A COMPUTER PROGRAM TO FACILITATE THE STUDY OF MEANING IN A COGNITIVE STRUCTURE

A Thesis

Presented to

the Faculty of the Department of Computer Science

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Jeffrey N. Wilkes

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ABSTRACT

A discussion of the merits of interdisciplinary cooperation between researchers in artificial intelligence and psychology is presented along with a computer program which exhibits this type of cooperation by being firmly based in the developmental theories of Jean Piaget. The program is designed to facilitate the investigation of the representation of meaning in a cognitive structure. The program is provided with a set of simple sensory-motor facilities with which it interacts with a simulated environment and in doing so progresses intellectually through the creation of a cognitive structure. This structure interrelates the experiences of the simulated organism and directs the behavior of that organism. A preliminary structure is investigated through experimentation with the program, and the results of that investigation are discussed. These results are used in the creation of a second version of the structure. This new structure is investigated, and preliminary results are discussed. Improvements and future experimentation suggested by the results from the second version of the structure are discussed.

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INTRODUCTION

Section 1 - Purpose

The purpose of this paper is twofold: first, to present a case for more interdisciplinary co-action among those working in the fields of artificial intelligence and psychology; second, to present a computer model which is a step towards realizing an artificial intelligence system which takes psychological theory into account.

Section 2 - Computer Science and Artificial Intelligence

In the early years of the development of digital computers, the emphasis was on the development of hardware. The primary goals were to develop a machine that had the capability to handle mathematical and logical operations repetitively, that had a large memory, and that had the capability of efficiently communicating information to and from man in a form usable by both man and machine. The machine was required to be of low cost and high reliability and, as time passed, was required to become progressively faster and able to handle progressively more complex operations. As these goals were approached emphasis shifted to software. In recent years this emphasis on software has been concerned with development of capabilities to optimize the use of the available hardware through scheduling and managing of resources, to maximize the speed and efficiency of computation by development of more sophisticated logical approaches to problem solving, to maximize the transfer of usable information between man (or men in the case of time sharing) and machine in a timely manner by the development of better languages and I/O software, and to maximize the use of memory by development of more sophisticated storage and retrieval techniques.

Where does artificial intelligence fit into this picture? In his book Semantic Information Procession [1], Minsky says, "The third approach, the one we call Artificial Intelligence, was an attempt to build intelligent machines without any prejudice toward making the system simple, biological or humanoid.' [1, p. 7]." As was implied earlier, the main effort in computer science has been and is directed to increasing the efficiency, effectiveness, and usefulness of the computing machine as it exists today. Even hardware breakthroughs are primarily in this direction. Artificial intelligence is working to add a new basic capability to the machine, the ability to perform independent and original thought. The computing system today has a tremendous capability, but it is a dependent and rigidly directed capability, dependent upon the directions of the programmer. Artificial intelligence does not profess interest in improving the abilities of the computer to work in a dependent and directed fashion, but in adding a most important capability, intellect.

Section 3 - Artificial Intelligence and Psychology

What is the only completely operational, ultimately reliable, and fully useful thinking machine in existence? The answer is so obvious as to be trivial: man. If it is the goal of artificial intelligence to develop an intellect in a thinking machine, what is the obvious source of information concerning what intellect is--what makes up the capability? The same obvious answer. Finally, what is the standard by which intelligence is measured or even defined? Again, man. For these reasons, it is the viewpoint presented here that one of the subgoals of artificial intelligence must be the development of an understanding of the human thought processes which are involved in solving a problem which is to be addressed by a computer program. Minsky says:

> Even if simplicity of initial structure was to be an ultimate goal, one might first need experience with working intelligent systems (based if necessary on ad hoc mechanisms), if one were to be able to design more economical schemes. [1, p. 8].

The plea of this paper is commensurate with Minsky's thought; experience with working intelligent systems is needed, not just in the case of self-organizing systems as Minsky was referencing, but in all areas concerning artificial intelligence.

Does this mean that there can be no improvement over these processes, that the final goal of computer science is to duplicate human thinking in a machine and simply speed it up? This conclusion does not follow. What does follow is that a logical starting place in solving a problem by computer that requires intellectual activity, is in understanding how the human thought processes which can solve that problem work. No one could assert that the human method is the best that can be achieved and that only improvements in speed are possible. They are, however, the best available and the standard for judgment, and as such are deserving of consideration and, in some cases, copying.

If a subgoal of artificial intelligence is to understand human thought processes to some extent, this means that there is some overlap with the field of psychology. This is the point of this discussion. Psychology has as one of its goals the understanding of human thought processes, and, since it is a much older discipline, it stands as a great resource in the area of human intelligence. Psychology through experimentation has developed a methodology to studying intelligence and has accumulated a wealth of information on problems involving intellectual activity. In addition, psychological research has led to the development of substantial theories which attempt to describe the essence of human thought processes. It seems logical then for artificial intelligence to look to and work with psychology in trying to understand human intelligence and in developing computer programs which express some form of intellect.

The benefits of such co-activity are not one-sided. The success or failure of programs based on psychological theories could aid in the evaluation and development of the theories themselves. Since programs by nature are easily variable, elaboration or modification of theory could be easily effected and evaluated using computer modeling techniques. Programs are more controllable and not subject to the environmentally introduced variables that plague classical psychological experimentation. As W. A. Reitman said in his book, Cognition and Thought:

> In an information-processing model, we can state, manipulate, and deduce implications from our theories in a way that is at once sure, unambiguous, and yet independent of operations relating the theory to data on human behavior [2, p. 14].

And finally, the very process of programming develops a greater and more complete understanding of that which is programmed. One of the problems which any field of study faces is the way in which its theories can be expressed. Without the rigorous language of mathematics the theories of the physical universe could not be understood. As mathematics, a computer's language describes rigorously that which is programmed. In programming, all discontinuities and logical errors must be discovered or the program will either not run or not give the expected results. As Reitman said:

> With verbal models, it is practically impossible to be sure that conclusions follow only from explicit assumptions and that they in no way depend upon "unprogrammed" elements entering informally into the argument [2, p. 14].

Unfortunately, interdisciplinary co-action between research in artificial intelligence and psychology has been minimal. In general, psychology uses much more computer science than computer science uses psychology, but this is still not as it ought to be. The majority of work in artificial intelligence is being done without regard to the great resource represented by psychology. The work is typically based on a common sense approach or at best a limited amount of psychological-like experimentation, and theory developed by the individual computer scientist without regard to what might be potentially valuable psychological background. Even where the researchers are knowledgeable with psychological theory, there is typically no explicit attempt to apply that theory. This is at best a duplication of effort and at worst a completely invalid approach. These programs perform well for the most part and give in some cases what might be debatable signs of intelligence, but a very rudimentary level of intelligence. As a collectivity, however, they do not present a unified logical intellectual system.

On the other hand, psychologists for the most part continue in traditional methods when the capabilities afforded by computer science have such tremendous potential.

There have always been exceptions to rules, and there are growing numbers of exceptions to this attitude. The work of Kenneth M. Colby is a prime example of the application of computer science to psychological work [3]. Colby's work is centered on the development of an artificial belief system which can interact with human subjects and construct a belief structure which is analogous to that of the subject. One example of how a psychologist might use this structure is in developing an approach to treatment. The work of Robert P. Plummer is an example of psychological theory in use by a computer scientist. Plummer's work involves the development of a model which interacts with a simulated environment to investigate the development of abilities in a computer system similar to the development of hand and eye coordination by a child in the early stages of his development [4].

Plummer designed his program based on the developmental theories of the Swiss psychologist, Jean Piaget.* Both of these programs are enjoying a measure of success.

Section 4 - The Paper

At the beginning of these comments it was stated that one purpose of this paper was to present a case for more interdisciplinary co-action between artificial intelligence and psychology. The previous discussion has been presented to indicate why this type of co-action would be beneficial to both groups. Chapter 2 will introduce one psychological theory, the developmental theory of Jean Piaget--the theory on which the remainder of the paper is based. Chapter 3 will be

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*Plummer's model shows some clear similarities to the model presented. The differences between the two programs will be discussed in Chapter 6.

a short survey of selected artificial intelligence programs which are related to the model which will be presented in Chapter 4. Some of the psychological implications of these programs (relative to Piaget's theory) will also be discussed in Chapter 3. Chapter 4 will describe a model which is intended to apply Piaget's theory to solving the problem of representing meaning in an artificial intelligence system. Chapter 5 will discuss the implementation of the model, the results for experimenting with the program, and problem area observed. Chapter 6 will discuss the consistency of the model with Piaget's theory, the difference between it and the other model discussed, and the future of the program. The appendices contain detailed pictorial definition of the different structure utilized by the model and a listing of the programs which make up the model.

Chapter 2

THE THEORY

Section 1 - Piaget

The psychological background for the model to be described and for the remainder of this paper is the theory of developmental psychology developed in Jean Piaget. Piaget is a Swiss psychologist who, with his associates, has been working and publishing findings on the development of cognition in children since 1927. Piaget's technique is built around observation of a subject's environment and behavior, development of a hypothesis about the structure that underlies that behavior, and testing that hypothesis by altering the environment, by presenting the problem differently, or by suggesting a response to the subject which conflicts with the hypothesis. Piaget's work has become more widely known in recent years due to its consistency with contemporary views of the brain as an information processing system, and because of the availability of more information about his work. The lack of information about Piaget's work in this country is indicated by the fact that even though he has been publishing his work since 1927, the first concise and complete treatment of his theory was not available in the United States until 1963 when J. H. Flavell published his book [5].

