.

Another characteristic of present efforts seems to be that they are aimed either at a single neuron with a necessarily simple set of parameters or they are aimed at a fairly complex level in which a fairly large segment of the brain is simulated (viz., perceptron). There seems to be no work currently underway in which a known system of the brain (for example, the reticular system) is being simulated in terms of its known anatomical connections and properties. Certainly some work in this direction would seem both warranted and worthy. At the present state of neurophysiological knowledge there seems to be an unwarranted amount of theory and model building concerning the function of neural nets. While such work is certainly potentially useful, it is entirely speculative in terms of known functions of the neurons which make up these nets. In fact, the theories themselves are based on McCulloch's interpretation of a hypothetical neuron which he himself admits, is quite far removed from reality. More direct study of the neurons, themselves, is required so that their known functions are well established. Then it can be determined whether a given mathematical or logical approach to these functions is warranted.

Finally, coupled with a trend toward less theorizing, there is need for more direct research on the brain itself. An area that is virtually ignored by researchers in this field is direct study of the brain to observe its functions under various situations. Ablation, electrical stimulation, and electrical recording studies can give direct data on the function of brain nuclei as well as brain systems under various conditions of stimulation. Although there is a considerable amount of brain research going on at the present time, very little of it is motivated from the point of view of workers in artificial intelligence. This limitation should be overcome by more studies of brain function springing from the theoretical efforts of the model builders. Studies with higher animals will provide direct measurement of brain functions. This seems a much more satisfactory approach than simulation of hypothetical brain functions by computer program.

D. Conclusions

A few comments seem merited in conclusion. In the first place, the GPS approach initiated by Newell, Simon and Shaw seems to merit special attention and study in the future. Although this approach does not simulate neurological functions, nor does it reveal any insights about neurological events, it does seem to be a highly promising one in terms of simulating human behavior in decision-making and problem-solving situations. While its relationship to this field is peripheral rather than central, its success argues strongly that it should be pursued, particularly in connection with developing devices for space exploration. Secondly, it cannot be suggested too strongly that more direct research should be undertaken on the brain itself, and the functions of its central neuronal systems. Such studies could be motivated by hypotheses derived from work in the field of artificial intelligence, thus leading to direct tests, rather than indirect tests by means of simulation either on a digital computer or by analog device. Finally, the development of biochemical analogs certainly should be undertaken since the basic functions of the nervous system are chemical in nature. This does not mean that electronic simulation will be found lacking. However, a necessary support of such research certainly would depend upon the ability to demonstrate common electrical effects when the basic analog is chemical rather than electronic. In this regard, the work of Eccles should be especially useful in serving as the operational description of the neuron and its functional parameters.

III. SPECIAL PURPOSE COMPUTER MODELS

A. Overview

During recent years, many special purpose computers have been designed and built which simulate various aspects of intelligent behavior. These special purpose computers may be [illegible] by the fact that typically each one is designed to perform a particular type of task, such as recognizing patterns, or simulating problem-solving behavior. Such devices may be classified into three categories: neural nets, pattern recognizers, and problem solvers. The perceptron [illegible] is an example of the first; the line-drawing recognizer of Marmor [illegible] is an example of the second; and the tortoises of Grey-Walter [illegible] are examples of the third.

Neural nets use randomly interconnected elements ("neurons") together with some provision for reinforcing certain connections and inhibiting others. In general, neural nets are connected to a set of input elements, and the outputs are connected to response units which are responsible for issuing reinforcement or inhibition. The elements are usually based on the McCulloch-Pitts neuron model which is too simple, since it represents the minimum structure to enable the neural nets to be adequate Turing Machines. A major shortcoming of these devices is that they require large numbers of elements in order to "learn" very little. However, the most criticized and perhaps the most controversial issue is the assumption of random interconnections between elements of the net. It should be observed that the problem of simulation cannot be solved merely by providing a connection from each "neuron" to every other "neuron." In so doing, the problem changes from "how shall the neurons be interconnected?" to "how shall the [illegible] of these neurons be set?" It has been suggested that the human brain is neural precisely because of its non-randomness. Because of this, it has been argued that neural net models based on random interconnections cannot be adequate models of the human brain.

The function of pattern recognizers is to select, from a finite set of alternatives, the closest match to some unknown input. The usual context is a written, printed, or spoken alphabet. The most successful method in pattern recognition has been to choose a set of variables, or characteristics (for example, the number of straight lines in hand-lettered characters) and to form a vector whose components are the different values of the characteristics for both the input and the various output categories. Although no

single characteristic may be adequate (i.e., the characters 3, 6, 8, and 9 have no straight lines), the totality of tests should provide adequate discrimination between characters. Speech recognizers work in a similar fashion.

Most of the work on problem solvers has been done on programmed computers. Examples of this type are the Logic Theorist of Newell, Simon and Shaw, Gelernter's studies on geometry theorem proving, and the various chess and checker playing programs. These will be considered in Section IV. This section, on the other hand, is limited to a discussion of self-organizing devices which are special purpose mechanisms designed to solve particular problems. A battery-driven machine, which seeks out electric wall sockets to recharge itself, is solving a most serious problem--namely that of keeping "alive." The problem-solvers all have the same common trait of showing goal-directed behavior. Unfortunately, no non-trivial problems have been solved by physical problem-solving devices. These devices have all been of the form of "survival" devices; they simply try to go on "living."

The various devices to be discussed in this section have been grouped into two categories. The first includes special purpose mechanisms of a global nature which are considered complete models capable of solving problems or of "learning." Some of these are perceptrons and pattern recognizers. The second class consists of devices which are closer to the component level of complexity. These devices, such as "Artron," do not have as broad objectives as the more global models and are well suited for use as building blocks for larger, more complicated systems. Also included in the "component" class are multi-aperture cores, neuristors, and general memory devices which enhance the memory capability of the more complete global models.

B. Global Models

1. Perceptrons

When Rosenblatt (1959) first proposed perceptrons, he was concerned with the problem of memory storage in biological systems. The perceptron was intended to be used as a study device to investigate brain function and organization. In Rosenblatt's own words, "The essence of a theoretical model is that it is a system with known properties, readily amenable to analysis, which is hypothesized to embody the essential features of a system with unknown or ambiguous properties . . . ." Put another way, it is argued that a theoretical model is valuable since it

is possible to control its environment and its complexity.

The three main units of a perceptron (sensing, association, and response units) are joined serially as shown in Figure 1. The sensing units (S-units) are transducers that respond to exterior stimuli by emitting signals which are [illegible] of the stimulus strength. The function of the [illegible] of S-units is that of a retina. The S-units are multiply-connected to the association units (A-units), i.e., a single S-unit is connected to many A-units. An A-unit is a signal generating unit with input and output connections. It may emit a signal or not, depending on whether or not its threshold has been exceeded. The A-units receive inputs from S-units and have their outputs multiply-connected to response units (R-units). The R-units emit signals which are transmitted to the environment.

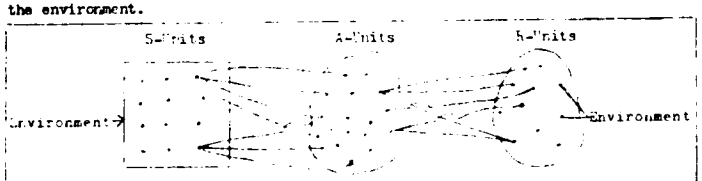

Figure 1. Simplified Perceptron

The output of a given S-unit (or A-unit) may be excitatory or inhibitory; i.e., the probability of firing of a unit to which the S- or A-unit is connected is increased if the output is excitatory and decreased if inhibitory. This is a well-known property of real neurons.

Coupling refers to the way in which various parts of a perceptron are joined together. A series-coupled perceptron is one in which the connections run directly from functional layer to functional layer (a functional layer might be a layer of A-units or S-units). In a cross-coupled perceptron, some of the connections join elements of the same type (e.g., A-units connected to A-units in the same layer). Finally, in a back-coupled perceptron some units in one functional layer are connected to some units in an earlier functional layer, e.g., A-units are connected to S-units or R-units or A-units. The purpose of both

cross-coupling and back-coupling is to provide greater characteristic filtering properties. Back-coupling accomplishes this by means of feedback.

A three-unit series coupled perceptron has a layer of S-units, a layer of A-units and a layer of R-units. However, a four-layer perceptron has two layers of A-units, usually designated by A^{I} and A^{II}. The information flow is then represented by $S \longrightarrow A^{I} \longrightarrow A^{II} \longrightarrow R$. A four-layer perceptron may, of course, incorporate cross- or back-coupling.

A perceptron "learns" by a reinforcement process. If it responds correctly, the number of impulses that each active connection may carry is increased. This will tend to increase the excitation level of the terminal unit. Thus the perceptron is said to have a form of memory. The S-, A-, and R-units are similar to the McCulloch-Pitts neuron. For example, they exhibit threshold stimulability, attenuationless propagation, and excitatory and inhibitory impulses.

The main arguments in favor of perceptrons are:

a. As hardware models, they have probably progressed further than any other devices.

b. Perceptrons have learned simple tasks such as alphabet recognition.

c. By using preprocessing techniques, perceptrons can be made more powerful. This will reduce the volume and complexity of impinging information.

d. The main function of perceptrons is not that of learning but rather the study of brain functions; how organisms gain knowledge of their physical environment, and how this information is stored, represented, and recalled. Therefore, objections to perceptrons on the basis that they have not made much progress in "learning" are not valid, since the function of this device is <u>not</u> learning.

Objections to perceptrons center about the underlying philosophy of random connections and also the triviality of the problems solved to date. Specific objections are:

a. So far as is yet known, the brain is a powerful organ because its neurons are <u>not</u> randomly connected. By connecting the various

units of the perceptron at random, much of the organization which comes prepackaged in the human brain is lost. Apropos of random interconnections, Keller (1230) questions whether an automaton constructed mainly by random processes can yield the desired discrimination function in discrimination problems, a function Keller has shown to be unique.

b. The number of connections in a preceptron is on the order of 10^6 whereas the human brain has a total number of connections on the order of 10^{12}. This limits the capacity of a perceptron to learn as great a variety of responses.

c. Perceptions have been used to solve only rather simple problems which usually can be better approached by a special purpose device. For example, in the recognition of alphabetic letters, perceptron's success is highly dependent on size and position of the letter on the "retina."

d. The amount of information available to a perceptron is much larger than the amount of information it can use. There is a pressing need for a method of preprocessing information to eliminate noise and unnecessary redundancy.

e. The perceptrons are uneconomical in the sense that they discard connections which are meaningless to the problem, i.e., the probability of firing is low in such cases. The resulting net is a sparse one using few connections and thus no more complex than a special purpose device designed for the job.

Much effort has been devoted to developing adequate mathematics and statistics for the study of perceptrons. From the beginning, the progress was hindered by a lack of mathematical theory. It is unlikely that perceptrons will be of use in space probes, as they are too large and too heavy. In addition, they simply have not yet been shown capable of performing the complex and subtle nuances of human intellectual functions that are required (e.g., fine discrimination and decision making).

2. Speech Recognizers

The major goal in the area of automatic speech recognition is the development of an automatic speech recognizer which will produce an accurate transcription of the speech presented to it. Practical reasons

for developing such devices are the time and money which would be saved in transcribing speech to writing, the alleviation of the man-machine communications problem by using an automatic speech recognizer as a liaison agent, and the economy of eliminating useless information. Marill (1238) discusses three fundamental concepts pertaining to this problem:

a. Acoustical. Sound may be most easily analyzed in terms of the time, frequency, and amplitude of the pressure wave form of the sound. This is usually accomplished by breaking down the wave form into the above three components by means of band-pass filters which smooth the output of each channel.

b. Physiological. Speech also may be analyzed by the way in which it is actually formed. Speech sounds are produced by exciting in one of several ways what is essentially a system of cavities. By determining a number of parameters, it is possible to state the key characteristics about the vocal tract during the generation of a sound.

c. Linguistic. Speech also can be analyzed from phonemic considerations. Each distinct phoneme has characteristics which are different from other phonemes. The vector whose components are the presence or absence of given characteristics uniquely determines a given phoneme.

Most automatic speech recognizers have utilized aspects of all of the above concepts. They generally suffer from two major defects. First, they must be individually adjusted to each speaker. This can be time consuming if many different speakers are to use the device. Secondly, they have very limited vocabularies. This latter problem may be overcome by increasing the size of memories. However, a fundamental revision of thinking along those lines may be required to correct these shortcomings.

Marill cites four areas of difficulty in the various theoretical aspects of speech recognition. First, there is the problem of segmentation. Speech is a continuous phenomenon; that is, there are no spaces to indicate when one segment finishes and the next begins. Secondly, suitable measurements must be defined to distinguish between members of a set of sounds. Present efforts generally are directed toward selecting

measurements on the wave forms. Third, there is a need for adequate statistical decision procedures. There can be little question that the determinations must be made statistically since there is great variation in speech from individual to individual. These variations depend on many factors, such as locality, sex, and health. This leads to the problem of combining the various measurements needed to classify a sound. The fourth problem area concerns large scale real-time data processing. With enormous amounts of information available, the automatic speech recognizer must sort it out, and make its decisions in a finite length of time. If it cannot make its decisions rapidly, it is of little value either as an automatic secretary or as a warning device.

Automatic speech recognizers (or automatic sound recognizers) could be used as warning devices in space explorations to planets where an atmosphere exists in which sound may be conducted. Inclusion of a fairly sensitive device of this type could circumvent to some degree the disadvantages of having to depend solely on optical warning systems to avoid natural catastrophes.

3. Printed Material Recognizers

Another area of considerable interest is the recognition of printed matter. While much of the work has been directed toward the development of machines, a great deal of the development has been done by simulating machines on a computer. However, [illegible] or simulation suffers from the defect of [illegible] while most of the pattern recognition [illegible] in parallel.

All printed material recognizers contain a sensory unit and a response unit. The sensory unit or retina consists of photocells or other devices which pick up and transmit data to the response unit. This unit processes the data it receives from the retina and prints out its decision about the character it is currently sensing. Perceptrons, for example, operate somewhat in this fashion; they, of course, have an additional section (a-units) interposed between the sensory unit and the response unit.

In general, the problem of pattern recognition is treated as one of testing multiple hypotheses in statistical inference. Chow (1209), as well as Hawkins (1226), gives a formula for the magnitude of expected

risk in making a given decision. Minimum risk networks can be constructed by using this formula.

Bledsoe and Browning (1302) have simulated a network which approximates Chow's calculations. They have had very good success with typewritten numerals, and fairly good results with hand-block print when the letters are rotated and not exactly positioned on the input raster. The model has exhibited some learning capability of four alphabets.

Roberts (1250) studied hand-printed character recognition by means of a perceptron-like network. He obtained results comparable to those obtained by Bledsoe and Browning.