In describing Piaget's work, J. L. Phillips, the author of The Origins of Intellect--Piaget's Theory, said:

> In any case, Piaget's observations and formulations are today a definite focus of theoretical and professional interest in psychology. The theory is cognitive rather than associationistic; it is concerned primarily with structures rather than content--with how the mind works rather than with what it does. It is concerned more with understanding than with prediction and control of behavior [6, p. 10].

Section 2 - Piaget's Theory

Piaget's theory is based on the concept of invariant functions which act on a dynamic structure. Structural change is what is known as cognitive development.

The theory requires that the subject interact with an environment. This interaction supplies the input to the cognitive system.

The two basic invariant functions are organization and adaptation. Organization is the function which relates to the methodology of an act, while adaptation is the dynamic aspect of organization--the function which varies the methodology of the act. Adaptation and organization are tightly woven together. An underlying organization is a prerequisite to adaptation. Piaget stated:

> Organization is inseparable from adaptation. They are two complementary processes of a single mechanism, the first being the internal aspect of the cycle of which adaptation constitutes the external aspect. . . . It is by adapting to things that thought organizes itself and it is by organizing itself that it structures things [7, pp. 7-8].

Adaptation is made up of two cognitive operators which are called assimilation and accommodation. These invariant operators are continually applied to the cognitive structure to produce a modified structure. These operators are predefined and in operation from the very first.

Assimilation is defined as occurring whenever the system utilizes something from the external environment and incorporates it into the cognitive structure. An example commonly given for this is the ingestion of food. The food is taken from the environment, changed in a chemical process, and incorporated into the body. This is a form or assimilation. J. L. Phillips describes assimilation by saying,

> In sum, the input is changed to fit the existing "mediating" processes. The organism is always active, and its cognitions--even perception of its immediate surroundings--are as much a function of this activity as they are of the physical properties of the environment [6, p. 8].

Accommodation is defined as the mechanism by which the mediating processes are being changed by the input. In the example of ingestion, the change of the body chemistry which is required to allow the body to accept and use the food is a type of accommodation.

There is never pure accommodation or assimilation. Both are always present to some extent in every cognitive process. Behavior is considered most adaptive when they are in balance. Temporary imbalance is defined as imitating when accommodation is more active than assimilation, and playing when assimilation is the more active. An example given by Phillips is a baby looking at a rattle and picking it up. The structure relates the means (looking, reaching, grasping) and the end (sensory stimulation) [6, p. 7]. The basic structural unit is called the schema. Flavell gives a preliminary definition:

> A schema is a cognitive structure which has reference to a class of similar actions sequences, these sequences of necessity being strong, bounded totalities in which the constituent behavioral elements are tightly interrelated [5, pp. 53-55].

Phillips describes schema by stating, ". . . they form a kind of framework onto which incoming sensory data can fit--indeed must fit; but it is a framework that is continually changing its shape, the better to assimilate those data [6, p. 9]."

Unlike many of his contemporaries, Piaget believes that there is a built-in need for cognitive system to function. That is, there is a built-in motivation to adapt. Piaget does not deny that the primary physical drives of hunger, thirst, sex, etc., motivate cognition, but he does feel that there is a necessary and sufficient drive that is inherent in the cognitive system. In Flavell's words:

> The cognizing organism is neither pulled from without by external stimuli which, in poultice fashion, draw or "elicit" reactions from him, nor is he primarily pushed from within by imperious bodily needs of which cognition is a mere instrumentality (as in early Freudian theory). Rather, the "need" to cognize is contained in and almost synonymous with intellectual activity itself, an assimilatory activity whose essential nature it is to function [5, p. 80].

Another important part of the theory is the Piagetian concept of structural equilibrium. As Phillips states: "It was the inspiration for the theory in the first place and remains its overarching principle [6, p. 10]." The concept is that the cognitive structure is continually moving towards a state of equilibrium at which point it is better defined--sharper and closer to complete equilibrium--but it still contains discontinuities which cause it to progress to another state of relative equilibrium. Piaget has listed these states of relative equilibrium (stages), and asserts that they are universal in human development. These stages always occur in the same in the development of a child, but do not always occur at the same age. At equilibrium accommodation and assimilation are in balance; that is, behavior is completely adaptive. As Flavell states:

> In short, intelligent, functioning, when equilibrium obtains, is made up of a balanced recipe of about equal parts of assimilation and accommodation. Through this fine balance, a both realistic (accommodation) and meaningful (assimilation) rapport between subject and object is secured [5, p. 65].

Thus, by the internal drive of cognition for cognition's sake and the natural progression toward structural equilibrium, the organism develops, aided by the natural physical drives related to the organism's physical needs and the surrounding environment.

The next portion of Piaget's theory which will be treated here is the make-up of meaning. This involves the concept of models of reality. These models of reality are based on the existing structure. For example, the meaning of the word <u>mountain</u> may be based on the sensory-motor schemata of climbing a mountain long before the symbol (i.e., the word <u>mountain</u>) is related to that schema or to other symbols which form a semantic definition. Thus, meaning is based on structural organization of schemata which constitutes a model to the organism in terms which are significant to the organism. Piaget states:

> No one has ever "seen" a mountain or even an inkwell from all sides at once in a simultaneous view of their different aspects. . . . In order to perceive these individual realities as real objects, it is essential to complete what one sees by what one knows. Concerning the "signifier," it is nothing other than the few perceptible qualities recorded simultaneously and at the present time by my sensory organs, qualities by which I recognize a mountain and an inkwell. . . . Here again the signifier refers to a system of schemata (of vision, prehension, hearing, sucking, etc.) and only has meaning, even with regard to the precise image given through perception, in relation to the whole of the system [7, p. 190].

It can be seen then that a model of some physical reality is developed in the cognitive structure based on the subject's perception of that reality through his senses. The more the subject interacts with the environment and the more the structure is changed through adaptation, the closer the internal model comes to fully describing the reality.

Finally, Piaget's theory

> . . . accepts with the theory of groping the interpretation that acts originating in the subject either drop out, get established as is, or get established with correction, as a function of their success in coping with objects. However, such gropings with after-the-fact selection by reality are never initiated in complete independence from the milieu; all present cognitive behavior is constructed on the base of past accommodatory experience with the outside world and has some reality-oriented aim [5,p. 77].

To sum up this brief discussion of some of the major points of Piaget's theory which relate to modeling of intellectual development, consider Flavell's statement: "We do not inherit cognitive structure as such; these come into being only in the course of development. What we do inherit is a modus operandi, a specific manner in which we transact business with the environment [5, p. 43]."

Section 3 - Why Piaget's Theory

In utilizing Piaget's theory, it is not the intention of this paper to endorse that theory as the best and most correct available. Certainly that is completely without the realm of a paper on computer science. In pursuing the idea of utilization of psychological theory in artificial intelligence work it is hoped that all psychological work will be consulted that concerns the problem under consideration.

Piaget's theory was utilized in this paper for three general reasons. First, Piaget's theory was familiar to the writer. Piaget's theory was introduced in graduate level artificial intelligence courses at the University of Houston, Houston, Texas, computer science department. Second, Piaget's theory was directed towards the developmental side of cognition.

This was the area of interest of the writer. Third, Piaget's theory is structured in such a way as to be very consistent with the capabilities presently utilized in many artificial intelligence models (even though these models were not designed with Piaget in mind).

Consider some examples of the consistency of Piaget's theory with artificial intelligence. Piaget's ideas about structure seem very consistent with the type of structures utilized in contemporary artificial intelligence programs. That is, a structure which is made up of a fairly rigid framework (schemata) into which incoming sets of related information is placed and then related by the structure to other stored sets of information. The structure grows and changes with the introductions of more information which is incorporated into more interrelated schema. This is very much in agreement with the net-like list structures typically used in artificial intelligence program. Some specific examples will be discussed in Chapter 3.

The concept of invariant predefined operators which are applied to the cognitive structure and effect change and growth of that structure certainly fits into contemporary model design. In any model, the incoming information must be changed into a form which is useful to that model and fitted into the structure (assimilation); likewise, when that information is placed into the structure, the structure itself must change to accept that information (accommodation). This is consistent with Piaget even if it only amounts to translation of incoming information to a structured format and storing that format in a list (assimilation) by changing pointers to fit that format into the list (accommodation). In contemporary artificial intelligence as in Piaget's theory, these operators are predefined and invariant, while the structure is variable.

Piaget's concept of the importance of the primary physical drives in motivation of cognitive activity is also consistent with (and even comforting to) contemporary artificial intelligence work which typically lacks any motivation based on physical needs. Piaget indicates that it is not necessary for for a program to model physical drives since this type of motivation is a "subset" of a more general mechanism which he calls "the need to function."

The idea of internal models of reality is consistent with artificial intelligence work. In every program which attempts to give meaning to reality, the meaning is basically formed by an internal model. Unlike Piaget's theory, however, these models typically are high level models; that is, the models are made up of units of information higher than Piaget's sensory-motor perception information. Normally, models utilize words, symbols, and numbers in giving meaning to reality. The meaning consists of the interrelationship among words, numbers, or symbols as defined by the structure. But, even though at a different level than Piaget's concepts, they are internal models just the same.