Doyle (1214) tested various samples of hand printing using such measurements as number of horizontal line intersections and convexity to the right, left, up or down. He used a limited alphabet consisting of 10 characters. The results were slightly poorer (by about 7%) than those obtained in a test of humans reading the same letters in a context-free field.

Harmon (340, 439) has constructed a machine which recognizes elementary geometric shapes independent of their orientation and size. It is one of the first devices to use a circular scanning method. Harmon has also studied handwriting recognition and has built a small device that recognizes the script representation of the digits. This digit recognizer is based on letter-by-letter analysis of writing. In a subsequent study, Frishkopf (340) has outlined a method of recognition by using whole words as a meaningful unit. Unfortunately, this requires a large dictionary or vocabulary with which to compare object-words.

Some work has been done on machine interpretation of radar displays (195, 518). The pattern recognition problem is similar to that confronting the frog in his search for food. The radar operator must pick out his "insect" from background noise. Cote (195) suggests a Pandemonium-like net to process data. He claims the system is able to distinguish target from noise. The network is essentially a property filter that picks out the systematically moving blip from the noise, which is relatively constant.

There are many unresolved problems in this area, but much work is being done. Given certain constraints on the object-space, many printed material recognizers can do a commendable job. However, if an unrestricted alphabet is used (e.g., all forms of fonts, human printing, and script), there are severe problems. Since no character is ever formed in quite the same way by humans, a set of templates which might be quite satisfactory for printing would fail in scanning handwriting. A solution remains to be found for this problem. Little work has been done toward recognition of phenomena that would be of interest to a space probe, such as recognition of geological patterns, rock types, or patterns formed by living organisms.

4. Learning Machines

A learning machine is one whose response to current input is a function of its previous experience. The value of having a machine which exhibits learning properties is obvious, for it is this ability to "profit" from experience which makes man vastly superior to other organisms and any devices yet developed.

At present, the best efforts have produced machines with only rudimentary learning ability. The most advanced machines show some capability in rather simple situations, but with increasing complexity, they cannot handle the problem. The main interest in these machines, however, is not in their present capabilities, but rather as future supplements to man's intellect. Gilstrap and Lee (388) speculate that future applications may include exploring devices for navigating over the surface of planets without human control, high speed war gaming machines that can formulate their own strategy, medical diagnosis machines that learn which variables are the significant ones, and many more.

An early learning machine was the maze learner of J. R. Pierce (806). Internal noise generators introduced a random element in the operation of the machine. Pain (or pleasure) signals were used as reinforcement when the machine did not (or did) solve the maze correctly. If the machine received a pain signal, it would try a new solution; if it received a pleasure signal, the probability of correct response would be increased.

Another maze solver, reported by Shannon (932), operated on a trial-and-error basis until it reached its goal. Then its relays would "fix" the path that took it to the goal. Subsequently, it would make no further mistakes.

The homeostat of Ashby (1197) was an early device which adapted to changes in its environment. While it was concerned primarily with adaptation processes, it did display some ability to learn. The major import of the homeostat was that it focused attention on problems of stability and homeostasis.

Grey-Walter (1063, 1064, 1269) constructed his well-known "turtles" which were programmed to recharge their batteries. The later model had a circuit which was capable of developing conditioned reflexes. It was the first model to exhibit conditioned reflex learning.

In 1954, R. J. Lee (577) designed a theoretical model which used adaptive elements called Serons -- now called Artrons. The model reacted to trial and error feedback in seeking its goals. Gilstrap and Lee state (388), "Thus, incoming experience information could be utilized to cope with previous unexpected environmental developments." (The Artron is described in detail later in this section.)

The Cybertron of Litt (1234) is one of the most recent developments in the learning machine field. It consists of four components: a memory, a multiplier circuit, an integrator circuit, and a threshold circuit. The machine compares only the differences between two signals. After learning, it will ignore parts of a signal which are the same for all signals. Reinforcement takes place only when the machine makes an error. The Cybertron has been able to distinguish between sonar signals from submarines and sonar signals from whales.

C. Component Models

1. Artron

The Artron, as described by its designer, Lee (192), is a neuron analogue. It is a two-input, one-output, sixteen-state logical device with a delay capability (see Figure 2). All of the 16 logical states and the delay values are initially set at random. Then, as a result of

learning, a definite combination of logical output state and delay is developed. The conditioning process rewards or punishes the Artron according to the trial-and-error feedback. The Artron, it should be emphasized, does not learn perfectly. After the conditioning process, there still will be error. The frequency of errors decreases as the number of trials becomes large.

Input	Output	The possible values "c" may assume are:	
a, b	c	$a \equiv c$	$\bar{a} \cdot \bar{b} \equiv c$
("+" = OR, "·" = AND, "$\bar{a}$" = complement of a)		$b \equiv c$	$\bar{a} \cdot \bar{b} + a \cdot b \equiv c$
		$a \cdot b \equiv c$	$\bar{b} \equiv c$
		$\bar{a} \cdot b \equiv c$	$a + \bar{b} \equiv c$
		$a \cdot \bar{b} \equiv c$	$\bar{a} \equiv c$
		$a + b \equiv c$	$\bar{a} + b \equiv c$
		$\bar{c}$	$\bar{a} + \bar{b} \equiv c$
	$a \cdot \bar{b} + b \cdot \bar{a} \equiv c$		

Figure [illegible]. The Sixteen Logical States of Artron

Early development of the Artron (then known as Heron) is described in two copyright publications by Lee: Internal Circuitry of a Heron, (578), and A Generalized Learning Machine (577). Recent developments on Artrons are available as Interim Reports from Melpar, Falls Church, Virginia (151, 1[illegible], 1[illegible]4).

2. Multi-Aperture Cores

There has been a great deal of interest in neuron simulation using multi-aperture cores (1205). These cores exhibit the following four properties which are important in simulation studies:

a. Multi-level storage -- the outputs are weighted depending on the history of the neuromime.

b. Gating -- permits the neuromime to emit or not emit a signal.

c. Controlling threshold level -- the signal is transmitted or not, depending on whether or not it exceeds a given value Θ. Brain (1205) notes that a given threshold may control several circuits at one time.

d. Summation -- the input may consist of several signals which are summed to form an input.

Multi-aperture cores have the attractive advantages that analog storage can be accomplished by reversing the magnetic properties of only a fraction of the core material, and that readout can be performed without destroying the memory contents (1200, 1212). At Stanford Research Institute simulation of neural elements has been attempted by Crane and his associates (1212) using multi-aperture cores. The same group has shown the feasibility of constructing a bi-stable logic element from multi-aperture cores.

3. The Neuristor

Crane (208) conceived of the neuristor in attempting to answer the question, "Is it possible to build an electronic system . . . in which good conductors, or 'wires,' are not available for the signalling variables?" The name "neuristor" refers to a class of devices which satisfy the four following properties:

a. Threshold stimulability. There is no response until a threshold value, Θ, is attained.

b. Attenuationless propagation

c. Uniform velocity of propagation

d. Refractive period following the passage of a signal past any point of a channel. During this time, the point cannot be restimulated.

Crane notes that a neuron is an example of a neuristor in a liquid environment. A consequence of the refractory period is that two impulses traveling in opposite directions on the same line will destroy each other when they meet. This [illegible] limits the maximum frequency at which pulses may appear.

Neuristors may be connected in two ways. Crane refers to one way as T-junctions. If a signal reaches a T-junction from one line, it will be propagated on all other lines meeting at the T-junction. An S-junction has the property that a signal passing on one member of the junction causes all other lines at the junction to become refractive. This mutually refractive property implies that if pulses are approaching an S-junction on two different lines, they will annihilate each other at the junction.

Neuristors can be used easily as memory elements. The memory is based on the principle that, given a close-looped neuristor whose length is greater than the refractory length, a pulse, once started, will continue to circulate in the neuristor. A T-junction is made with the ring, and every time the pulse passes, it sends a pulse along the take-off wire (Figure 3). A "one" is represented by a train of pulses, a "zero" by no pulse. Crane also shows how neuristors may be used as gates (i.e., logical decision elements).

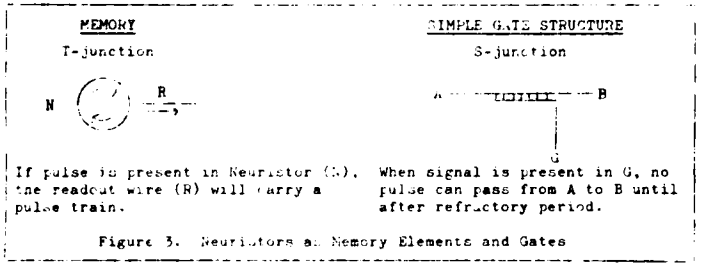

Figure 3. Neuristors as Memory Elements and Gates

4. General Memory Devices

Perhaps the most important area of advanced computer development is storage techniques. In any device claiming to possess artificial intelligence, there is some memory apparatus. This section deals with several techniques which may be applied to these devices. Much of the material presented here [illegible] found in an excellent article, "Computer Memories, a Survey of the State-of-the-art," by Jan A. Rajchman in the January 1961 issue of the Proceedings of the IRE (1,49).

A random-access memory is one in which any register containing information may be addressed. That is, one is not required to use memory cells in a particular preset order, but may choose one at will. This feature was one of the major breakthroughs in increasing the flexibility of modern computers. Each memory cell has its own address which usually consists of a 16-bit binary number. The contents of the addressed cell are also binary numbers of a given length. The length varies with the make of the computer used; the number of bits may range from 24 to 48. Each bit is represented on a physical device which can assume two possible states.

Early computers used electronic tubes, cathode ray tubes, and the like. The binary digits could be represented as 1 = ON, 0 = OFF. Currently, small magnetic cores are used in many computers. If their magnetic flux is in one direction, a "1" is said to be stored; if in the other direction, a "0" is stored.

As the demands of computer users increase in number, time, and complexity, computer manufacturers are being forced to increase memory size. When computers become physically large, the time of transmission of signals within the computer cannot be ignored. Precautions must be taken to insure that all memory transfers are completed before the next instruction is executed. One way of doing this is to reduce the size of the components. This means building a memory which is physically small, has a rapid read-write time, and is inexpensive. This last consideration, cost, may be the biggest obstacle to the development of new computers. If, when memory size goes up by a factor of 10, cost goes up correspondingly, larger computers may not be economically feasible.

Rajchman classifies memories into four types: magnetic memories, ferroelectric memories, cryoelectric memories, and tunnel diode memories.

a. Magnetic Memories

Magnetic memories are arrays of individual magnetic cores. Each core is a small ring of magnetic material which represents one bit of a word. The core may be magnetized in a clockwise or counterclockwise direction. This is accomplished by directing a current along a wire which passes through the center opening of the core. The induced magnetic field then causes the core to be magnetized in the appropriate direction. Readout, i.e., sensing the state of the core, is done in an analogous fashion. Unfortunately, when readout is attempted, it changes the magnetic state of the cores read from, so the original contents must be rewritten on the affected cores. The most widely used cores are made of manganese magnesium ferrite. They are relatively immune to demagnetization from nearby currents.

An important technique used with cores is magnetic switching. A matrix of cores is linked by row and column windings. A third type of line is a DC bias line which keeps the cores in a given state.

By passing current through a row and a column line at the same time, the core at their intersection is switched. When the current ceases, the DC bias line causes the core to return to its original state. This technique is important for a number of reasons:

(1) It reduces power requirements.

(2) It reduces the number of transistors and diodes that must be used.

(3) Address decoding is simplified.

(4) Impedance matching is simplified.

(5) It can be used to direct power from several sources to a single load.

Word-organized core memories consist of a matrix of cores with row and column windings. Each row corresponds to a word and each column to a bit. Thus the number of columns is the number of bits per word, and the number of rows is the memory capacity given in words. This memory can be any of several types: one-core-per-bit, two-cores-per-bit, transfluxors, or multi-aperture cores. The one-core-per-bit and two-cores-per-bit type memories are memories in which the read-write functions are accomplished by using either one or two cores for each memory bit. Multi-aperture cores have already been discussed (page 26). Transfluxors are closely related to multi-aperture cores since they transfer magnetic flux by geometric means between branches of cores. They also are used as switching and storing devices.

The main advantage of transfluxors and multi-aperture cores is the ability to read from them without altering their current state. This property is known as non-destructive readout and permits readout without the necessity of rewriting the contents of the memory cell read from. It is also possible to read information to several points at one time by using additional readout apertures. The major difficulty is the relatively slow writing time. Rajchman notes that, in general, the nondestructive memory is more complicated because separate addressing circuits for write-in and readout are necessary; for this reason the simpler destructive readout memories are used more commonly.

In extremely large computers, the cost of fabricating and wiring a large number of individual cores can be considerably reduced by the use of ferrite apertured plate memories. A plate with a number of evenly spaced holes is molded from magnetizable material. At each hole one bit of information can be stored. This information is found in the direction of magnetization about each hole. It is also possible to print the wirings on the plate itself, thus eliminating the necessity for wiring the cores individually.

The Twistor is a method of using magnetic wire as a memory element. It consists of a piece of magnetic wire wound in a helix around an insulated non-magnetic wire. In addition, a solenoid is around both wires. Current passing through the solenoid and the nonmagnetic wire induces a magnetizing force in the helical wire. (See Figure 4.)

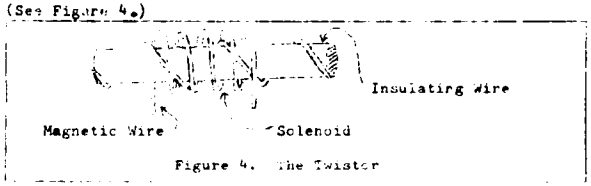

Figure 4. The Twistor

Readout is performed by sending a sufficiently strong current through the desired memory location. The Twistor's magnetic state is changed. This induces a current in the appropriate central wire. Write-in is obtained by passing current through both the solenoid and the central wire.

There are some circumstances in which information of fairly permanent nature must be referred to frequently. In these cases a read-only memory may be used. This is a random access memory which has no write-in capability. It necessitates having memory elements with non-destructive readout. These memories are useful for storing standard subroutines and tables of standard arithmetic functions.

Thin film memories have aroused much interest in the industry because of their light weight, small size high switching speeds, and ease of production (813). Basically, a thin film memory is obtained

by depositing a magnetic alloy on a smooth base. This may be accomplished by means of electroplating or by evaporation of a vacuum. One difficulty involved with these memories is in making the deposit uniform for all memory locations.

b. Ferroelectric Memories

This memory technique is still in the experimental stage. The principle behind the technique is based on the fact that when a ferroelectric condenser is driven from one state to the other, a large current flows momentarily. Proposed systems use a matrix of these condensers where each condenser is connected to a row conductor and a column conductor. When current is supplied to a particular pair of wires, the condenser connected to both of them is reversed. Some of the problems which have impeded the use of ferroelectric memories at the present time are:

(1) Sensing is awkward because it is a two-terminal device.
(2) Making electrodes for close stable contacts is difficult.
(3) The energy requirements are quite high.
(4) Ferroelectric condensers are not as fast as magnetic materials.

c. Cryoelectric Memories

The phenomenon of superconductivity is well known. At low temperatures (near absolute zero) conductors have very low resistance; so, if a current is started, it will continue for a long time. Gating is based on the action of a magnetic field on materials in transition from the superconductive to the normal state. Memory cells make use of the property of persistent currents in superconductors. Since persistent current is a natural form of storage, there is much hope for the cryotron. Other advantages of cryoelectric memories are:

(1) Precise switching thresholds
(2) No undesired signals
(3) Fast switching times
(4) Low energy per bit requirements
(5) Small size
(6) Ease of manufacture

Disadvantages are:

(1) Low temperature requirement is difficult to attain at present.
(2) Coolant (liquid helium) is not always readily available.