The idea of groping is often utilized in developmental or learning programs. This concept of Piaget's is normally recognized as a necessary part of a learning program if that program is to have the ability to discover new things to be added to its structure.

It can easily be seen that the terminology and general concepts of Piaget parallel many contemporary artificial intelligence efforts in many ways, usually by change. Some specific examples will be presented in the next chapter. There are some very important differences, however, between Piaget's theory and contemporary artificial intelligence programs. It is some of these differences that are discussed in subsequent chapters and are treated by the model presented in Chapter 4.

Chapter 3

A SURVEY OF RELATED WORK

The purpose of this chapter is to discuss some contemporary artificial intelligence programs which bear a resemblance to Piaget's theory and which relate to the program presented in Chapter 4.* In all but one case, these programs were designed without any intention to utilize Piaget's theory. But in each case the program fits some Piagetian concepts. Why? The only answer is because those facilities work. These programs fall into three general categories: processors, learners, and interactive learners. Example programs which are typical of each category will be discussed in detail.

Section 1 - Processors

Processors are programs which utilize a cognitive structure in some form of information processing, but exhibit no learning. The structure is predefined to the program. Since learning is not intended, those attributes of Piaget's theory which concern development are lacking. Processors are

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*The relationship between the programs discussed here and the program presented in Chapter 4 will be made clearer in Chapter 4.

designed to solve a variety of problems. Processors include question-answering programs, semantic processors, analogy solvers, some game playing programs, and others. Two examples of processors are Quillian's semantic memory [1, pp. 227-270], and ARGUS [2, pp. 203-226].

Quillian's Semantic Memory

In Quillian's semantic memory, meaning is defined in the relationship among words in a highly interconnected structure. Different types of interconnections or links determine the type of interrelationship between the words linked. An example of this structure is given in Figure 1. By interpreting the different types of links, the meaning of words can be determined. Figure 1 is a structure which represents Webster's definition of mountain as "any part of a land mass which projects conspicuously above its surroundings [8]." "Mountain" is linked to "mass" by a link which indicates that "mountain" is a subclass of "land mass." "Land mass" is modified by "above." "Above" participates in a link which indicates that "above" specifies the manner by which "mass" (indicated by "A" because it is used more than once in the structure) is related to "surroundings." That is, "mass" is "above" "surroundings." "Above" is further modified by "projects," and "projects" by "conspicuously." Therefore, "mountain" is that subclass of "land mass" which "projects conspicuously above surroundings." Since "surroundings" is modified by "mass" ("=A" again), it can be determined that the surroundings referenced are the land mass's surroundings. The dotted lines shown connect the words used in this structural definition of mountain to more structure which defines those words.

Quillian has written a program which uses this structure in comparing and contrasting words. Two words are given as input, and the program searches through the structure until an intersection between their schema is located. The program traces the path between the words via the intersection. This path is formatted into crude English statements and outputted to the experimenter. This path description describes the relationship between the two words.

It can be seen that Quillian utilizes schema which is related to other schema to provide a Piaget-like cognitive structure which defines the program's perception of reality. The schema is, as in Piaget's theory, a framework into which incoming information fits. The framework in this case is a structure of different types of relational links. Although the program does not learn and therefore has no adaptation facility,

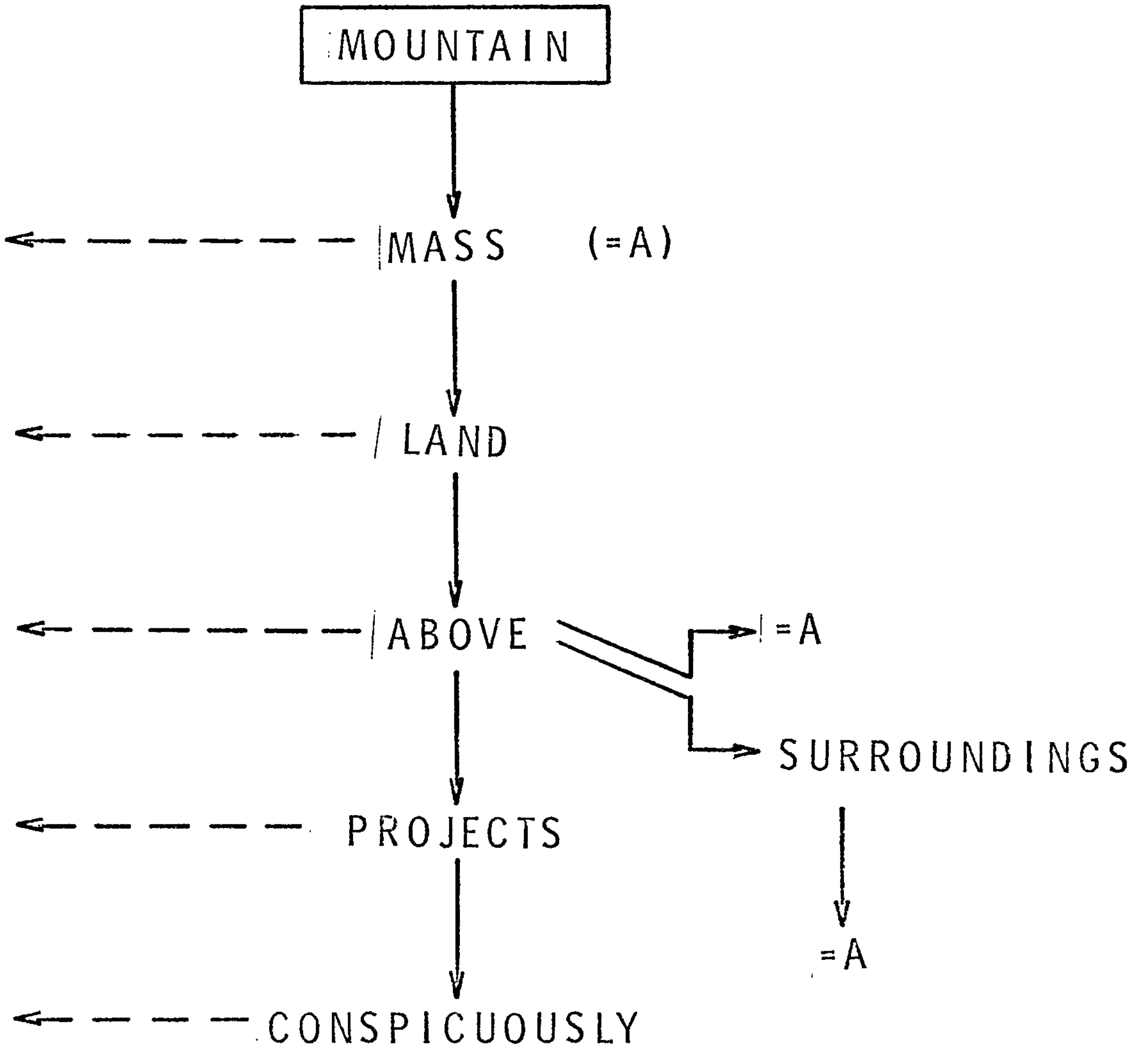

FIGURE 1

EXAMPLE SEMANTIC MEMORY

it would seem that if learning were to be added, it would be implemented in a manner consistent with the adaptive concepts of Piaget. Some facility would be required which would change the incoming information into the schema of linked words and add that schema to the structure (assimilation). Likewise, the structure would have to change existing links, add new links, and add nodes to accept that new schema (accommodation).

No physical drives are present in Quillian's program. The program's behavior is simply "wired-in," much in the way that Piaget discusses the "wired-in" need to function.

Although Quillian utilizes a Piaget-like structure and gives meaning by an internal model of reality as perceived by the program (in this case words related to other words), this system does not relate the schema to reality in the manner which Piaget intended. There is no facility to relate those words to the physical reality of those words. Figure 1 indicates what the word mountain means to Quillian's program. The word only has meaning in the way it relates to other words. There is no relation to what mountain means to the program itself in physical reality. Piaget requires that mountain not only be defined in a semantic way, but through a sensory-motor perceptual model as well. For this to be possible, the system must be able to interact with a physical environment and gain understanding of the components of that environment in terms of how it perceives that component and how it can affect that component. This is the missing facility which causes the greatest inconsistency with Piaget.

ARGUS

Reitman's ARGUS is a program which was designed with the goal of making a system sensitive to the information it is processing. That is, its goal is to give the information some meaning to the system so that alternatives can be assessed based on the desirability of the alternative to the system. The system was also designed to possess a form of parallel processing, an ability to be interrupted or distracted from one process by another with the ability to return to the original process, and the facility to forget. Reitman felt that these facilities more accurately simulated the human process than programs like GPS [9, pp. 207-216] and LT [9, pp. 109-133] which progressed single-mindedly toward a goal without any sensitivity to what is being processed.

In order to accomplish these goals, Reitman created a cognitive structure of "active" elements. This structure not only defines the relationship between semantic elements, as in

Quillian's semantic memory, but also indicates a relative strength of each association and a current state for the element. The current state of the element and strength of the relationship are dynamic and make up the active part of the elements. The current state of the element consists of five parameters which define how active the element is (i.e., how much it is in use), the level of activity above which the element is to "fire" (i.e., affect other elements and come to the attention of the program), and how much effect that element will have on others when it fires. Although the contents of the structure are dynamic, like Quillian's program, the structure itself is not dynamic and does not change. It is predefined and given to the program by the experimenter. Figure 2 shows a sample of the structure used by ARGUS. "Snow" is related to "white" by a link which indicates that "white" is an attribute of "snow." The strength of this link is low--equal to 1. "Snow" has a state equal to W and "white" has a state of X. The link between "snow" and "cold" is also an attribute link, but this time the strength is greater. "White" and "black" are related in the same way as "cold" and "hot" are related--they are opposites.