Rajchman also mentions a device called the cryosar, a high-speed semiconductor cryoelectric element. There are two types of cryosar. One, a monostable diode, is usable as a fixed memory device; the other, which has two stable states, can be used in memory arrays.

d. Tunnel Diode Memories

The desire to shorten memory access time to 10 nanoseconds (1 nanosecond = 10^{-9} seconds) has led to the consideration of tunnel diodes as memory elements. By placing a tunnel diode in series with a resistance, a bi-stable device can be obtained. Switching times of the order of 1 nanosecond have been reported in use currently available in 2 to 3 nanosecond units. To read out, one pushes the selected element to the high state and notes whether switching occurs. Write-in is performed by appropriate voltage on the line to the diode. Advantages of the tunnel diodes are their small size and high speed. Their major disadvantages are high power consumption, more complicated structure than magnetic devices, and the requirement for DC holding power.

IV. GENERAL COMPUTER PROGRAM MODELS

A. Introduction

Computers, by virtue of their great speed and accuracy, have enabled men to explore numerous areas of research which would be inaccessible without them. They have been used in many disciplines both for reduction of experimental data and for simulation research. In simulating human thought processes, a number of studies on checkers and chess playing programs have been made; other games such as "tic-tac-toe," "nim," and "go" have been studied; theorem provers have been programmed; pattern recognition has been attempted with computers; learning programs have been written; and programs to simulate human decision processes have been investigated. This section gives a brief overview of these studies. For convenience, the studies have been grouped under the following headings:

1. Game playing programs
2. Theorem proving programs
3. Pattern recognition programs
4. Concept formation programs
5. General Problem Solver (GPS), Elementary Perceiver and Memorizer (EPAM), and the Binary Choice Program
6. Pandemonium
7. List processing languages
8. Neural net simulation

B. Game Playing Programs

The principal efforts in these programs have been directed toward finding heuristics, efficient measures of good moves, and rapid learning methods. All the game playing programs are characterized by attempts to reduce complex situations to a number of simple ones. The differences in the programs are the result of the ways in which the problem is attacked.

In 1950, Shannon (1157) noted that since there is a finite game with complete information, there is a "best" strategy available. However, because of the large number of possible strategies, it [illegible] computer to determine the best one. He suggested that an evaluation of the moves be made by the following analysis and the best move selected on this basis.

1. Explore the continuations for a given number of moves ahead.

2. Evaluate the positions reached at the end of each of these continuations in terms of playing strength.
3. Choose the move with the highest score, using a minimax procedure.

A minimax procedure is one in which each player makes the best possible move available. Thus, looking at the game from player A's views player A chooses the alternative which has the maximum score for himself; then player B chooses the alternative with the minimum score for player A; and so on.

Shannon's evaluation metric used a weighted sum of values of the mobility of the pieces, attack possibilities, and other important features.

In 1956, Kister, et al. (1231) programmed a computer to play chess on a 6 x 6 instead of an 8 x 8 board. By removing both bishops and making other concessions, the alternatives that had to be considered were considerably reduced. The program operated in the manner that Shannon suggested. It was able to beat beginners, but could not compete with an experienced chess player. The main import of this program was that it showed that Shannon's ideas could be translated to a digital computer.

Another chess program which followed Shannon's suggestions was one programmed by Bernstein and Roberts (1201) for the IBM 704. It had a selection function which enabled it to consider only a portion of all possible moves, and not all of them. To do this it employed a series of subroutines to generate moves that appeared to hold some promise. In evaluating a move it considered four factors: King defense, material balance, area control and mobility. The program chose its moves using minimax procedures. The key difference between this program and the Kister program was the manner in which the moves were made. The Kister program examined all possible moves, while the Bernstein-Roberts program selected seven plausible moves. This feature of the Bernstein-Roberts program decreased the running time of the program to one-third.

The Newell-Shaw- iron program (1242, 1243) utilized essentially the same criteria for [illegible] exception of the numerical evaluation function. In the evaluation scheme a vector of component values was formed with the high priority moves in the first positions and the low

iority moves in the last positions. Two vectors were compared position by position. If one vector's highest priority value was greater than that of the other vector, the move corresponding to the high value was chosen. Thus, the vector space was completely ordered. Unfortunately, the program was quite slow--it took from one to ten hours per move.

Checkers has long existed in the shadow of chess. The relative simplicity of the rules alleviates some of the tremendous problems of complexity that arise in chess. A. L. Samuel of IBM (1254) used the methods described by Shannon to program an IBM 704 to play checkers. The machine also had some learning ability. In one experiment, storage of all board positions that were previously encountered was used as the learning mechanism. The general conclusions reached from this rote learning study were:

1. Rote learning of this type must include some way to direct the search for information.
2. It is feasible to use this type of learning if the information occupies a sufficiently small volume within the computer system.
3. The game of checkers, played under the conditions imposed, requires information exceeding this volume.

Since it appeared unfeasible to achieve machine learning of very large amounts of information by rote, Samuel turned to a study of learning which utilized generalization. The program generalized various situations in checker playing and then stored the generalizations for later use. Some of the generalization techniques were: modification of the evaluation polynomial's coefficients; replacement of terms in the polynomial; and inclusion of interaction terms in the polynomial. From these studies, Samuel drew the following conclusions, but cautioned that they were to be considered tentative:

1. Generalization can be an effective learning device.
2. The memory requirements are modest.
3. Operating times are fixed and not exorbitant.
4. The computer can play a better-than-average game of checkers using this method of learning.

Finally, Samuel suggested combining both rote learning and generalization as the next step in his studies. For example, the program might be arranged to save only the "piece advantage term" for each piece at the start. At

some stage in the learning process the next term could be added, for example, a position evaluation term. An appropriate time for the addition of a new term might be when no change had been made in the new parameter during some fairly long period, for example, for three complete games. If the program was able to play an additional period without changes in the next parameter, this also might be added, etc.

C. Theorem Proving Programs

Two important studies are described in this section. These are the logic theory machine (LT) of Newell and Simon (1245) and Gelernter's geometry theorem proving machine (1223).

The LT program was coded for the RAND JOHNNIAC computer. Elementary symbolic logic was chosen as the subject because it consists of a number of axioms together with rules of inference for generating new statements. Newell, Simon and Shaw used the five-axiom, three-rules-of-inference-system that Russell and Whitehead employed in the Principia Mathematica.

The axioms are given to LT in the form of punched card inputs. By its nature, the computer can perform the inference operations: substitution, replacement, detachment. The computer then uses these operations to prove various theorems. Previously proved theorems are stored in the memory for reference when needed. In addition to the methods prescribed by the rules of inference, LT also uses a method known as chaining. This method involves the creation of a new subproblem by the "relation of implication" (1244). When the subproblem is solved, it provides a proof for the problem expression. A very important feature of LT is a feedback process which informs the machine of its progress towards the proof.

In a test consisting of proving the first 52 theorems of the Principia, proofs were given for 38 of them. Seventeen were one-step proofs, 19 were two-step proofs, and two were three-step proofs. Of the 14 unproved theorems, Newell, Simon and Shaw believed that 12 of them might be proven if LT had greater time and memory capacity.

Gelernter's program consists of three main subprograms which he calls the heuristic computer, the syntax computer and the diagram computer. The heuristic computer is an executive routine which directs the search for a

proof. The syntax computer contains equivalents of most of LT's syntactic heuristics. The diagram computer has a coordinate representation of the theorem to be established, together with a series of routines that produce a qualitative description of the diagram. Gelernter describes his machine operation in 11 steps:

1. Scan the diagram and report pertinent features such as angles, segments, triangles.
2. Set up the initial conditions listing premises and conclusions.
3. Expand definitions to include the given non-primitive predicates.
4. Choose the subgoal to be established from the problem-solving graph. (The problem-solving graph is defined by the system and includes a series of subgoals which are generated by the program. This is the "generating subgoal.")
5. Choose lower subgoals so that if any one of these is established the higher subgoal is established.
6. Discard unwanted lower subgoals.
7. Test to see if generating subgoal is established. If so, the program branches to Step 9. If not, the program branches to Step 8.
8. Add acceptable lower subgoals to the problem-solving graph and choose new subgoal generator (i.e., branch to Step 4).
9. If the generating subgoal is established, add it to the list of established formulae and tests, provided there are parallel subgoals to be established. If there are, the program branches to Step 4; if not, to Step 11.
10. If every generating subgoal has proved fruitless, the machine fails.
11. The machine reconstructs the proof from the problem-solving graph and prints it.

The majority of the heuristics are found in Steps 4, 5, and 6 where subgoals are tried and accepted or discarded.

The main goal of Gelernter's study was to understand the uses of heuristics in problem-solving rather than to construct a geometry machine. The next step in the research along these lines is to provide the geometry machine with some learning ability, as well as the ability to recognize recurring patterns.

D. Pattern Recognition Programs

Pattern recognizers attempt to abstract from an unknown input the key features that allow a positive identification with a known character. The problems of pattern recognition range from detection of visual or acoustical signals to detection of recurrent forms in games and cryptanalysis. Harmon (441) defines a pattern as a detectable structure in a set of signals. Common methods of pattern recognition are template matching and property-list matching. Template matching consists of comparing the input pattern with a standard pattern and selecting the closest match. If the patterns are chosen from the same set as the template, the method is satisfactory. However, since handwriting and speech usually do not have such invariant properties, template matching is not as adequate as property-list matching for these patterns. In property-list matching, instead of comparing various patterns with idealized forms, certain features are abstracted such as cusps and parallel lines. While property-list matching is an improvement over template matching, it cannot yet be regarded as the final answer.

Vossler and Uhr (1056, 1264, 1265), in their studies on pattern recognition by computers, have set up five goals for an intelligent machine. Such a device should: (1) sense its environment, (2) act on its environment, (3) search for redundant patterns, (4) form concepts (i.e., generalize), and (5) store and use symbols and relationships between symbols. Initially, the computer has no operators or concepts about the meaning of its outputs. The operators are generated by two methods. The first is an abstraction process which uses parts of the inputs that are presented to the machine, while the second requires the random generation of Boolean functions of input states. These operators then map inputs into output sets, and feedback controls generation and refinement of subsequent operators.

In this program, the inputs are presented on a 20 x 20 matrix of binary symbols. This gives a possible 2^{400} input states, which is much too large to handle unless further restraints are placed on the problem. Uhr and Vossler suggest that the generators produce operators that are functions of connected elements only, and that these operators be generated in a smaller matrix which is translated across the larger space. The program has had considerable success to date. It has improved from an initial recognition of 0% to better than 90%. In a test comparing the program's ability with

that of human subjects (using characters which were unfamiliar to both computer and human) the program quickly outperformed the humans. In another test, the input patterns were distorted and their size varied, but were rotated minimally. The program scored between 70% and 80% on these tests.

At System Development Corporation, Simmons, Klein, and McConlogue (951), using a system called proto-synthax, are investigating various patterns which occur in language. The system consists of a reading and indexing program, a grammatical analysis machine, a question analysis system, and a program to select the best available answers from the text. Input is in the form of punched cards. The reading program separates the "function words" (such as articles, prepositions and conjunctions) from the "content words" (the remainder). The frequency of the content words is noted and the text is stored on tape with appropriate referencing. The indexing program arranges the content words in a manner similar to the Uniterm system. Every occurrence of a given content word is noted. There are also up-dating programs which allow additional text to be inserted at a later time.

When a question is asked the machine, it is subdivided into three types of words: question words (who, what, how, etc.), other function words, and content words. Next, the question is broken down into phrase structures from from which "information requests" are formed. The content words in the information request are looked up in the index and a logical intersection is performed on them. If a question word is not in the index, the program either checks for synonyms or requests a rephrasing of the question. If no intersection is found [illegible] made for intersections with synonyms for the content words. [illegible] fruitless, an attempt is made to find a link between two content words of the question and a third common content word. The grammatical analysis system determines the part of speech for each word in the sentence. It then attempts to eliminate ambiguities in the first pass-through and to identify noun phrases, verb phrases and modifiers. The third pass tags the subjects, predicates, objects and modifiers. Finally, an answer is chosen on the basis of the number of content words it intersects, and how closely it matches a formula for answering the question.

David (231), working at Bell Telephone Laboratories, has studied digital simulation of various facets of human communication. Before and after

digital processing of visual and auditory information, it is necessary to translate the analog into digital signals and vice-versa. The value of the conversion back to analog form is that it permits evaluation of the output to be made by eye or ear which, at present, have finer discriminatory capabilities than instruments. Any simulation involves processing large amounts of data. A fast computer with large memory and rapid input-output capacity is needed. Because of present limitations in computer technology, however, the time for simulation is anywhere from 10 to 50 times that of the actual process. In extremely elaborate programs, the time dilation may be even greater.

The programming of the computer for simulation differs in two respects from the programming of the computer for mainly computational tasks. First, more logical operations are usually required. Second, due to the large amount of input data, most of the programming consists of bookkeeping and data transfer operations.

A compiler specifically designed for signal processing has been written at BTL. It converts source programs presented to it in the form of block diagrams into machine language programs. While coding directly in machine language results in a more effective program, use of a compiler permits a person relatively unfamiliar with computers to use one effectively after only a few hours training.

David's studies have shown that digital coding of human communication is advantageous for a number of reasons. For example, when transmitting in a noisy environment, digital coding can be regenerated perfectly, providing the signal-to-noise ratio is high enough. Also, it has been shown in studies on the recognition of various signal properties that simulation of various speech measuring devices is feasible. Such simulations alleviate the problems of reproducing input conditions and of observing "nonrepetitive dynamics." Finally, David notes that the computer can be used as a signal generator by employing the data translator.

Selfridge (1255) suggests that the study of pattern recognition may be quite interesting and rewarding, since brains recognize patterns very well and computers, to date, do not. In extracting significant features from a pattern, Selfridge notes that there are two components which comprise

significance: context, and experience; and that pattern recognition is inextricably bound to ways of determining what is significant and what is not.

In a recent article with Neisser (1256), Selfridge describes two pattern recognition devices. A program named MAUDE translates hand-sent Morse code. The problem is not trivial since the spacings and durations for the dots and dashes are not always the same. The program has overcome these difficulties and performs at a level only slightly below that of a skilled human operator.