ARGUS is given an analogy problem of the form A:B::C: (W, X, Y, or Z). ARGUS must determine which of the choices of

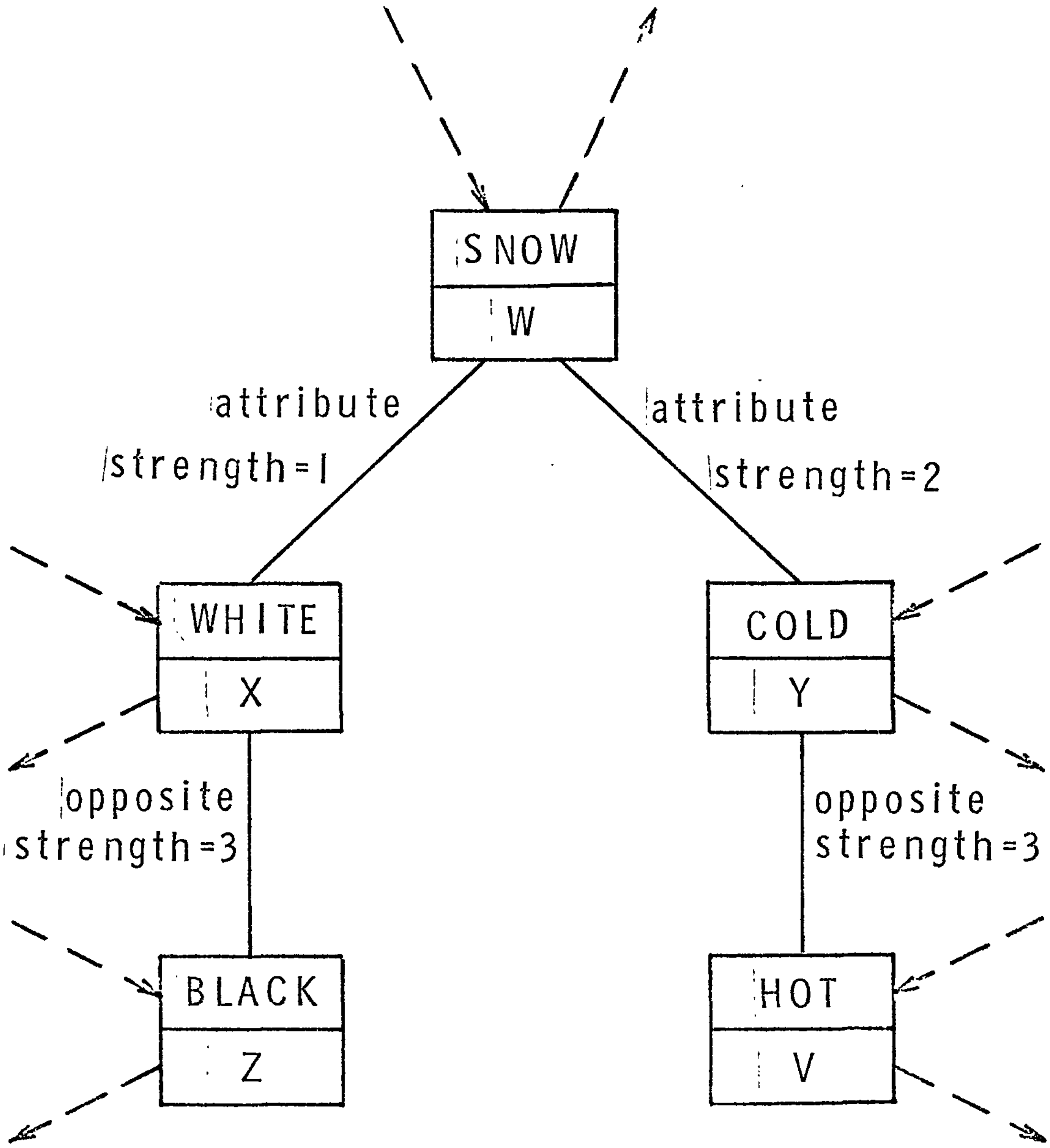

FIGURE 2

TYPICAL ARGUS STRUCTURE

W, X, Y, or Z is related to C in the same way B is related to A. ARGUS searches the structure modifying the states of the various elements of the structure which are accessed in the search. If an element reaches the proper level of activity, it will fire, and in doing so it will affect other elements, possibly causing them to fire spontaneously. The element that fires should be the element which contains the correct answer to the problem presented.

It is quickly seen that the comments made concerning Quillian's program also apply to ARGUS. The information is maintained through schema which is related to other schema. In this case the schema is more complicated due to the active parts of the structure. The schema interrelated to other schema form a structure which defines the information in terms of an internal model. Unlike Quillian's semantic memory, however, Reitman's structure includes facilities which attempt to relate that which is stored to the program through the idea of active structure and elemental firing. The words are related to one another, and to the system through the effect that one element can have on the rest of the structure. However, this is still not the relationship that Piaget would wish. ARGUS does not interact with its environment, and therefore cannot develop the sensory-motor model of the components of its environment that Piaget's theory requires.

As in Quillian's program, learning in ARGUS would also require structural change through a form of assimilation and accommodation. And as in Quillian's program, no physical drives exist--once again the program's motivation is "wired-in."

Section 2 - Learners

Learners are programs which are designed to develop through changes to a cognitive structure. An excellent example of this type of program is EPAM [9, pp. 297-309].

EPAM

Feigenbaum's Elementary Perceiver and Memorizer (EPAM) is designed to perform in a manner similar to human subjects in memorizing lists of nonsense words (serial-anticipation) and in associating one nonsense word with another (paired-association). In order to accomplish this, EPAM utilizes a binary-tree structure as shown in Figure 3. The structure consists of test nodes, branches, and terminal nodes. Each test node defines a test which is applied to an inputted word by EPAM when the node is reached. These tests are used to determine if the word being tested has some physical characteristic which was defined in the test when the node was built. Depending on the outcome of the test, EPAM then progresses to the next node of the structure via either the test successful branch (+) or the test not successful branch (-). If the structure is sufficient, eventually a terminal node is reached which contains either the word or a cue to the word that was related to the inputted word. If the structure is not sufficient, new nodes are created and added to the structure.

As in the case of the other programs discussed, this program is consistent with Piaget in terms of the make up and use of the structure. A framework of a set of interconnected nodes into which incoming sets of related words must fit is provided, parallel to Piaget's schema. These schema are related to other schema to provide an internal model of the program's view of reality.

Unlike the processors, however (and consistent with Piaget), the structure is dynamic and structural change is equated to cognitive growth.

Since EPAM does develop, a Piaget-like adaptive facility is provided. EPAM changes incoming words to schema of tests, branches, and terminal nodes, and incorporates that