The second device is a mechanical reader. For input, the letters are encoded on a matrix of photocells or a similar reading device. Identification is by means of topological features. (Identification by template matching was rejected because its discriminative capacity was too slight.) In identifying the pattern, features such as concavities and vertical and horizontal lines are considered. Selfridge and Neisser note that no single feature can uniquely differentiate all letters, but that, in combination, they succeed fairly well. The choice of features is a critical part of the program. Ideally, the machine should learn by experience which features are helpful and which are not. Unfortunately, no current programs are able to generate internally the test features that are needed for this type of program.

Clark and Farley (1210) studied perceptual generalization in a randomly connected network of non-linear elements, connected to a circuit which modified various parameters of the net to reorganize itself to produce a specified output. The experiments were designed (1) to ascertain whether the system would organize itself according to randomly varying inputs, and (2) to examine what kind of classifications would be made on the input sets by nets trained with fixed and varying input patterns. The entire process was simulated on a computer. It was found that the system did organize itself and was able to generalize the concepts of "horizontalness" and "verticalness."

In another paper, Farley (1218) delineates several problems in constructing models of learned perception. He defines this process as the ability possessed by complex organisms to organize their classification procedures to take account of increasingly complex features of their environments. One of the problems is generalization from particular stimuli to new

stimuli. Such generalizations may be of three types: those which arise from disregarding differences, those which come from making predictions about the environment, and those which are based on similarity. Farley then suggests a model based on property classes. To identify an input, it is only necessary to measure its properties and to determine to which class it best conforms. The property classes are determined by frequency of simultaneous occurrence of properties, constancy of some property values such as spatial or temporal contiguity, and the like. As a simple decision rule he suggests a weighted average procedure which can use correlation rules to allow for contextual information.

E. Concept Formation Programs

A concept may be considered to be a rule for determining whether a given object is a member of a given set. This set may be denoted by a symbol which is its name. The rule is the concept of the name while the set is the denotation of the name. The two papers discussed here report on programmed attempts to simulate concept formation.

E. B. Hunt, now at UCLA, and the late Carl Hovland of Yale, constructed a model of human information processing and programmed it for a computer (1229). In their approach, the computer is given specific objects which may or may not belong to the selected class (the concept) and informed whether that object is an example of the concept. An object may, of course, belong to several classes besides that of the concept. These, too, are reported to the computer. Based on previous and current information, the program tries to form a decision rule to assign objects to their correct set. After it has done this, the computer reports the concept it forms to the programmer who may then supply the program with more instances if the machine is incorrect, or may stop the program if the computer reports the correct concept.

Kochen (1232) describes an algorithm to characterize classes of objects. These classes may have rules of inclusion such as "all red, round, objects or all small, square objects." This could be written $\{(R \cap r) \cup (S \cap s)\}$ where R = red objects, r = round objects, S = small objects, s = square objects, $\cap$ = logical product (or intersection), and $\cup$ = logical sum (or union). This sort of criterion for class membership defines a "disjunctive

hypothesis." A simpler task would be to characterize a class such as "all red, round objects." The algorithm initially has the hypothesis "everything goes." If an instance confirms the hypothesis at any step, the hypothesis is unchanged, and the degree of confidence is increased. If a contradictory instance appears, the hypothesis is changed so that all previous statements hold under the new hypothesis. This may involve adding an additional term to the hypothesis [e.g., all (A and B) or all (C and D)]. Kochen found that the machine would "guess" the actual solution to the problem far faster than if it carried out a complete truth table evaluation.

Concept formation programs may have widespread applicability in space explorations. A large number of specific cases, e.g., samples taken from the environment, may be used to obtain generalizations by the techniques described. The results of such a computation could then be transmitted to earth rather than the data itself. In such a manner, more information could be obtained than by the direct transmission method.

F. General Problem Solver, Elementary Perceiver and Memorizer, and the Binary Choice Program

GPS, EPAM, and the Binary Choice Program are three programs written in IPL-V (see Page 49 for a description of IPL-V). They are all heuristic programs; that is, when they are presented with a problem, they are not given explicit instructions to solve it, but rather are supplied with general rules to make their decisions.

GPS uses heuristic means to perform a variety of tasks such as proving theorems and identities, solving elementary calculus problems, or playing chess. It grew out of earlier work on the logic theorist which is described elsewhere in this section (see Page 37). It attempts to simulate protocols of college students trying to solve various problems. These consist of elementary logic problems (with a list of axioms and rules of inference supplied the subject), and the "missionaries and cannibals" problem.

The problems with which GPS works are characterized in terms of objects and operators. The objects are distinguished by various features and by observable differences between pairs of objects. A task environment is defined by the objects and operators within it. Given a specific task environment, GPS needs two vocabularies: one to discuss the task environment,

another to discuss the organization of the problem-solving processes. In addition, it needs two sets of programs one to define the terms of the problem-solving vocabulary by terms in the task environment vocabulary and one which applies the terms of the task environment vocabulary to the specific environment (741). GPS attacks problems given to it by evaluating the goal (not attempting to solve the problem if it rejects the goal), selecting a method to use for this type of goal, and executing this method by selecting appropriate subgoals. These subgoals are selected by using the heuristic principle of substitution of easier subgoals in place of a higher order goal to achieve a solution. Another important technique is the planning method. This method abstracts from the objects and operators, formulates the problem in the abstract task environment, uses the solution of the abstract formulation as a plan for the original problem, and finally applies this plan to the original task environment.

A number of phenomena observed in the earlier studies will be incorporated into GPS for future experimental work. One of these is a "behavior" in the protocols which is similar to parallel processing. In some protocols, the subjects carried along compound expressions as they solved problems. What probably occurred was that two unlike concepts were combined into one concept which was manipulated, and the results were then applied to the two separate concepts. At the present time, GPS cannot do this, but it is planned to incorporate this feature. Another area concerns levels of human thought. Humans apparently think on many levels in the experimental situation. Some ideas are expressed directly to the experimenter, some ideas are not expressed but conscious, and others are not even conscious. This is the problem of overt-covert thinking. A manifestation of this was that Newell's subjects soon <u>learned</u> the various rules of inference and did not have to scan the list in working the problem. The machine will be programmed to do this in future studies. A final phenomenon is the avoid-consequence mechanism. Human subjects recognized that they "should have" followed some alternate rule when one rule led to failure. An "avoid-consequence" mechanism will be included in future GPS models.

EPAM simulates the behavior of subjects in experiments involving the rote learning of nonsense syllables. It should be emphasized that EPAM is a behavioral rather than a neurophysiological model of brain function. It has

an associative memory which is based on a discrimination net. Feigenbaum (1219) states that there are certain elementary information processes which an individual must perform if he is to discriminate, memorize and associate verbal items. EPAM does not completely represent these processes although it does simulate certain basic ones.

There are two modes of operation in EPAM, a performance and a learning mode. The performance mode receives a stimulus, codes it, tries to find the appropriate response, and finally emits a response. The answer EPAM gives may or may not be the correct one. If it is not, the program must learn to make a finer discrimination. This is accomplished by the discrimination learning process which builds a net of tests and associated branches. The association process stores response cues with stimulus images.

A very interesting aspect of EPAM is that it can forget items which are seemingly well-learned. Feigenbaum offers the possible explanation that forgetting occurs not because of information destruction but because learned material becomes lost and inaccessible in a large and growing association network. This occurs in EPAM because at some point a cue does not contain enough information to retrieve the appropriate image. For example, suppose that the syllable "DOG" were stored with the response cue "D." If, at some later time, "DOT" were stored using the cue "D," DOT could be recovered but DOG could not. By relearning the syllable "DOG," an appropriate distinction could be made. However, the relearning time for "DOG" seems to take as long (in computer time) as does the time it takes to form the original distinction. This does not seem to agree with evidence indicating that for humans, relearning time is shorter than original learning time.

The Binary Choice Program simulates behavior of an individual in an experimental situation (1221). The binary choice experiment consists of asking the subject to predict which of two events will occur on each of a series of trials, the sequence of events being determined in a random fashion. In performing the experiment, there was no apparent difference between subjects who were asked to "think aloud" and those who were not.

The program has been developed to predict the same event series that the subject did. Its predictions and reasons for the predictions are then compared with the human subject's predictions and reasons. The model is an

attempt to specify the relationship between the reasons or hypotheses that the subject offers for his predictions and the preceding hypotheses, predictions, and events. In general, if the prediction is right, the hypothesis is retained; if not, a new one is proposed. The model is limited in several ways. It does not form very sophisticated hypotheses, and is limited to nine possible patterns. It does not "guess opposite" (i.e., the event will be opposite that which the hypothesis predicts, as often as human subjects do. The pattern change mechanism is felt to be too simple. There is no means for perceptual errors ("seeing" the wrong symbol).

The programs are fairly complex behavioral models. These models, however, seem to reject the accepted verbal conditioning model by their relatively close agreement with the behavior of human subjects.

G. Pandemonium

Pandemonium is the name of an adaptive pattern recognition model (923). In an idealized Pandemonium, there are a number of cognitive "demons," each of which computes its similarity to the given pattern and gives an output (shouts) which depends monotonically on that similarity. A decision demon listens to the "shouts" and selects the pattern corresponding to the "loudest shout." In a more refined Pandemonium, additional layers of demons are added. The hierarchy now reads (from the bottom up) data demons, computational demons, cognitive demons, and decision demon. (See Figure 5.) The data

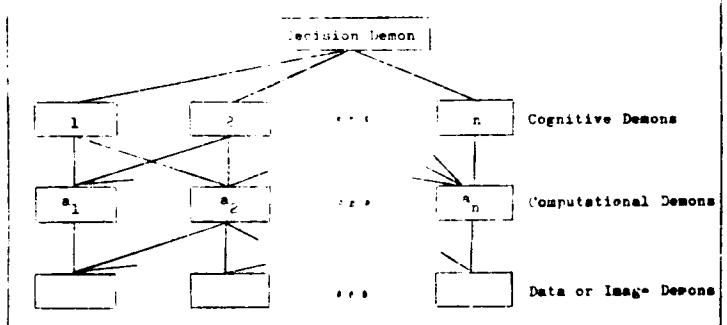

Figure 5. Diagram of Heirarchical Structure of Pandemonium

demons store and pass on the data. The computational demons perform certain more or less complicated computations on the data. The cognitive demons evaluate these results, and "compute a shriek" that is heard by the decision demon which then merely selects the loudest of them.

The cognitive demons perform their evaluation by taking a weighted sum of the outputs of the computational demons. Selfridge describes a process called feature weighting which consists of altering the weights of the computational demons to improve the performance of the Pandemonium. To find these optimum weights, a procedure known as hill climbing is described. A set of randomly selected weighting vectors is examined until a vector is found that produces considerably better performance than the others. Then small random vectors are added to this one until a direction that increases the performance is found. The process is repeated until an optimum is reached. Selfridge also comments on the possibilities of climbing a peak which is a local maximum but is not the maximum for the entire space. The changes which occur as a result of the hill climbing procedure are akin to learning. The system as a whole improves because of its past experience.

Another method to improve performance is by proper selection of subdemons. After feature weighting has stabilized and the machine's performance has been approximately optimized, subdemons with low worth will be eliminated. Mutations will be made to the surviving subdemons. A mutation is made by altering some parameters at random. The collection is then reweighted.

H. List Processing Languages

List processing languages have been included in this review because a number of the programs described in this section have been written using these languages. Most digital computers are designed to perform complex arithmetic and logical calculations when given a relatively small number of inputs. If the amount of input data is large, problems of storage allocation and increasing efficiency of computation appear. List processing programs attempt to alleviate the programmer's problems in these areas. They are particularly useful when the data being processed are not complete. If more information is entered, it can be placed in proper sequence with the rest of the data. Two such programs are LISP (for LISt Processor) and IPL-V (for Information Processing Language--V).

LISP is a programming system developed at MIT by John McCarthy (602). It is a general purpose system which is used in various heuristic programs. LISP is used to perform symbolic calculations such as those which arise in calculus, circuit theory, mathematical logic, and artificial intelligence. It consists of a central core based on recursive functions of symbolic expressions.

The basic ideas of IPL-V derive from the work of Newell, Shaw and Simon (1246). Current versions are available for the IBM 650, 704, 709, and the RAND JOHNNIAC. This language gives the computer a flexible memory and a capability of doing recursive sub-routines. When recursive sub-routines are attempted, an endless loop may result with concomitant disastrous consequences (1225). There are a number of sub-routines available to the programmer. A program can be broken down into sections, each of which may be handled by one of the sub-routines. Also, there are several debugging aids included in IPL-V. The program functions by manipulating symbols which may be single items or names of lists. Any given list may have sublists which also may be manipulated. IPL can operate on lists at the level of the single item, the sublist, the main list, or the complete list structure. IPL also may be used for handling non-numeric data such as algebraic expressions and self-modifying programs. One of the most important aspects of the IPL language is the variable list length feature. Every cell on a list has an IPL symbol and the location of the next item on the list. By changing this location, items may be inserted or deleted from the list. The program itself occupies from 3,000 to 6,000 cells of storage, depending on which computer is used.

IPL-V has been used by a number of investigators. Newell, Simon and Shaw began with the Logic Theorist (1244) and have since programmed the General Problem Solver (741). Feigenbaum (1219) has used it on EPAM and Feldman (1221) on a model of human performance in binary choice experiments. Clarkson has studied trust investment heuristics with IPL-V (1211). Green believes that the success of the RAND and Carnegie groups in this effort are harbingers of things to come (1225). Because of its widespread availability and success, use of IPL-V will probably increase and fulfill Green's prophecy.

I. Neural Net Simulation

These studies are directed toward the simulation of neuron functioning. They assume that "neurons" are interconnected into a system or network, and

that simulation of such a network will result in a device which will simulate the function of human nerve processes. Typically, the following assumptions are made concerning the properties of neurons:

1. At any given time, a neuron either fires or it does not. This is the familiar "all-or-none" firing pattern. The neuron fires if a given stimulus threshold has been exceeded.
2. After firing, the neuron is refractory for some period of time. That is, its threshold is effectively raised to infinity for a short period.
3. After this refractory period, the threshold declines to its normal level.
4. Shortly after firing, the neuron transmits impulses to all of the neurons to which it is connected.
5. At the synaptic junction, there is spatial summation and quasi-temporal summation of impulses. It is not a true temporal summation because time is quantized into discrete units.

Farley (310) has written a program simulating neural nets for the TX-2 at Lincoln Laboratories. The nets which are being simulated are relatively small, having only 1,296 elements in a 36 x 36 array. Connections to a given cell range from 1 to 50. He discusses two classes of nets: tightly coupled nets in which cells are connected only to their immediate neighbors, and loosely coupled nets in which there are significant numbers of connections long enough to reach beyond the refractory trough of a wave.

In tightly coupled nets, if only one stimulus is given, the wave fronts form expanding rings much as if a pebble were dropped in a pond. However, if a rapidly repeating stimulus is applied, the wave front becomes fuzzy and may actually continue after the stimulus ceases. It is also possible, by applying more than one stimulus, to obtain effects which are not produced when the stimuli are given singly. It is also noted that by resetting the thresholds externally, some control of the net's activity can be obtained.

The connection length for loosely coupled nets is, of course, dependent on the values of connections and refractory trough lengths. In such a net it is possible for backfiring to occur which may dampen a given stimulus. It is also possible for the net to oscillate diffusely, indefinitely, or stop

suddenly after oscillating for just a few cycles. The period of oscillation appears to be a complex function of refractory time constant, length of connections, and excitatory time constant. The equations describing these relationships have not yet been determined.

Crichton (212) uses the Hebb Theory of synaptic change in programming a net of 10,000 neurons with, on the average, 150 inputs per neuron from other neurons. The value of a stimulus depends on the neuron from which it emanates. The neurons themselves are distributed evenly over a surface such as a cylindrical, torus, or rectangular surface. The neuron fibers are distributed in a locally random fashion with density being a function of distance and direction. Crichton notes that because of the magnitude of the problem, it is not possible to run the program on the high speed memory of the 709. Therefore, he is attempting to use some of the redundancy in the net to enable the program to fit inside the computer. One method is by partitioning the neurons into sets and storing the histories and states of the sets. Sometimes it is desirable to combine or split various sets. Finally, he notes that in any sort of a programming chore, it is advisable to include as much flexibility as possible.

Neural net simulation on computers is quite difficult because of the size of the problem. In Crichton's study, a complete description of the neural net at a given time is impossible because the amount of information needed to do this is well beyond the storage capacity of the 709 computer. Addition of larger memories will be of little help since larger nets eventually will be studied. A method of dealing with nets in terms of classes of neurons must be developed.

J. Summary

The computer programs which have been discussed in this section have all been concerned with the same problem: the reduction of complex situations by various means into simpler ones. In some situations, particularly game playing, pattern recognition, theorem proving, and list processing languages, considerable progress has been made. Suitable techniques have been developed and applied. In others, much hard work remains. The simulation of neural nets, for example, suffers from a dire need of a method to cope with the vastly complex computations and tabulations that must be made. A great

deal is known about problem solving, but there are still many unanswered questions concerning actual techniques, capabilities, and limitations of these programs. Future work should help supply the answers to these questions.

V. AUTOMATIC DEVICES IN SPACE MISSIONS

As recently as a year ago it appeared that the exploration of space would be dependent largely upon the design and implementation of automatic systems. With the exception of the X-15 and Mercury programs, which aimed chiefly to determine whether man could survive and function at all in space, virtually all mission planning was based on fully automated equipment. It was in this context of general thinking that the concepts of "self-organizing systems" and "adaptive devices" received their greatest impetus. In this regard it is interesting to note that their recognized need was derived from an appreciation of the loss in system capabilities that would result from omission of man as an integral part of the payload. The greatest source of anticipated system degradation would occur from the inability to design devices capable of yielding the flexibility, reliability, and self-programming features of a human operator. This certainly would forecast failure in coping with the unavoidable unknowns of any space probe. The accelerated efforts in the computer technology field to develop such devices are thus not too surprising.

The recent successes of the X-15 and Mercury programs, especially the Glenn flight, suggest strongly that a reappraisal of our scientific and technical efforts be made. The Friendship 7 mission provides irrefutable evidence that man not only can survive the rigors of space but that he can perform quite capably and efficiently, and that the unique capabilities he adds to the system contribute directly to system function and reliability. Col. Glenn's manual control of vehicle attitude and observation and description of luminous particles are excellent samples of the human capacity for responding to unexpected aspects of a situation in a highly satisfactory manner. As a contrast to this performance, it can be pointed out that override of the vehicle attitude control system was required <u>after the automatic system had failed</u>, and that the luminous particles would not have been detected at all by a video sensor unless one had been designed specifically to respond to their particular characteristics. Frankly, there seems little doubt that a man could successfully pilot a vehicle to the moon and accomplish a landing rather than a 25,000 mile miss.

The point of this discussion is not to argue for a cessation of research and development of automatic devices, but to suggest that their objectives

and capabilities be cast in a different light. There is no question but that they are important adjuncts to man in systems of all types, and improvements should be pursued toward that end. However, they are not going to replace man in key roles within systems, including space missions, for a long time--at least as much as 20-25 years. In the meantime, it is proposed that the most fruitful approach is to design devices to aid and supplement man in his role as space explorer.

There will be situations in which environmental requirements place such severe penalties of weight and cost on the biological support system that only specialized automata will be feasible. But even in many of these cases, it is suggested that if the magnitude of research efforts on the biological problems were equivalent to engineering effort on problems associated with other subsystems, the results might be quite surprising. After all, the weight of a man plus the entire biological package necessary to support him for about a two-week space flight can be kept around [illegible],000 pounds.

These sentiments reflect the position taken in this report as a result of this survey. There appears to be no device or theoretical formulation which is capable of generating a self-initiated program to adjust to novel situations and which also shows promise of being implemented to meet the requirements for a space mission within a 3-5 year time period. On the other hand, there are a number of observations which can be drawn from the survey which outline much further work that remains to be done, and which suggest significant developments and discoveries that are certain to follow. Specifically, the more provocative of these conclusions are as follows:

A. Neurological Considerations

1. Virtually all models and simulations are based on the Hodgkins-Huxley neuron as it has been elaborated by McCulloch and Pitts. This is a highly abstract and mathematically idealized neuron as opposed to the raw data type of neuron that is disclosed by direct electrophysiological research. The studies of Eccles are recommended as a source for providing a truer picture of actual neurological parameters for theoretical or simulation attempts.

2. Only the physical characteristics and functions of somatic nervous system neurons have been considered to date. There is no question but

that autonomic centers must be included even in the investigation of higher intellectual processes, for interaction and mutual function does occur. Certain portions of the brain (e.g., the reticular system and hypothalamus) have been found to be adrenergic rather than cholinergic. This suggests that central nervous system autonomic neurons may exhibit properties in common with autonomic neurons in the peripheral system. Electrical characteristics of autonomic neurons in general are very poorly understood.

3. All analog simulation of neurons and neural nets is predicated on the electrical theory of synaptic transmission, even though chemical transmission is better established by physiological research. As a validity check on electrical simulation, it would be quite interesting if chemical simulation were undertaken to determine whether the electrical effects could be produced as a result of the chemical processes that would take place in the simulation. Actually, Lillie's iron wire model was a step in this direction. Also, some of the solid state and thin-film devices that are being developed are similar in nature.

4. More direct study of brain centers and functions should be initiated from the discoveries and hypotheses of researchers in the field of artificial intelligence. If this should take place, understanding and knowledge of the brain will be considerably enhanced. This will almost certainly feed back more ideas and information to advance the field of artificial intelligence itself. In the direction in which research appears to be moving, a breach seems to be developing between knowledge of brain functions and work on artificial intelligence. In order to learn about the brain, the brain itself must be studied. However, hypotheses and guesses about brain functions can be very profitably derived from any of the formal brain models or analogs developed within the field of artificial intelligence.

B. Special Purpose Computer Models

1. The Perceptron project has caused much furor in the press and in scientific circles. Its early development was hampered by too much newspaper publicity. Its basic principle is the random interconnection of a net of McCulloch-Pitts neurons and subsequent appropriate reinforcement

of the net to produce the desired signals. This principle may be false, or at least the time required to produce the desired behavior patterns may be so long as to make any practical use of such a device impossible. To date, the finest discrimination accomplished by the perceptron has been distinguishing a block F from a block E.

2. The only Pattern Recognizers that have met with considerable success, and are being widely used, are the magnetic ink readers which are found in banks. The biggest deterrent to a successful reader has been the fact that it must be able to read all fonts of type. When the interpretation of handwriting is considered, the problems become much more severe. Reasons for this are that no two people write alike; there are occasional missing letters and punctuation; and there typically is continuity between letters in handwritten script, without clearly defined segments. In speech recognition the problems are much the same as in handwriting recognition. Also, the segmentation problem is increased, as there are not equal or standard spaces between words unless the speaker is talking in a very strange manner. Practical applications of pattern recognizers are limited, in addition to the problems mentioned above, by cost and by engineering difficulties.

3. Heuristors appear to be a very promising avenue of research. They have many properties of neurons, yet they are much faster in actual operation. The possibilities of using them in computer circuits are being explored at SRI.

4. The most prominent work on Learning Machines is being conducted by such researchers as Ashby, Farley and Clark, Selfridge, and von Foerster. Results to date indicate that machines can be built which do learn from experience. However, such machines are still very primitive and do not approach a level of performance that one could consider challenging to man.

C. General Computer Program Models

1. Game Playing Programs have demonstrated the ability to manipulate large amounts of information to arrive at a decision in a situation which is basically unknown to the participants. Samuel's checker program has had the greatest success and consistently beats its inventor. (Samuel

admits that he is a poor player, so it remains to be seen how the program performs against a master.) The Newell-Simon-Shaw chess program performs well; however, it takes too long to make a move. While research in game playing, such as chess, checkers, musical composition, dominoes, and tic-tac-toe, superficially seems to be trivial, it has indeed contributed very materially to progress and knowledge in the use of heuristic programming as a problem-solving method.

2. Theorem Proving Programs have been constructed for almost the same reason as game players. However, by use of efficient techniques, such a program may some day prove a fairly advanced and non-trivial mathematical point. Studies at IBM performed by Gelernter, Rochester, and Gilmore are especially noteworthy in this area.

3. Both Kochen and Hunt, working independently have met with some success in developing Concept Formation Programs. Work is progressing rapidly, and this seems to be one of the brighter spots in the field. While practical machines are generally limited by the necessity of large memories, it is apparent that machine systems will some day accomplish cognitive tasks which have been, until now, the sole province of man. Specifically, a space mission application is the generalization of a large number of specific cases by computation, and the subsequent ease and economy of transmitting this relatively small amount of information to earth.

4. In the field of Heuristic Programming, Newell, Shaw, Simon, Feigenbaum and Feldman have published voluminously on GPS, EPAM, and the Binary Choice Experiment. There is much interest in GPS, although the actual results have not been published. There are some very interesting potentials here such as simulating the decision-making behavior of a human. These techniques seem to hold the greatest promise for designing some useful devices for space probes in the very near future, assuming that the required digital computer could be miniaturized to required size-weight specifications.

5. Selfridge's Pandemonium was one of the first models to consider the possibilities of hill-climbing and property filtration. It is very much like a perceptron except for the absence of back-coupling. However, it

does not depend on reinforcement in order for learning to take place. Selfridge strongly emphasizes the importance of parallel processing of data--an event which is believed to be necessary in order to produce useful machines which will be "thinking aids" to man.

6. In the future, List Processing Languages should enable more powerful and general programs to be written. It seems feasible that someday a computer will be built which uses a list processing language as its prime language rather than indirect communication by means of an interpretive routine.

7. The major problems in the area of Neural Net Simulation arise because when an effort of any size is attempted, the computer's memory capacity is quickly exceeded. However, some very promising results have been obtained in the efforts of Farley and Crichton.

VI. A GLOSSARY OF TERMS

There has been much loose usage of terms in artificial intelligence studies, not always intentionally. A word meaning something quite specific in one discipline may have a very different significance in another. During the course of this study, definitions of some fundamental terms have been collected. These are defined below as they have been used in this report. Appropriate references are cited for the interested reader.

A. Adaptive control process

In many situations, a decision device must operate under conditions of uncertainty varying from complete ignorance to complete knowledge. As the situation unfolds, additional information may be put into the device. As it becomes available, this additional information is utilized by the decision device, which thus adapts to its environment. More formally, the decisions of the device are a function of its initial state and the input information. For further details, refer to Adaptive Control Processes, A Guided Tour, by R. Bellman, Princeton University Press, 1961 (1199).

B. Artificial intelligence

The phrase, artificial intelligence, is used in connection with efforts to enable non-biological devices (such as computers) to exhibit certain behavior patterns which are commonly classified as intelligent patterns in man.

Definitions of artificial intelligence and of intelligent machines as well as arguments for and against the epistemological question, "Can machines think?" may be found in the proceedings of the 1960 Bionics symposium (1131) and the 1961 Proceedings of the Western Joint Computer Conference (1133). Other pertinent references are: Proceedings of the Symposium on the Mechanisation of Thought Processes (1141) and the summer conference notes, Computer Programming and Artificial Intelligence, by J. W. Carr, III at the University of Michigan (1143).

C. Automata and mathematical machines

In common usage, an automaton is any apparatus that can move or work by itself. A mathematical machine is thought of as a machine which performs arithmetic calculations, such as a computer. Recently, however, some fields of mathematics have been concerned with abstracting the interesting features

of the modern electronic equipment so widely used nowadays. Thus, a mathematical machine has a set from which inputs can be selected, a set from which outputs can be selected, a set of internal configurations or states for the machine, and a function relating the input to the next state of the machine. The definition of an automaton is similar to that of a mathematical machine. It has a set of inputs, a set of states, a set of next states, a starting state, and a set of final states. A rich literature abounds in these fields. An excellent starting point is E. F. Moore's paper, "Gedanken Experiments on Sequential Machines," in Automata Studies, No. 34, in the Annals of Mathematics Studies (1241).

D. Bionics

Bionics, as originally defined by Maj. J. E. Steele of Wright Air Development Division is "the science of systems which function after the manner of, or in a manner characteristic of, or resembling living systems." In practice, this means the science of using biological knowledge and technique in system design. More detailed definitions of the meaning and scope of Bionics may be found in the preface and the keynote address in the proceedings of the first Bionics symposium, September 1960 (1131).

E. Brain models and neuron models

Of the numerous brain models in existence, the Hebb model (1227) and the Milner (680) modification of it have been studied intensively during the past few years by Rosenblatt (889) with the perceptron program, Crichton (212) at Michigan, and others. These models attempt to simulate the physiological aspects of brain function. A different method of attack is to consider functional simulation. Simon (1258) notes four types of simulation:

1. Abstract simulation of adaptive, goal seeking, learning mechanisms
2. Simulation of the processes by which humans recognize visual and aural symbols and patterns
3. Simulation of the self-organizing capabilities of neural nets
4. Simulation of the processes used in rote learning, problem solving, and concept formation

Neuron modeling was given a major boost when McCulloch and Pitts (1237, 1248) showed that the correct mathematics of the nervous system was Boolean Algebra, not the complex partial differential equations of electromagnetic

theory; and that it was theoretically possible to obtain reliable output using neurons that might occasionally fail. A summary of the mathematical models may be found in McKnight, J. D., Mathematical Neurophysiology. Sunnyvale, Calif.: Lockheed Aircraft Corporation, October 1959 (637).