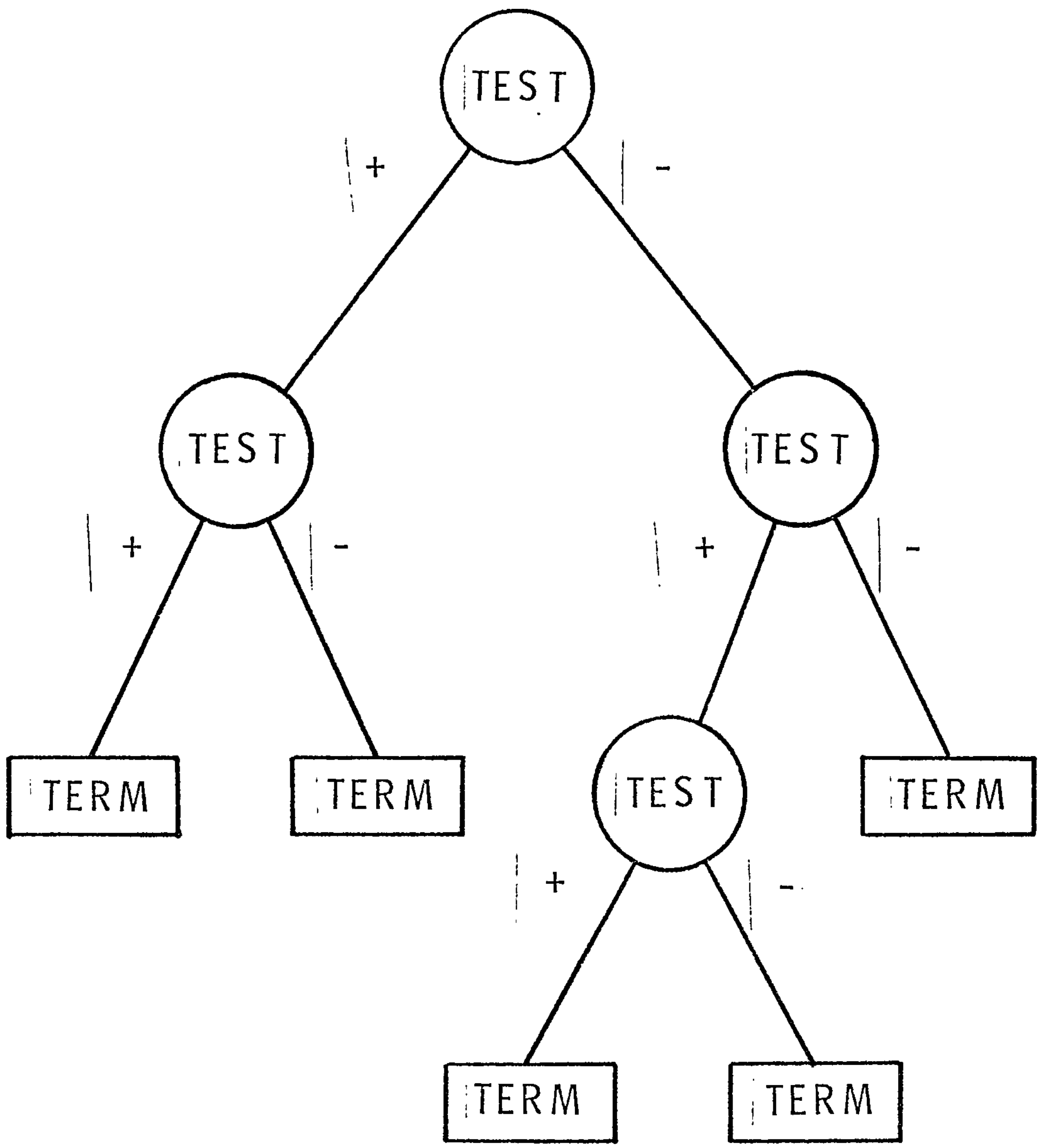

FIGURE 3

TYPICAL EPAM STRUCTURE

schema into the structure (assimilation). Likewise, the new nodes and branches are added to the old structure through changes to existing branches and nodes (accommodation).

Like processors, EPAM has no physical drives. Its motivation is wired-in. Unlike processors, EPAM has a groping facility. When a new word is inputted, the structure adapted, and groping is essential for that adaptation. EPAM chooses some characteristic of that new word and develops new schema designed to allow that word to be discriminated. If the characteristics chosen are sufficient, the next time the word is inputted the proper response will be made. If they are not sufficient, further adaptation will be required.

Finally, like the processor, EPAM assigns meaning in terms of relationships among words. EPAM is only "one-way" interactive with a verbal environment. EPAM categorizes the environment but does not act on it. EPAM is not fully interactive with a physical environment and can have no understanding of the information it processes in terms of sensory-motor perceptions of a physical environment.

Section 3 - Interactive Learners

This class of programs interact with an environment and develop utilizing a changing cognitive structure. These programs are the nearest to being completely consistent with Piaget's theory. The program presented in Chapter 4 fits into this class. Examples of interactive learners include Doran's automaton [10] and Plummer's programs mentioned in Chapter 1.

Doran's Automaton

Doran's automaton interacts with a simulated physical environment to produce behavior which is analogous to a rat attempting to cope with its surroundings. The environment that is involved is similar to a maze. The environment that is involved is similar to a maze. An example of this environment is shown in Figure 4. The exact construction of the environment as to size and placement of interior walls is variable. This environment is represented in the computer by a list structure made up of letters which define the walls and borders of the environment. The letters also represent to the program the desirability of being in that portion of the environment defined by those letters. For example, a wall might be represented by a row of "A's," where "A" represents an area of comfort to the programs. If the automaton is then positioned by a wall of "A's," it experiences comfort. The program is driven by a function which works to otimize the "pleasure" experienced by the system. That is, there is a set of parameters

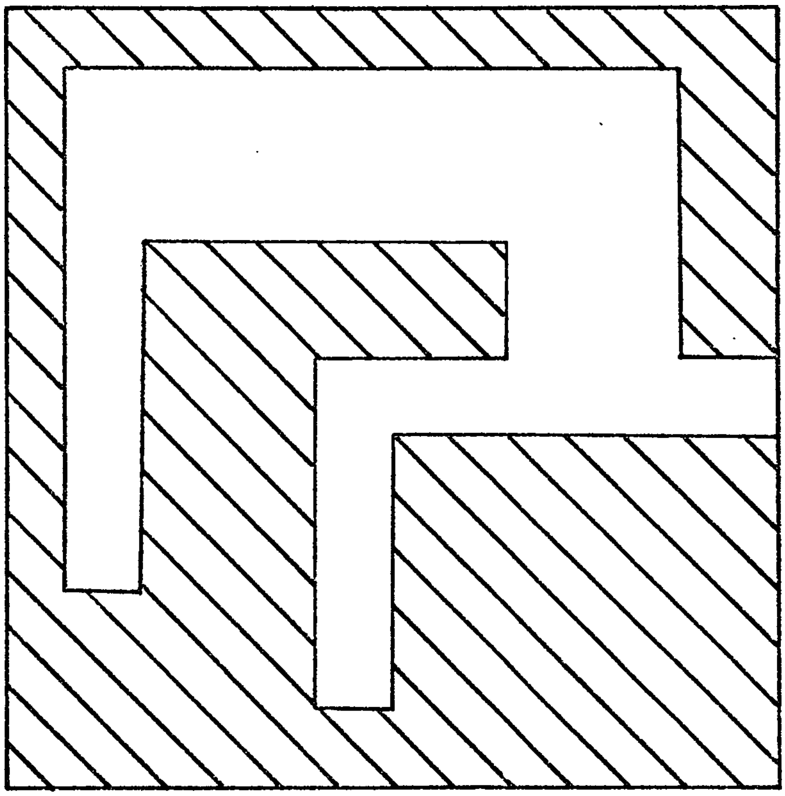

FIGURE 4

EXAMPLE OF DORAN'S ENVIRONMENT

associated with each position the automaton may be in (the state of the system).

The system perceives its environment through a knowledge of the state which it is in. This includes a set of parameters which identify where the automaton is within the environment in terms of the distance the automaton is from the wall it is facing. The system, then, has a facility roughly equivalent to sight. The system also remembers the last movement the automaton made. The system therefore interacts with the environment through a perceptual facility akin to sight, and a motor ability akin to locomotion.

Although this program has a very limited sensory-motor capability, it does exhibit many facilities which are consistent with Piaget's theory. It is clear that like the learning programs, Doran's automaton is consistent with Piaget in structure, use of structure, adaptation, and modeling of reality. In addition, this program is interactive at a physical level and relates information stored in its structure to the physical environment through a perceptual model of the environment. The automaton has a model of mountain, for example, which is related to the desirability of a system state which relates to proximity to the mountain, the proper way to reach (or escape) that state, the motor implications of reaching that state, Doran's automaton has a definite groping facility which he calls "explore." This facility causes the system to grope for an action when it reaches an unfamiliar state. Based on the outcome of the action taken, it may reach a new state. New structure is added to the memory through this facility, and the automaton is ultimately able to construct "plans" for reaching desired states.

However, Doran's automaton is still lacking in being completely consistent with Piaget. The internal model is in terms of the states that the system may be in and in terms of the transitions between states. This is still not quite the same as Piaget's model of the actual components of the physical environment in terms of the sensory perceptions which are obtained from that component and the effects of motor activity on that component.

Finally, Doran has so far investigated only motivation based on physical drives. The sole motivation of the system is to maximize pleasure. There is no cognitive functioning motivated strictly by a need to function.

Plummer's Program

Plummer's program is designed to simulate sensory-motor learning which is similar to that observable in children. This involves the coordination of hand and eye movement. Plummer's model is the only program discussed here which is a true attempt to apply Piaget's theory. Like Doran's program, this system utilizes a simulated environment made up of a list structure. An example of this environment is shown in Figure 5. The environment is contained within a border and may contain objects of various shapes, sizes, and characteristics. The system interfaces with this environment by means of facilities which are akin to touch and sight. That is, a movable window, represented by the dotted square in Figure 5, represents the area of the environment which can be viewed by the system. The system may move this window or "eye" anywhere within the environment. An arm, represented by the narrow rectangle, can also be moved anywhere within the environment and may be used to push objects within the environment. The arm has a sense of touch which informs the system of contact between the arm and an object and of the relative location of the point of contact on the arm. The system's view of the environment, then, consists of a field of view within the environment and a perception of the arm contact with something. This is contrasted with the knowledge of a state in Doran's program.