F. Computer languages

Instructions are inserted into computers in the form of a "word" consisting of a string of binary digits (bits). However, coding the computer directly in this form is laborious and leads to many errors. Therefore, computer manufacturers have written interpretive programs which enable programmers to write their codes in symbolic language rather than in binary form. The interpretive routine converts the instructions to binary form. For example, in binary form, an "add" instruction is represented in IBM machines by 000101, while in the mnemonic form used for the interpretive routines, the instruction is simply ADD. Various computer languages are FORTRAN, COBOL, UNCOL, IPL-V and LISP. The last two are list processing languages which are discussed in section IV of this report. Other references on computer languages are the papers read at Session 2 (Automatic Programming) of the Symposium on the Mechanisation of Thought Processes in Teddington, England, November 1958 (1141).

G. Conditional probability computers

These machines are still in the speculative stage. Interest in them has been stimulated by two phenomena that appear in animals:

1. Different stimuli evoke the same response.
2. Similar stimuli evoke different responses which resemble each other.

Conditional probability computers will be able to evaluate similarities between inputs. They will make computations on the representation of the objects, not the external configuration. That is, they will recognize the difference between the internal representation and the external object. Conditional probability is used as a measure of the frequency of joint occurrence of two distinct representations. It measures the degree of resemblance between the two. Early work on this subject appears in two papers by Uttley: Temporal and Spatial Patterns in a Conditional Probability Machine (1043) and Conditional Probability Machines and Conditioned Reflexes (1266).

H. Cybernetics

When Wiener named the subject, he gave it the subtitle, "Control and communication in the animal and machine." One of the main concerns of cybernetics is that of feedback mechanisms. Cherry (1208) notes that, during World War II, feedback was intensively studied with the object of developing "automatic-following, self-controlling, or goal-seeking systems." Bionics, artificial intelligence, and adaptive control processes may be considered as subjects embraced by cybernetics. In France, the term "la cybernetique" corresponds to our term, "information theory."

Appropriate references are: N. Wiener, Cybernetics, now in a revised, second edition, 1961 (1271); W. Ross Ashby, An Introduction to Cybernetics (1158), an excellent, readable account of the subject; and N. Wiener, The Human Use of Human Beings (1095), which describes cybernetics in lay terms.

I. Decision-making models

Many studies have been made on how man arrives at decisions. He must choose one of several possible alternatives under difficult conditions. There may be incomplete information or too much information to handle in the allotted time. In addition, no two humans will make all of their decisions in a like manner. Thus, in making a model of these processes, one can hope that it will satisfy population-wide behavior, or individual behavior, but not both. The von Neumann-Morgenstern theory of games can be classed as a population model, whereas the Newell-Simon-Shaw General Problem Solver approach models individual behavior. A starting point for further reading might be: (1) Thrall, R. M., Coombs, C. H., and Davis, R. L. (Eds.) Decision Processes. New York City: John Wiley and Sons, Inc., 1954 (1262) and (2) Simon, H. A. Models of man: social and rational. New York City: John Wiley and Sons, Inc., 1957 (955).

J. Feedback

In control systems, the direction in which the signal flows is known as the principal transmission path. In a feedback system, there is another path which carries part of the output back to an input channel. This permits the system to "check up" on itself to ascertain if it is performing as desired. For example, a thermostat is an elementary feedback device. In the human body, there are a number of feedback interactions; e.g., in vision, if the

object of interest is out of focus, the eye muscles adjust the size of the pupil. Feedback, as it applies to cybernetics, is discussed in Wiener's Cybernetics (1271).

K. Heuristics

The word "heuristic" means "related to improving problem-solving performance." It also can be used as a noun to designate the method which effects the improvement of the performance of some problem-solving system. Minsky (1240) lists several types of heuristic methods. These include methods that set up searches, methods that formulate new problems (as either subgoals or models), characterization and description methods, and self-improvement methods. In any program which makes use of heuristics, a great deal of bookkeeping must be done. Routines must be established for estimating the difficulty of the sub-problem, selecting the method of attacking the problem and choosing the order of solution of the various problems.

Heuristic methods too often have been regarded as foolproof. They are not; a heuristic program which causes an occasional failure may, in the long run, improve the performance of a system. However, to be successful, a heuristic program must work well on a variety of problems. Suggested readings are: (1) M. L. Minsky, "Some methods of artificial intelligence and heuristic programming," in Proceedings of the Symposium on the Mechanisation of Thought Processes (1141), (2) M. L. Minsky, Steps Toward Artificial Intelligence (1240), and (3) Newell, Shaw and Simon, Empirical Explorations of the Logic Theory Machine, A Case Study in Heuristics (1244).

L. Information theory

If a member of a set of n independent complete messages, with probabilities $p_1 \ldots p_n$, is to be identified, the information is $H = -\sum_i p_i \log p_i$. This expression is identical to that for entropy in thermodynamics. The quantity H is also known as the uncertainty. Clearly, if $p_i = 1$ for some i, then $p_j = 0$ for $i \neq j$ and $H = 0$. H attains its maximum when $p_1 = p_2 = \ldots = p_n$, that is, when all events occur with equal probability.

In his article in The Mathematical Theory of Communication, Weaver (935) points out some typical problems in the field:

1. Transmission problems--Is the received signal a faithful copy of the transmitted signal?

2. Semantic problems--Is the interpretation of the signals the desired one?
3. Effective problems--Does the received meaning affect behavior in the desired manner?

Of the voluminous literature on this topic, the original works are in Shannon, C. E., and Weaver, W. The Mathematical Theory of Communication. Urbana, Illinois: University of Illinois Press, 1959 (935). Also, bibliographies on this subject have appeared in the IRE Transactions of the Professional Group on Information Theory: Vol. IT-2, November 1953; Vol. IT-1, (2), September 1955; Vol. IT-2, (2), June 1957; and Vol. IT-6, (1), March 1960 (1190).

M. Learning

The definition of learning has been the province of psychologists for almost 100 years and yet there is no single definition that would find unequivocal support among them. An excellent summary of difficulties psychologists have encountered with the term is given in Hilgard, Theories of Learning (1228), and no attempt is made here to cover that history. The concept of learning which best fits the theoretical position taken by most researchers in the field of artificial intelligence is known clasically as "contiguity" or "association" learning. In it, learning is viewed as a change in performance in a desired direction as a result of previous performance and the operation of the "empirical law of effect." This latter law states that behavior leading to positive outcomes (reward) is more likely to reoccur under similar conditions and that behavior leading to negative outcomes (punishment) tends to disappear.

With the exception of relatively minor theoretical details, this view of learning is compatible with the theories of Guthrie, Hull, Spence, Skinner, and Estes. Basically, it is incompatible with the positions of Tolman, Köhler, and other Gestaltists.

N. Machine translation

Translating from one language to another is a long, slow job which requires skilled personnel. There are far too few people who have the requisite skills to meet the demands. Articles in Russian and Chinese are increasing in number and even relatively unused languages are appearing in journals.

Since most American scientists are trained only in German and French, machine translation is looked to as a possible solution. A major stumbling block has been the translation of idiomatic expressions. Introductory readings are: (1) Proceedings of the International Conference on Information Processing. Paris, France: UNESCO, 15-20 June 1959 (1162), (2) Edmundson, H. P., (Ed.) Proceedings of the National Symposium of Machine Translation. Prentice-Hall, 1961 (1217), and (3) Bar-Hillel, Y. "The present status of automatic translation of languages" in Alt, F. L. Advances in Computers. New York: Academic Press, 1960, 91-163.

O. Mind-brain problem

According to Sperry in his Neurology and the Mind-Brain Problem (1259), "the discrepancy between physiological processes in the brain and the correlated psychic experiences to which they give rise in consciousness has ever posed a baffling puzzle to students of psychology, neurology, and the related sciences." The question here is what is the relation between the mind (that which perceives, remembers, imagines, feels, conceives, reasons, wills, etc.) and the physical entity, the brain? Sperry's article, which appeared in American Scientist, April 1952, is an excellent introductory source to these problems.

P. Neural nets

The term "neural net" is found frequently in the literature on artificial intelligence. A neural net consists of a set of elements which act alike and are connected in some manner. Connections between elements of the net may be selected in a random fashion or in a completely deterministic manner. The elements are called "neurons" or "cells." They may or may not be models of real neurons or nerve cells. Some of the cells are used to accept data from the outside world (input cells) and others to emit the transformed data (output cells.) According to Minsky and Selfridge (691), the underlying reason for the belief in random nets is that such nets have the ability to "learn," i.e., will organize themselves to make the right responses when the nets are "reinforced" or "punished" for right or wrong responses, respectively. Further suggested readings, in addition to Minsky and Selfridge, Learning in Random Nets, are: (1) Farley, B. G. Some Results of Computer Simulation of Neuron-like Nets. Lexington. Mass.: MIT, Lincoln Laboratory, 1961 (310) and (2) Rochester, N., Holland, J., Haibt, L. D., and Duda, W. L. "Tests on a

cell assembly theory of the brain, using a large digital computer," in the 1956 IRE Transactions on Information Theory, IT-6 (1251).

Q. Non-mathematical data processing

This subject is of such interest because most of the information processing activity in the nervous system is of this nature. A large amount of information that is available is not easily quantifiable, yet useful results are obtained by processing these data. The processing may be by ranking a list in order of the presence of some attribute. For example, A, B, and C might be ranked for attribute X by the following process: B has more X than A, and A has more X than C. The ordering is, then, B, A, C. This process assumes that the set of objects can be ordered. In some cases they cannot be so ordered, but can only be described in terms of relative attributes. For example, without a means for measuring light frequencies, but only a circular spectrum, a means of describing purple might be that it lies between red and blue on the spectrum. Other examples might be:

1. Decision making, using data which is not given specific numerical values, but is presented in a qualitative manner, such as ranking
2. Property filtration
3. Reflex actions, such as removing one's hand from a hot surface

The problem is to process this form of data efficiently. Another problem intimately connected with this is weighting the data to elicit the appropriate responses. For further information and examples, see: (1) Newell, A., Shaw, J. C. and Simon, H. A. Report on a general problem-solving program, in Proceedings of the International Conference on Information Processing, 1959 (741) and (2) Green, B. F., Jr. "Non-computational use of digital computers," in Behavioral Science, 1959 (404).

R. Pattern recognition

Selfridge defines pattern recognition as ". . . the extraction of the significant features from a background of irrelevant detail" (1255). The problem of pattern recognition is a very important one. Any machine which claims artificial intelligence, of necessity, will have to be able to classify various configurations into categories from which further reductions can be made. Both visual and auditory patterns are very important in our lives. It is from visual patterns that most of our information about our environment is drawn. For example, we obtain much information by reading books.

The words and pictures which comprise books are sets of complex patterns. A key problem involved in pattern recognition is the development of a selective attention device. Auditory patterns in conversation are an aid to visual patterns in shaping a consciousness of the emotions and actions of others. The major differences in visual and auditory patterns are the primary difference in the sense organ, the speed of transmission, the effect of a "direct line of sight" and the effect of distance. Visual images are transmitted at the speed of light, auditory images at the speed of sound. While visual images must be in an unobstructed line with the viewer, sound does not have this limitation. A can talk to B from a different room and still be heard and understood. Finally, because sound is attenuated quite rapidly, it is impossible to hear a sound from a great distance. While light intensity also decreases with distance, it decreases much more slowly than does sound, and visual images, therefore, can be perceived at much greated distances than auditory ones.

Selected references on pattern recognition are Selfridge's paper, Pattern Recognition and Modern Computers, read at the Western Joint Computer Conference in 1955 (1255), Dineen's paper, Programming Pattern Recognition, read at the same conference (272), and the Bledsoe and Browning paper read at the 1959 Eastern Joint Computer Conference, Pattern Recognition and Reading by Machine (1202).

3. Probabilistic logics

A probabilistic logic is one in which not only the value of the argument is uncertain, but the function is uncertain as well. Von Neumann (1268) worked on this in connection with three problems about the action of the nervous system:

1. Circuits which produce the same output for a given input when the threshold of the component neurons are shifted by a constant amount. Thus, each neuron computes a new function of its input.
2. The design of circuits which are more reliable than their components
3. The unalterable fact that neurons are more flexible in computation than any device that man can produce

For further details, see von Neumann, J. Probabilistic logics and the synthesis of reliable organisms from unreliable components. In Automata Studies, No. 34, in Annals of Mathematics Studies (1268).

T. Self-organizing systems

Although von Foerster (1054) has professed that there is no suchthing as a self-organizing system, the term is still widely used. It refers to systems with the capability of organizing themselves by using energy which is obtained from their environment. The "turtles" of Grey-Walter (1269), Ashby's (1197) Homeostat, and Pierce's (806) maze learner are examples of self-organizing systems.

Additional references are: (1) Yovits, M. C. and Cameron, S. Self-organizing Systems (1173) and (2) Hawkins, J. K. "Self-organizing systems: a review and commentary," in Proceedings of the IRE, 1961 (1226).

U. Thinking

Thomson (1261) refers to thinking in the sense of the process of reasoning, reflecting, and pondering. Briefly, thinking may be considered to be the mental processes that occur when information is received, organized, and appropriate responses are made.

In discussing the possibilities of a machine that thinks, the mathematician, Alan Turing, proposed the following criterion: a machine is said to be capable of thinking if it can imitate a human by answering questions well enough to deceive a human interrogator. Thomson's views are detailed in his book, The Psychology of Thinking, published in 1959 by Penguin Books, Inc., in Baltimore, Md. (1261).

V. Turing machine

A Turing machine is an abstract mathematical formulation of a special kind of computing machine. The machine can be in one of some finite number of states. There is a "tape" leading to and from the machine which is infinitely long in both directions. This tape is divided into squares, each of which has one of a finite number of symbols written on it. At any time, the machine can "see" only one square and the symbol on it. The machine can perform three functions:

1. Change the symbol on the tape
2. Move the tape one square in either direction
3. Change its internal state

Using just these properties, Turing showed that such a machine could

compute any computable number. Further related reading in addition to Turing's paper (1263) are: (1) Holland, J. Survey of Automata Theory. Ypsilanti, Mich.: University of Michigan, Willow Run Laboratories, September 1959, R 2900-52-R, DA 36-039-sc-78801, ASTIA Document AD-226,595, and (2) Burks, A. W. "The logic of fixed and growing automata," in Annals of the Computation Laboratory. Cambridge, Mass.: Harvard University, 1959, 29, 147-188.

VII. AN INDEXED BIBLIOGRAPHY IN THE FIELD OF BIOLOGICAL AND ARTIFICIAL INTELLIGENCE

A. Introduction

This bibliography is a supplement to the Jet Propulsion Laboratory (JPL) literature searches dated December 1960 and 31 May 1961 (1192 and 1193). It is a fairly extensive list of over 1150 references compiled from other bibliographies and from information obtained by personal visits to investigators in the field of biological intelligence and its simulation. References are included in the areas of intelligence, perception, learning, and decision-making, and in the simulation of these abilities. Also represented are the related areas of logic, automata theory, decision theory, theory of games, information theory, and cybernetics. The bibliography is indexed to ten relatively broad subject areas. Subject divisions closely parallel categories used in the JPL searches; however, some synthesis and reorganization has been necessary to reduce the number of categories to ten. These are described in the classification system in Section B, on the following pages.

Basically, the bibliography lists 1129 references which are supplementary to the two JPL searches. Though references which are cited have been checked carefully to insure that they were not included in the earlier searches, some duplications may have occurred. This is especially true in the case of papers published under the auspices of the facility at which the investigation was conducted and which also appear as journal articles. In addition to the basic supplementary list, the bibliography includes a list of general sources, such as proceedings of symposia or conferences, and a fairly complete list of bibliographies currently available in the field of artificial intelligence and related disciplines. Finally, included in the bibliography is a list of the additional sources used in compiling this report. Most of these have appeared in the two JPL searches and are so identified.

All entries in the bibliography are numbered consecutively to avoid confusion when a reference is made in the text. Therefore, while the total number of entries in this bibliography is 1274, only about 1150 of these are truly supplementary to the JPL literature searches.

While this list is rather extensive, it is not to be considered exhaustive. The ten subject areas are, in themselves, so broad that the hundred or so references in each category can be considered only a sampling of the literature available. This is particularly true in the areas of neurophysiological research and learning.

The several published bibliographies which were used to compile a substantial portion of this bibliography are those of Minsky (1178), Simmons and Simmons (1186 and 1187), and Pierce (1183). Finally, a large number of previously unknown references were obtained from the very large and valuable unpublished collection of Professor Heinz von Foerster (1194).

B. Classification and Subject Index

The bibliographic entries, while arranged by author, are referenced to a subject index by a numerical code at the end of each entry. Ten broad subject categories are used, representing a synthesis of the twenty-one categories appearing in the Jet Propulsion Laboratory Literature Searches (1192, 1193). Appendix B shows the relationship of the JPL categories to the categories used in this report.

The ten categories are:

1. Feasibility of Simulating Thought Processes by Machine.
   References on epistemological questions (e.g., can machines think?); references of refutation or sanction for developing such machines; theoretical discussions of thinking or learning by machines.
2. Mathematical Machines, Automata, and Logic.
   Mathematical theory of computers and automata; general computer structure and design; problems related to search; probabilistics; mathematical logic.
3. Neurophysiological and Brain Function Research.
   Nerve elements and neural circuits; transmission of nerve impulses; physiology and anatomy of the nervous system; electrical studies of the nervous system.
4. Neurophysiological Models: Simulated Neurons, Neural Nets, and Organisms.
   Theoretical, hardware, or computer program models based on neurophysiological principles; models of the neuron and neural circuitry (e.g., Perceptron).
5. Pattern Recognition and Perception.
   Includes theoretical papers as well as those describing hardware or computer program models.
   a. General discussions; reviews; schemata; physiological and psychological properties (relevant to both visual and non-visual perception).
   b. Visual perception; pattern or character recognition machines.
   c. Non-visual perception; phonetic recognition machines; models simulating other sense organs.
6. Theory and Models of Learning, General Thinking Processes, and Behavior.
   Theories of inference, learning, memory, and other cognitive processes; programs or machines that modify their behavior as a function of experience.
7. Heuristics, Problem-solving, and Games.
   Specific application of machine learning theories to problems such as geometry theorem proving, symbolic logic, or reasoning; to game playing such as chess, checkers, and bridge; and to such exercises as maze learning and music composition.
8. Cybernetics.
   Cybernetics; adaptive control systems; homeostasis; stability; servo-mechanisms; self-organizing systems; self-reproducing systems; self-repairing systems.
9. Language Processing.
   Information theory; coding theory; mechanical translation; storage, information retrieval; studies of language; research on natural, formal, and programming languages; list processing languages.
10. Man-Computer Symbiosis.
    Man-computer interactions; future uses of computers.

It is readily apparent that these categories are not entirely discrete and mutually exclusive. Many of the bibliographic entries might be classified in several related categories. For simplicity, however, each entry has been given only one classification. Therefore, the reader may find it helpful to scan entries in other logically related categories for his specific purpose. For example, while articles describing Perceptron are classified in Category 4 as neural net models, an article describing an experiment in pattern recognition by perceptron-like machines might be classified in 5b as a pattern-recognition machine.

The subject index follows:

1. Feasibility of Simulating Thought Processes by Machine.

   14, 22, 29, 38, 45, 53, 60, 82, 85, 87, 107, 110, 114, 184, 197, 199, 215, 216, 270, 279, 312, 320, 352, 366, 369, 384, 403, 452, 510, 523, 584, 585, 586, 587, 590, 591, 599, 611, 616, 621, 628, 629, 631, 632, 633, 634, 663, 689, 701, 724, 729, 745, 804, 805, 806, 812, 842, 899, 907, 920, 947, 981, 985, 1011, 1012, 1027, 1028, 1031, 1047, 1066, 1104, 1105, 1110, 1116.

2. **Mathematical Machines, Automata, and Logic.**

9, 16, 61, 86, 105, 200, 201, 218, 220, 221, 222, 223, 242, 243, 244, 253, 285, 286, 287, 303, 304, 305, 306, 313, 331, 350, 353, 355, 364, 372, 373, 377, 378, 379, 380, 386, 387, 392, 395, 396, 413, 420, 467, 468, 469, 520, 527, 528, 532, 533, 534, 541, 560, 561, 564, 565, 574, 595, 601, 642, 659, 662, 664, 667, 668, 679, 686, 687, 690, 699, 700, 707, 708, 709, 710, 714, 717, 718, 719, 720, 721, 722, 728, 734, 822, 834, 835, 836, 861, 862, 877, 881, 882, 892, 914, 928, 930, 933, 934, 952, 977, 1010, 1040, 1042, 1043, 1044, 1068, 1094, 1106.

3. **Neurophysiological and Brain Function Research.**

4, 8, 23, 30, 72, 73, 74, 116, 121, 126, 127, 132, 158, 160, 176, 179, 180, 185, 193, 202, 211, 214, 225, 227, 246, 250, 273, 275, 278, 280, 281, 290, 291, 316, 324, 327, 332, 341, 343, 345, 351, 354, 367, 391, 407, 410, 411, 421, 431, 436, 457, 464, 470, 491, 500, 503, 504, 505, 508, 524, 526, 548, 553, 556, 566, 567, 569, 571, 593, 598, 610, 613, 617, 618, 619, 620, 622, 623, 624, 626, 630, 637, 639, 643, 646, 647, 654, 657, 658, 665, 677, 692, 702, 726, 727, 748, 749, 750, 754, 757, 764, 765, 766, 768, 771, 787, 793, 798, 816, 826, 828, 829, 837, 838, 843, 844, 855, 860, 873, 874, 880, 883, 891, 896, 901, 936, 939, 946, 978, 979, 982, 983, 984, 988, 1013, 1023, 1025, 1037, 1038, 1071, 1076, 1077, 1082, 1083, 1090, 1100, 1101, 1112, 1117, 1123.

4. **Neurophysiological Models: Simulated Neurons, Neural Nets, and Organisms.**

6, 7, 10, 17, 51, 88, 99, 103, 104, 115, 141, 146, 183, 205, 206, 207, 208, 209, 210, 212, 213, 217, 240, 258, 310, 329, 437, 438, 440, 442, 449, 450, 455, 456, 461, 475, 476, 477, 478, 481, 499, 509, 511, 514, 518, 536, 543, 558, 559, 568, 570, 625, 636, 645, 655, 680, 685, 691, 704, 713, 716, 725, 733, 770, 779, 784, 824, 840, 841, 847, 848, 849, 869, 870, 884, 885, 886, 887, 888, 889, 905, 908, 913, 916, 925, 940, 971, 993, 1004, 1005, 1008, 1021, 1045, 1046, 1048, 1049, 1065, 1087, 1103, 1126.

5. **Pattern Recognition and Perception.**

a. **General**

3, 5, 49, 54, 58, 59, 62, 66, 89, 97, 118, 137, 140, 145, 156, 188, 189, 272, 296, 299, 328, 337, 382, 408, 412, 451, 460, 4[illegible], 490, 512, 513, 544, 573, 638, 652, 669, 688, 723, 730, 731, 732, 781, 786, 807, 890, 912, 921, 924, 997, 998, 999, 1003, 1009, 1067.

b. **Visual**

12, 21, 25, 26, 46, 68, 101, 102, 124, 157, 161, 162, 163, 186, 187, 195, 219, 224, 247, 254, 274, 282, 283, 284, 289, 295, 297, 298, 317, 318, 323, 333, 334, 335, 336, 340, 356, 358, 359, 360, 361, 362, 370, 374, 375,

376, 381, 385, 401, 405, 406, 425, 432, 433, 434, 435, 439, 441, 472, 473, 479, 482, 492, 506, 515, 521, 522, 529, 531, 539, 542, 557, 583, 650, 653, 670, 671, 681, 682, 760, 761, 767, 769, 782, 783, 815, 846, 856, 857, 858, 919, 959, 965, 966, 991, 994, 1006, 1032, 1033, 1035, 1036, 1056, 1057, 1062, 1119, 1122, 1124, 1129.

c. **Visual**

11, 71, 226, 229, 230, 231, 232, 233, 235, 236, 237, 238, 241, 257, 259, 262, 276, 308, 311, 322, 342, 344, 427, 428, 429, 430, 474, 484, 501, 530, 554, 562, 755, 756, 794, 795, 796, 797, 808, 814, 823, 830, 897, 903, 917, 918, 941, 945, 960, 970, 986, 990, 992, 1069, 1108, 1109, 1127, 1128.

6. **Theory and Models of Learning, General Thinking Processes, and Behavior.**

13, 24, 31, 39, 40, 43, 47, 48, 50, 91, 98, 133, 134, 135, 136, 138, 142, 148, 175, 203, 248, 267, 269, 300, 301, 302, 309, 338, 339, 388, 394, 397, 398, 409, 415, 417, 418, 422, 446, 453, 454, 462, 485, 486, 538, 540, 545, 549, 550, 551, 576, 577, 578, 579, 580, 640, 641, 651, 656, 676, 678, 762, 800, 801, 802, 811, 825, 839, 852, 853, 867, 871, 872, 876, 898, 902, 904, 909, 910, 923, 926, 932, 944, 953, 954, 955, 956, 957, 961, 962, 963, 975, 1018, 1020, 1029, 1039, 1050, 1063, 1064, 1075, 1080, 1081, 1085, 1113, 1118.

7. **Heuristics, Problem-solving, and Games.**

20, 34, 37, 79, 80, 92, 95, 144, 181, 190, 249, 268, 277, 319, 346, 363, 371, 399, 423, 424, 426, 489, 496, 507, 519, 523, 546, 552, 683, 684, 735, 736, 737, 738, 739, 740, 741, 742, 743, 744, 752, 753, 799, 810, 817, 818, 819, 821, 827, 850, 851, 864, 865, 866, 895, 906, 929, 931, 964, 969, 972, 976, 980, 987, 989, 1002, 1022, 1058, 1060, 1084, 1088.

8. **Cybernetics.**

15, 18, 19, 27, 28, 32, 33, 35, 36, 41, 42, 44, 63, 75, 76, 77, 78, 81, 90, 93, 94, 109, 119, 129, 130, 149, 159, 164, 166, 178, 191, 192, 194, 196, 198, 245, 251, 252, 255, 256, 271, 292, 325, 330, 348, 349, 365, 368, 389, 402, 414, 419, 458, 493, 494, 516, 517, 547, 572, 582, 605, 606, 607, 608, 609, 612, 614, 627, 644, 660, 698, 715, 747, 772, 773, 774, 775, 776, 777, 778, 780, 785, 792, 845, 859, 863, 893, 894, 915, 922, 927, 968, 973, 974, 995, 1014, 1015, 1019, 1024, 1026, 1030, 1051, 1052, 1053, 1054, 1055, 1078, 1079, 1092, 1093, 1095, 1096, 1097, 1098, 1102, 1107, 1111, 1125.

9. **Language Processing.**

2, 52, 55, 56, 57, 64, 65, 67, 69, 70, 83, 84, 96, 100, 108, 111, 112, 113, 117, 120, 125, 128, 131, 143, 147, 150, 151, 152, 153, 154, 155, 167, 168, 169, 170, 171, 172, 173, 174, 177, 228, 234, 239, 260, 261, 263, 264,

265, 266, 288, 293, 294, 307, 314, 315, 326, 347, 357, 383, 390, 400, 404, 443, 444, 445, 448, 459, 463, 465, 466, 480, 487, 488, 495, 497, 498, 502, 535, 537, 563, 575, 581, 588, 589, 592, 594, 596, 597, 600, 602, 603, 604, 635, 648, 649, 674, 675, 693, 694, 695, 696, 697, 703, 705, 706, 711, 712, 746, 751, 759, 763, 788, 789, 790, 791, 809, 813, 831, 832, 833, 854, 868, 873, 878, 879, 900, 911, 935, 937, 938, 942, 943, 948, 949, 950, 951, 967, 996, 1001, 1007, 1016, 1017, 1039, 1041, 1059, 1061, 1070, 1072, 1073, 1074, 1086, 1089, 1091, 1099, 1114, 1115, 1120, 1121.

10. Man-Computer Symbiosis.

1, 106, 122, 123, 139, 165, 182, 204, 341, 393, 416, 447, 471, 555, 615, 661, 666, 672, 673, 758, 803, 820, 958, 1000.

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APPENDIX A

CURRENT RESEARCH PROGRAMS IN BIOLOGICAL AND ARTIFICIAL INTELLIGENCE

Following is a partial list of current investigations in the field of biological and artificial intelligence, alphabetically ordered by the facility at which the research is being conducted. The list should not be construed as a complete one. It represents only those facilities visited during the course of this project, and those facilities about which information was obtained from the investigators who were visited.

A. Investigators in the United States

Facility	Person	Current Work and Interests
Adaptronics, Inc. Annandale, Va.	R. J. Lee, L. O. Gilstrap, M. J. Pedelty	Physical laws and their biological analogues. Stochastically varying devices. Adaptive control systems.
Aeronutronics Newport Beach, Calif.	P. M. Kelly	Bionics.
	J. K. Hawkins	Self-organizing systems. Multi-aperture cores.
Air Force Cambridge Research Laboratory (AFCRL) Bedford, Mass.	H. Blum	Recognition and ordering of objects in a visual field.
	T. Kalin	Pattern recognition.
Armour Research Foundation (Illinois Inst. of Tech.) Chicago, Illinois	G. T. Jacobi	
	S. Cameron	Self-organizing systems.
Bell Telephone Labs. (BTL) Murray Hill, N. J.	L. D. Harmon	Electrical models of neurons. Automata, pattern recognition, recognition of cursive script. Biological computers.
	W. H. van Bergeijk	Auditory perception.
	E. E. David	Auditory pattern recognition, digital simulation.
Bolt, Beranek & Newman Cambridge, Mass.	J.C.R. Licklider	Speech recognition.
	T. Marill	Speech recognition.
Brain Research Inst. Univ. of Calif. Los Angeles, Calif.	T. H. Bullock	Neurophysiology.
	D. B. Lindsley	Brain organization for perceptron.
	M.A.B. Brazier	Brain structure.
	W. R. Adey	Brain mechanisms in behavior.
	J. D. French	Reticular formation.