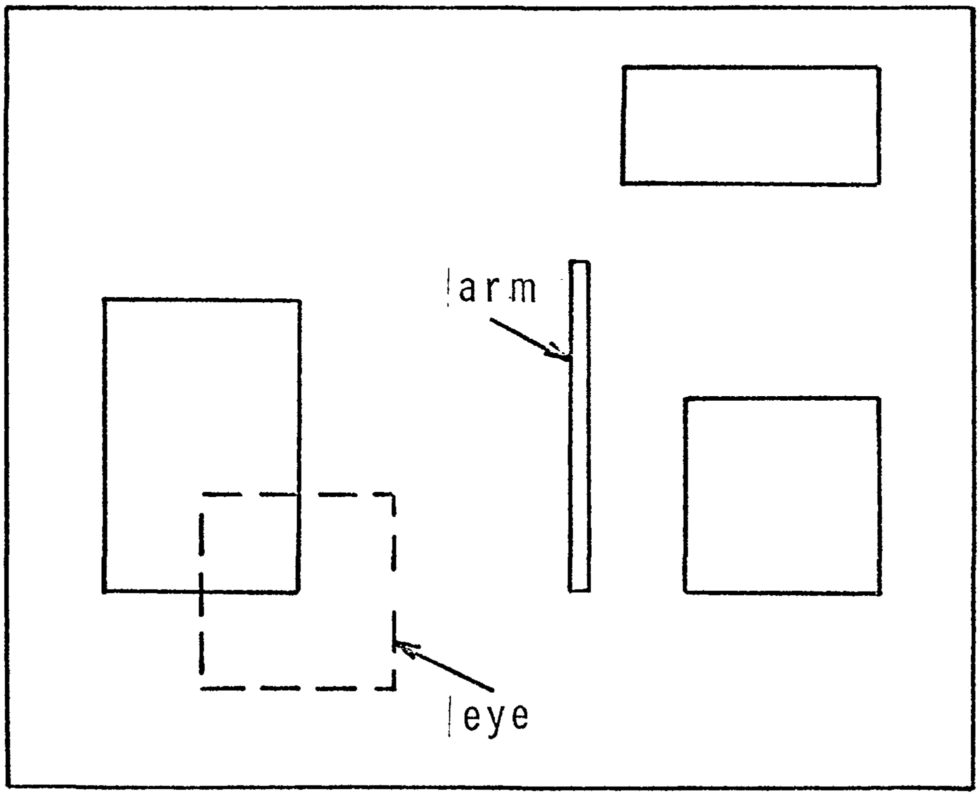

FIGURE 5

PLUMMER'S ENVIRONMENT

The structure utilized by the program is typified by Figure 6. The structure is basically an EPAM-type net which consists of test nodes and action nodes linked by paths which are reached either through the performance of an action (i.e., eye movement or arm movement) or by the successful or unsuccessful outcome of a test. It should also be noted that after an action, the system may return to the test node which led to that action, allowing a retest to occur. The tests performed compare that which is presently being perceived by the system through its sight and touch facilities to what had been perceived and stored as part of the test node when the test was constructed. A groping facility is provided which causes the system to make exploratory movements if it reaches a position in the structure which has no structure beyond it. Based on the principle that the number of tests which are satisfied should be as great as possible, the grope facility attempts to add a substructure which identifies situations in which known actions will lead to satisfaction of the "parent" test.

In addition to the grope facility, another facility is included which adds structure for the purpose of maximizing stimulus. That is, a series of operations similar to those involved in groping is performed with the goal of adding structure, which leads to maximizing the amount of area of the arm which

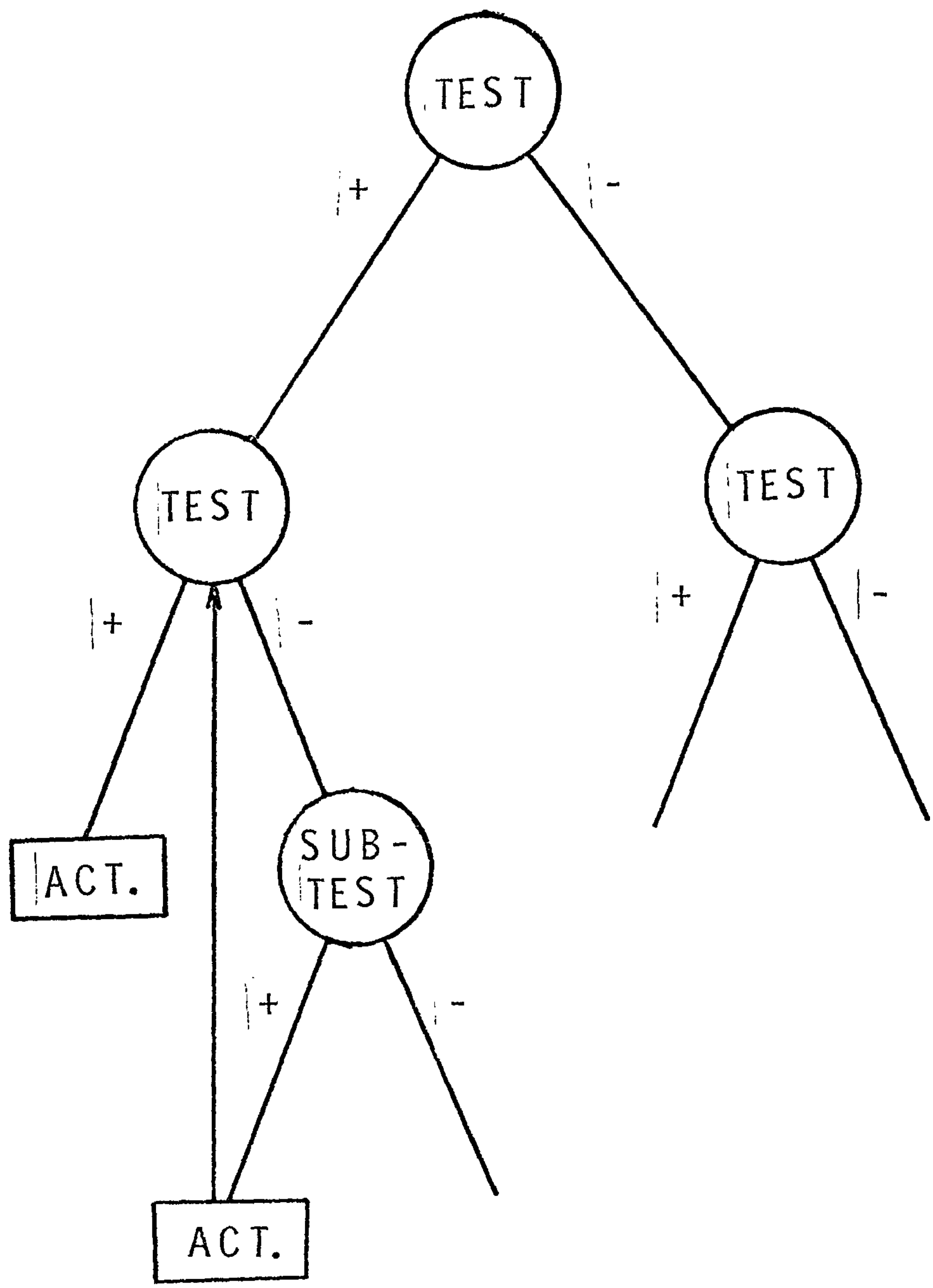

FIGURE 6

PLUMMER'S STRUCTURE

is in contact with something and the amount of area of the eye which contains something. Also included in the system are facilities for updating the structure (forgetting) by removing parts which are ineffective (i.e., those structures which do not maximize stimulation or successful tests).

In operation, the program is given an initial structure and a predefined environment. Based on the grope and stimulus learning facilities, the system grows structure and interacts with its environment to eventually produce a structure which coordinates hand and eye movement.

Consistent with Piaget, Plummer's program depends upon a cognitive structure to function. Cognitive development is provided by structural change. Plummer's structure is made up of Piaget-like schemata which are frameworks of interconnected test and action nodes. The relationship among the schemata which make up the cognitive structure defines an internal model of the physical environment in terms of the perception of that environment through the two senses of touch and sight and in terms of the motor effect on that environment through eye and arm movement. This perceptual information is formed into schema and added to the structure (assimilation), while the structure is modified to accept the schema by the changing of branches and addition of nodes (accommodation). Plummer's program is motivated by a drive to increase stimulation from its senses and to maximize the effectiveness of the structure. The drive to maximize stimulation can be related to a type of physical drive, while the drive to improve the structure is strictly an internal need to function. Thus there is a mix of physical and mental drives as Piaget theorizes is at work in human development. Plummer causes adaptation through a groping facility which is put into action when the program is in an unfamiliar situation. The facility allows the system to take some action even though it has no reason or experience from which to choose an action and incorporate that action, if desirable, into the structure.

Chapter 4

THE BASIC MODEL

Section 1 - Purpose

As alluded to in Chapter 1, the purpose of building this model is the construction of a tool to investigate representation of meaning in a computer simulation of human-like, cognitive development based on Piaget's theory (this is unlike Plummer's program, which is concerned with simulation of the sensory-motor stage of human development, and Doran's automaton, which does not explicitly apply psychological theory). This goal requires that meaning be based on sensory-motor perceptual models of reality. The program must, then, interact with an environment and through that interaction produce and adapt a cognitive structure.

A program which can interact with the human environment through the sensory-motor facilities available to man is outside the scope of this paper. This model, like Plummer's and Doran's programs, is, therefore, designed to provide a simulated organism which interacts with a simulated environment utilizing a set of simulated sensory-motor facilities. The environment and facilities provided are designed to be conceptually analogous to a subset of man's.

The model is a set of programs and structures which fall into three general categories: the environment, the organism, and the utilities.* The environment and the organism may be described subjectively from three different viewpoints: from that of the experimenter who uses the model, from that of the organism as it interacts with the environment, or from that of the programmer who created the model. The remainder of this chapter will discuss the programs and structures which make up these facilities from all three viewpoints, concentrating primarily on the organism and experimenter viewpoints. It should be noted that Appendix A provides a detailed set of examples of the structures utilized by the programs and Appendix B provides a set of listings for all of the programs which make up the model.