Facility	Person	Current Work and Interest
Brain Research Inst. (continued)	A. B. Scheibel & M. Scheibel	Reticular formation.
Brandeis University Waltham, Mass.	U. Neisser	Pattern recognition.
Brookhaven Nat'l. Labs. Long Island, N. Y.	H. Quastler	Information theory, biological computers.
Burroughs Corp. Paoli, Pa.	E. L. Glaser	Symbol manipulation studies, pattern recognition, adaptive techniques.
	J. Lynch	Albert I (a perceptron-like machine).
	S. Schneider	High density packaging techniques.
	P. E. Shafer	Magnetic integrators, multi-aperture cores.
	J. Kurtzberg	Success-reinforced stochastic nets, adaptive techniques.
	R. Jayson	Teaching machines.
California Inst. of Tech. Pasadena, Calif.	R. W. Sperry	Growth of nerve circuits.
	G. D. McCann	Computer logic and applications.
Carnegie Inst. of Tech. Pittsburgh, Pa.	A. Newell) H.A. Simon)	See RAND
	W. Reitman	Information processing languages.
Convair Astronautics San Diego, Calif.	O. E. Myers	Chemical computers.
	L. J. Fogel	Decision making.
Cornell Aeronautical Lab. Buffalo, N. Y.	W. S. Holmes & H. D. Block	Perceptrons.
Cornell University Ithaca, N. Y.	F. Rosenblatt	Perceptrons, brain functions.
	J. J. Gibson	Perceptrons.
General Dynamics/Elect. Rochester, N. Y.	L. Kanal	Pattern recognition, statistical approaches.
Harvard University Cambridge, Mass.	D. H. Hubel	Visual neuronal action.
	T. N. Wiesel	Visual neuronal action.
IBM Yorktown Heights, N.Y. IBM has no "formal" program in artificial intelligence studies but encourages staff members to do research by making computer time available to staff members.	M. Kochen	Disjunctive hypothesis formation by computer.
	A. L. Samuel	Checker playing program.
	M. deV. Roberts	Storage allocations, advanced debugging multi-processing.
	H. Bohnert	Logical language for computers.

Facility	Person	Current Work and Interests
IBM (continued)	H. Gelernter	Geometry theorem proving, list processing languages.
	W. R. Uttal	Light receptor of crayfish tail, pattern of interaction between inputs and sensory system.
	M. C. Andrews	Auditory and visual pattern recognition.
Johns Hopkins Baltimore, Md.	V. Mountcastle	Touch and kinesthesis, information transmission in the nervous system.
	P. Bard	Regulation of behavior by central nervous system.
Laboratories for Electronics Boston, Mass.	---	Dynamic self-organizing pattern recognizer.
Librascope Division General Precision, Inc. Glendale, Calif.	R. Reiss	Digital simulation of biological processes.
Lincoln Laboratories Lexington, Mass.	O. G. Selfridge	Pattern recognition, Pandemonium, learning machines.
	B. F. Green, Jr.	"Baseball" program, pattern recognition.
	G. P. Dinneen	Pattern recognition.
	B. G. Farley	Neural nets, pattern recognition of electroencephalograms.
	W. A. Clark	Pattern recognition.
Melpar Corp. Falls Church, Va.	E. B. Carne	Artron.
Mental Health Res. Inst. Ann Arbor, Michigan	R. W. Gerard	Information processing in the brain, neurophysiology, cybernetics.
	W. J. Horvath	Input-overload, information processing in neurons, "Frog's Eye."
	A. Rapoport	Mathematics of social sciences, mathematical models of learning and group dynamics.
	J. G. Miller	Information processing in the brain.
	M. Flood	Computer applications, operations research.
	P. Fitts	Information handling, input-overload.
	L. Uhr	Pattern recognition and concept formation.
	J. Gyr	Computer simulation of logic tasks.

Facility	Person	Current Work and Interest
Mental Health Res. Inst. (continued)	B. Peretz	"Frog's Eye."
	G. Rothschild	Taste preference in rats, fixation of behavior in starfish.
	S. Fox	Sensory integration, visual and auditory functions and their interrelationships.
Mississippi Southern Col. Hattiesburg, Miss.	R. Peters	Auditory parameter determination.
Mass. Inst. of Tech. (MIT) Cambridge, Mass.	N. Wiener	Cybernetics.
	W. S. McCulloch	Neurophysiology, information transmission in nervous system, logic and inductive inference, cybernetics.
	J. Y. Lettvin	Neurophysiology, "Frog's Eye" studies.
	J. Cowan	Neural nets, logic.
	M. C. Goodall	Logic, cognitive processes.
	M. Minsky	Neural nets, brain models, pattern recognition.
	L. Sutro	Models of visual space.
	W. Rosenblith	Auditory phenomena, sensory communication.
	J. McCarthy	List processing languages, recursive function theory.
	L. Stark	Servomechanisms in visual system.
	M. Halle	Hearing, sounds in speech.
National Biomedical Res. Foundation Silver Spring, Md.	R. S. Ledley	Feasibility study of a billion gate computer.
National Cash Register Dayton, Ohio	N. Nisenoff	Neuron element studies.
National Inst. for Health (NIH) Bethesda, Md.	R. Livingston	"Noise sandwich" theory of nervous activity. Studies of central nervous system.
	P. Nelson	Spinal cord research--taking sections of various levels of spinal cord to study changes after stimulation.
	R. Marimont	Visual perception--models of brightness perception.
	W. Rall	Mathematical theory of physiology of dendrites.
Office of Naval Research Washington, D. C. (ONR)	M. C. Yovits	Perceptrons, information theory, nets, storage in computers.

Facility	Person	Current Work and Interests
Penna. Res. Assoc. Philadelphia, Pa.	R. L. Boyell	Associative memories.
Purdue University Lafayette, Indiana	Ming-kuei Hu	Visual perception.
	King-sun Fu	Decision models for recognition.
RAND Corp. Santa Monica, Calif.	A. Newell*) H. A. Simon*) J. C. Shaw)	General Problem Solver (GPS), Information Processing Language V (IPL-V), models of human thought.
	E. Paxson	Simulation of nervous system.
	R. Bellman	Chemotherapy model, theory of control processes.
	E. DeLand & G. Dantzig	Model of human respiratory system.
Raytheon Norwood, Mass.	R. P. Witt	Cybertron, learning machine.
RCA Research Labs. Princeton, N. J.	E. E. Loebner & H. Belar	Auditory phenomena.
	K. K. Maitra & S. Amarel	Neural nets, synthesis of automata.
Space-General Corp. Glendale, Calif.	R. M. Stewart	Homogeneous logical nets.
Stanford Research Inst. Menlo Park, Calif.	C. Rosen & A. E. Brain	Selective attention mechanisms, perceptrons.
	A. B. J. Novikoff	Integral geometry for pattern recognition.
	H. D. Crane	Neuristors.
Stanford University Stanford, Calif.	K. Pribram	Models of behavior.
	B. Widrow	Adalines, adaptive switching circuits
Syracuse University Syracuse, N. Y.	S. Goldman & W. Baum	Multidimensional information theory, problem of shape.
Sylvania Elect. Systems Waltham, Mass.	H. Yilmaz & D. B. Brick	Models for color perception.
System Development Corp. Santa Monica, Calif. (SDC)	F. Marzocco	Statistical learning models for intelligent machine behavior.
	P.R. Bartram & G. P. DeFlorio	
	C. Vossler & L. Uhr (consultant)	Pattern recognition and concept formation.

*Now at Carnegie Institute of Technology

Facility	Person	Current Work and Interests
SDC (continued)	R. F. Simmons & S. Klein	Synthex--synthesis of human language behavior.
	S. Ginsburg & T. Hibbard	Theory of mathematical machines and automata.
	A. Hormann & L. E. Travis	Problem solving and complex learning.
University of Arizona Tucson, Arizona	W. F. Caldwell, F. Glaesser & J. L. Stewart	Model cochlea, analog ear.
	A. P. Sage, Jr. & J. L. Melsa	Biological clock.
University of Calif. Berkeley, Calif.	H. Bremerman	Artificial intelligence.
	E. A. Feigenbaum	Elementary Perceiver and Memorizer (EPAM), General Problem Solver (GPS), Information Processing Language (IPL).
	J. Feldman	Binary choice experiment, GPS, IPL.
University of Calif. Los Angeles, Calif.	E. B. Hunt	Concept formation.
	G. Estrin	Computer design.
	C. Chang	Mathematical machines.
	C. B. Tompkins	Computer applications.
University of Chicago Chicago, Illinois	N. Rashevsky	Mathematical biophysics.
	P. H. Greene	Mathematical biophysics.
University of Illinois Urbana, Illinois	H.M. von Foerster	Self-organizing systems, biological computers, cybernetics.
	W. R. Ashby	Cybernetics, homeostasis, intelligent machines, information processing techniques.
	M. L. Babcock	Speech invariants, extensions of McCulloch-Pitts neuron theory.
	G. Zopf, Jr.	Biological computers, self-organizing systems.
	L. Lofgren	Self-repair.
University of Michigan Ann Arbor, Michigan	W. Crichton	Cell assembly simulation.
	J. Holland	Mathematical machines.
	A. W. Burks	Mathematical machines.
	W. P. Tanner, Jr.	Decision making, pattern recognition.
	E. L. Walker	Learning theory.
	M. Bates	Biology.

Facility	Person	Current Work and Interests
University of Minnesota Minneapolis, Minn.	O. H. Schmitt	Biophysics.
Univ. of N. Carolina Raleigh, N. C.	J. W. Carr, III	Computer programing and applications
University of Wisconsin Madison, Wisconsin	C. N. Davidson & D. R. Smith	Neural nets.
Walter Reed Army Inst. of Research Washington, D. C.	D. M. Rioch, J. V. Brady, P. Galambos	Neurophysiological research.
Wright-Patterson AFB Dayton, Ohio	Maj. J. E. Steele	Bionics, speech recognition, neuron models.
	M. B. Mitchell, C. Owinn, Lt. A. Bell, L. Whitford	Bionics, Artron, neuron models, pattern recognition, self-organization, biological clock.
Zator Co. Cambridge, Mass.	C. N. Mooers	Information retrieval.
	R. J. Solomonoff	Inductive inference.

B. Investigators in Other Countries

Facility (or country)	Person	Current Work and Interests
Albany College Park Village East, NW I London, England	J. Z. Young	Neurophysiology, studies of octopus.
Australian National Univ. Canberra, Australia	J. C. Eccles	Neurophysiology.
Barth Foundation Locarno (Muralto) Switzerland	C. A. Muses	Biosimulation, self-organizing systems.
Cambridge University Cambridge, England	R. L. Gregory	Localising function in central nervous system.
	H. B. Barlow	Neurophysiology.
Hebrew University Jerusalem, Israel	Y. Bar-Hillel	Information retrieval, logic, mechanical translation.
Imperial College University of London London, England	C. Cherry	Information theory, communication, speech recognition.
	D. Gabor	Information theory, cybernetics, hearing.

Facility (or country)	Person	Current Work and Interests
McGill University Montreal, Canada	D. O. Hebb	Psychology, behavior.
	P. M. Milner	Behavior theory.
Montreal Neurological Inst. Montreal, Canada	W. Penfield	Brain research, neurophysiology.
National Physical Lab. Teddington, Middlesex England	A. M. Uttley	Conditional probability machines, mechanization of thought processes.
	S. Papert	Logical nets, redundancy in logical nets, conditioned probability computers.
Scuola di Perfezionamento in Fisica Teorica é Nucleare Naples, Italy	V. Braitenberg	Cybernetics, mathematical neurophysiology.
	F. Laurin	Cybernetics, synaptic transmission, mathematical neurophysiology.
System Research Ltd. 20 Hill Rise Richmond, Surrey, England	G. Pask	Concept formation, teaching machines, cybernetics, adaptive machines, self-organizing systems.
United Steel Cos., Ltd. Sheffield, England	S. Beer	Cybernetics, operational research.
University College of North Staffordshire Keele, Staffordshire England	D. M. MacKay	Information theory, artificial intelligence, information transmission in neurons, pattern recognition, cybernetics.
Univ. of Saskatchewan Saskatoon, Saskatchewan Canada	K. H. Reid	Conditional probability computers.
England	F. H. George	Learning theory, cybernetics, theory of behavior, probabilistic machines. perception.
England	D. A. Scholl	Cerebral cortex, neurophysiology.
France	P. deLatil	Cybernetics, thinking machine.
France	M. P. Schutzenberger	Cybernetics, linguistics. (Currently at Research Lab. of Electronics, MIT.)

APPENDIX B

RELATIONSHIP OF JPL SUBJECT CATEGORIES TO THE CATEGORIES USED IN THIS REPORT

	JPL Search, Vol. I	JPL Search, Supplement
1. Feasibility of Simulating Thought Processes by Machine	Feasibility of Simulating Thought Processes by Machine	- -
2. Mathematical Machines, Automata, and Logic	General Automata	General Computers and Automata
3. Neurophysiological and Brain Function Research	(Models and) Theories of General Nerve Transmission; Electrical Study of the Brain and its Functions; Physiology and Anatomy of the Brain	Electrical Study of the Nervous System; Physiology and Anatomy of the Nervous System
4. Neurophysiological Models: Simulated Neurons, Neural Nets, and Organisms	Models (and Theories) of General Nerve Transmission; The Perceptron	Models of Nerve Elements and Transmission; The Perceptron
5. Pattern Recognition and Perception	Models and Theories of Perception; Machine Perception, Mapping	Models and Theories of Perception; Machine Perception, Mapping
6. Theory and Models of Learning, General Thinking Processes, and Behavior	Models and Theories of General Thinking Processes and Behavior; Intelligence Testing; Machine Learning and Memory; Models and Theories of Learning; Models and Theories of Memory or Recall	Models and Theories of General Thinking Processes and Behavior; Intelligence Testing; Machine Learning and (Adaptive Mechanisms); Models and Theories of Learning; Models and Theories of Memory or Recall
7. Heuristics, Problem-solving, and Games	Decision Making by Machine; Models and Theories of Decision Making	Decision Making by Machine; Models and Theories of Decision Making
8. Cybernetics	- -	Machine Learning and Adaptive Mechanisms
9. Language Processing	Automatic Translators; Information Theory	Logical Nets and Languages; Automatic Translators; Storage and Retrieval; Information Theory
10. Man-Computer Symbiosis	Man-Computer Symbiosis	Man-Computer Symbiosis

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