Section 2 - The Environment

From the experimenter's viewpoint, the environment may be pictured as a plane divided into cells. This is best typified

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*The utilities consist of a set of housekeeping programs which are used by the model but have no bearing on the actual behavior of the model. For this reason they will not be discussed. The utility program listings are included in Appendix B.

by a sheet of graph paper which is ruled off into a number of squares ("cells").* Each cell may or may not contain something. The nature of the contents of the cells defines the environment and its contents.

The size and shape of the subjective environment (i.e., the environment in which the organism exists) is defined through the specification of boundary cells (see Figure 7). The boundary cells (or "B" cells) form a wall around the subjective environment and thereby define the size and the shape of the environment. It can readily be seen from the two examples given by Figure 7a and 7b that the variety of sizes and shapes for environments are limited only by the size of the graph paper and the relative size of the cells. The larger the cells, the fewer the number of shapes possible. Consider, for example, the impossibility of defining a round environment when the graph paper consists of only a few large cells.

The environment can contain any number of objects which may have varied sizes and shapes. The objects are defined in the same manner as the environmental boundary. An object is defined in size and shape through the delineation of

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*Graph paper is, in fact, the means by which the experimenter presently lays out an environment. The graph paper representation must then be coded into a list structure for input to the program.

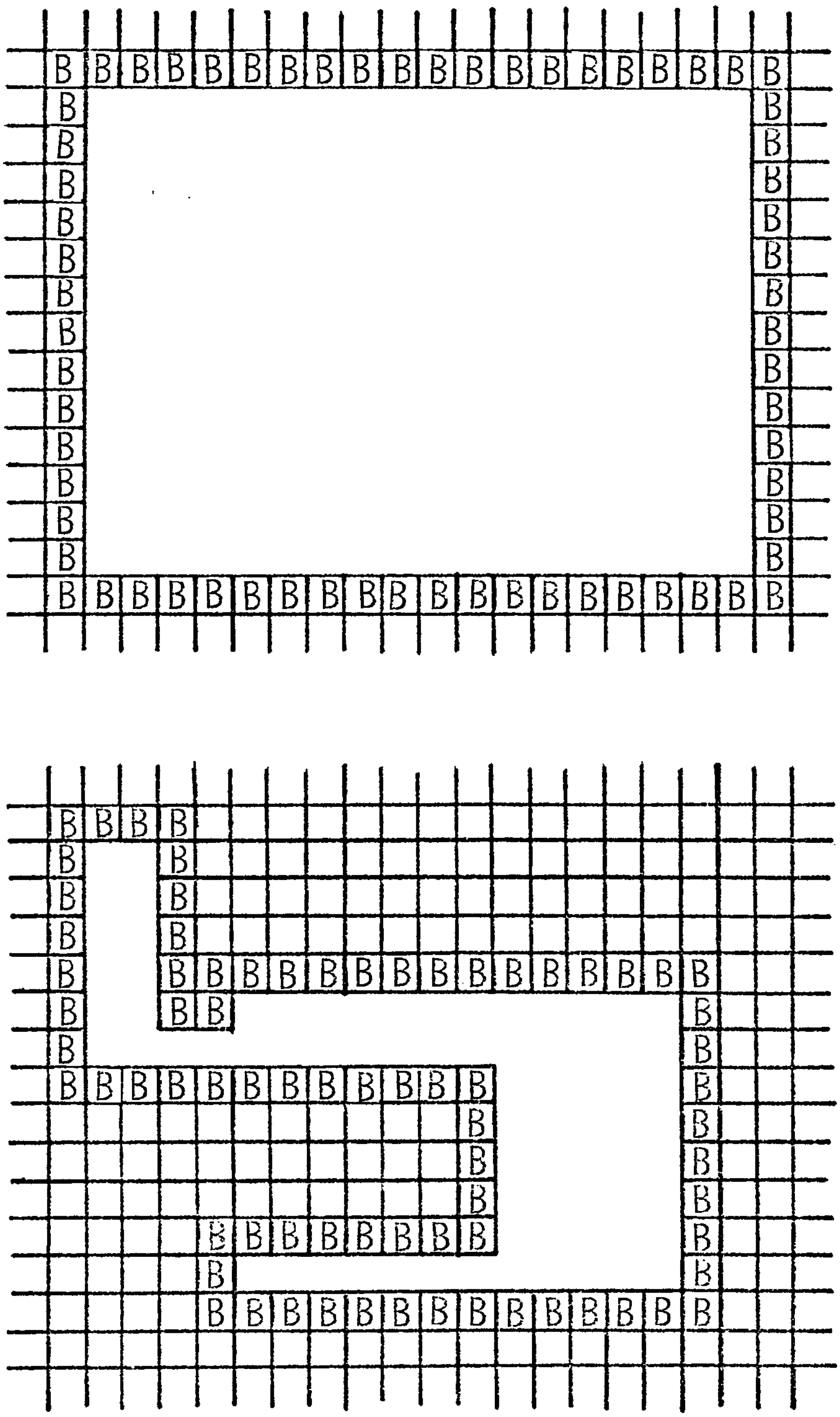


FIGURE 7

ENVIRONMENT EXAMPLES

the environmental cells which make up the body of that object. In Figure 8, for example, a rectangular object is defined in terms of the sixteen environmental cells which make it up. As the environment itself, the object's size and shape depend on the size of the graph paper and the relative size of the cells.

Each object has two physical characteristics besides shape and size: color and movability. Each object is assigned a color. There is no constraint on the assignment of colors; each object may have the same color as or a different color from each other object. Colors are fixed through a single experimental run, but they may be varied by the experimenter between runs. Each object may be defined as being fixed or movable. A fixed object cannot be moved by the organism, while a movable object may. The boundary is always automatically defined as fixed. As with color, the experimenter may vary movability between runs.

Objects obey a set of physical laws which require: no two objects may occupy the same cells at the same time, objects cannot be moved through the boundary, and only one object may be moved by the organism at a time. If one object is moved against a second object, it cannot be moved any further since it cannot occupy the same space as the second object and since the organism is not "strong enough" to push two objects at once.

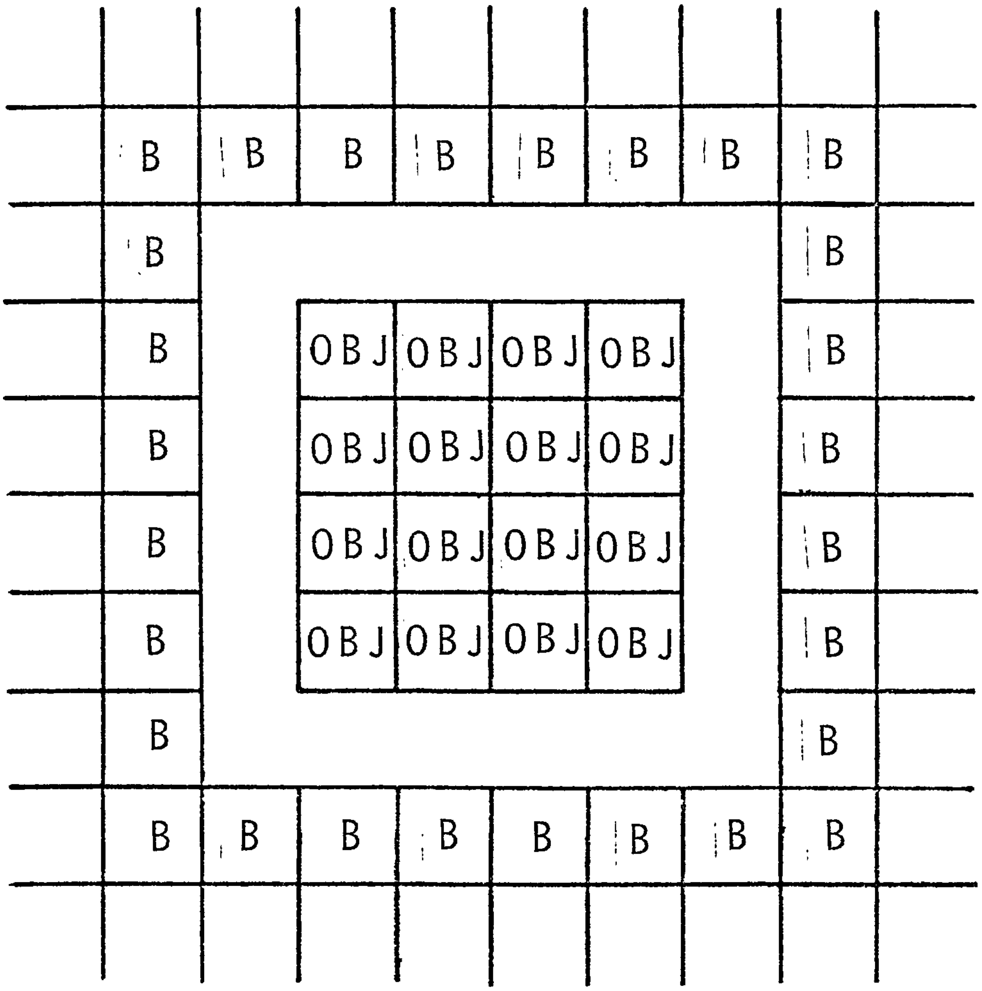


FIGURE 8*

ENVIRONMENTAL OBJECT

*Note: "OBJ" denotes that part of an object lies in that cell.

Also included in the environment is a physical representation of the organism itself as shown in Figure 9. The organism's body is limited to a square shape and a flesh color, but is variable in size. The organism is defined in the same manner as an object. The organism's hand (represented by the "H" in Figure 9) is flesh colored and is the size and shape of one cell. The hand is not connected to the body by a visible arm (i.e., an arm which is defined in terms of cells). The hand appears to float about the organism's body--disconnected but completely controllable. The hand is limited in the distance it may move away from the body. This is specified by the experimenter before a run. The hand has complete freedom of movement within this limit. Thus, a sort of arm does exist--an arm which consists of a limitation to hand movement.

The environment and its contents take on a different appearance when considered from the organism's viewpoint. The organism perceives only a part of the environment at a time, and that part does not appear as a graph paper layout as it does to the experimenter. The organism can perceive only the portion of the environment that is in contact with the sensory facilities provided to that organism. As the discussion on the

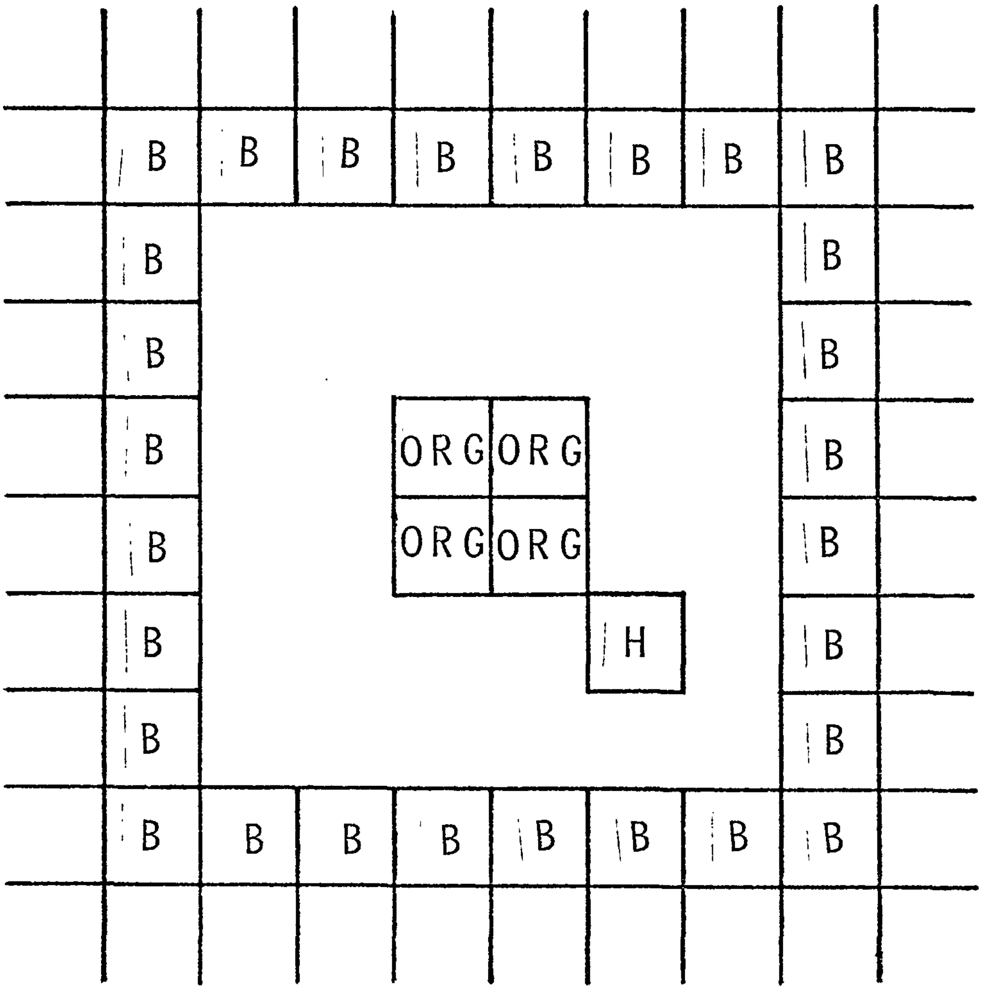


FIGURE 9*

THE ORGANISM

*Note: "ORG" denotes <u>organism</u> and "H" denotes <u>hand</u>.

sensory modalities will show, the environment is "coded by these senses to a form which represents the environment being viewed, but does not represent it in a graph paper form. For this reason, the organism can never perceive the reality of its environment as it actually exists and is viewed by the experimenter. The organism can develop a concept of that reality only through the development of the internal models of that reality based on perceptual impressions of that reality.

Finally, in the viewpoint of the programmer, the environment and the objects which are contained in that environment consist of a set of list structures containing alphanumeric characters defining the characteristics of the environment which can be manipulated by a set of programs. The structures include a list representation of the environmental "floor plan" shown in Figure 8 through 10; a list which defines the position, movement, limits, etc., of the organism's hand; a list which defines the organism in terms of cells and the other characteristics mentioned; and an index list of the objects which occupy the environment. Appendix B shows the exact form and makeup of these lists.

Section 3 - The Organism

From the experimenter's viewpoint, the organism is made up of a set of sensory modalities, motor facilities, and a cognitive structure which controls their operation. The sensory facilities translate the part of the environment under their view into perceptual impressions which can be manipulated by the cognitive facilities of the organism and can be stored in the cognitive structure. The motor facilities can be operated by the organism to allow it to manipulate its environment in a limited sense. The cognitive structure directs the organism's activity and provides it with a structural understanding of the environment, the contents of the environment, the physical laws of the environment, the organism itself, etc.

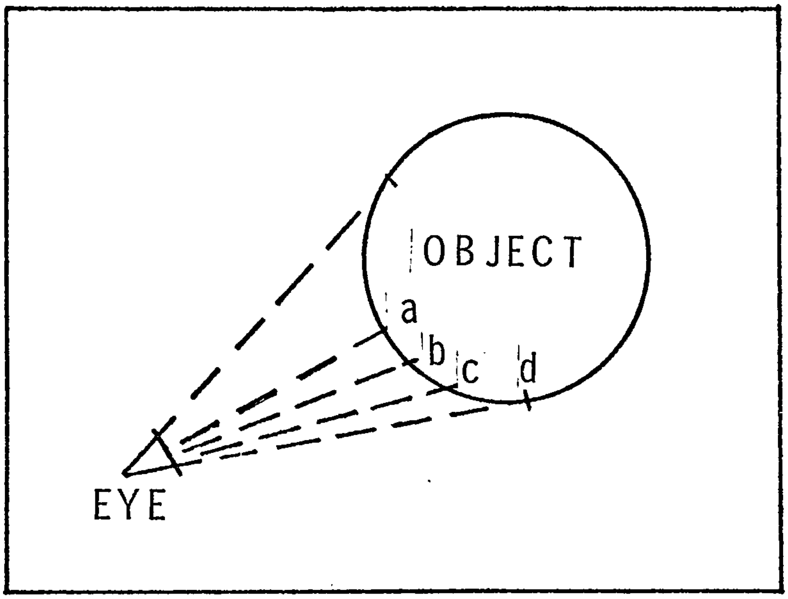
From the organism's viewpoint, the organism consists of a physical part (described in the preceding section) which is under "conscious" control and a mental part which provides that "conscious" control but is itself primarily "unconscious." The mental organism consists of a set of motor abilities and sensory perceptions and an "unconscious" ability to relate them and to adapt to new situations.

From the programmer's viewpoint, the organism is a collection of programs and list structures under the direction of an executive program. The executive utilities a net structure in directing the use of the other programs in manipulating the structures.

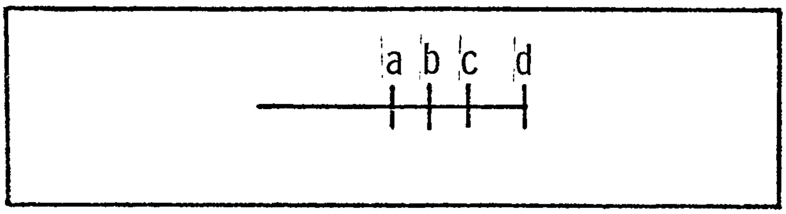
The Sense Modalities

In defining an optical sense which would logically fit with the environment provided, a primary goal was to provide a facility which would be two-dimensionally analogous to human vision. This is necessary to investigate meaning in a manner consistent with Piaget's theory. For example, it would not be consistent to allow the organism to see a square object as a square, since the organism "lives" in the same plane that the square exists in. Some method of perceiving this object in a way which would allow the organism to develop a concept of square, similar to the way in which man develops a concept of mountain without seeing it from all directions at once, is necessary. For this reason, the concept of visual perception as related to the number of dimensions of the perceiver as discussed by the mathematician Edwin A. Abbot in his book, Flatland [11]. was utilized in creating the sensory facility.

Abbot's concept is basically that a two-dimensional being existing in a two-dimensional environment will visually perceive all objects as a line (i.e., one dimensionally) which has a shading variation. For example, consider Figure 10. To the two-dimensional eye, the circle in Figure 10a appears as (or is coded to) the line in Figure 10b. Point a on the circumference of the circle nearest the eye would appear closer (be



a. Scene viewed by experimenter



b. Scene viewed by organism's "eye"

FIGURE 10

VISION

"shaded differently" in Abbot's terminology) than the other points in view. The way in which the points along the line appear in terms of distance from the eye defines the shape of the object. Thus, the object cannot be perceived as a circle. A concept of circle can be developed, however, through an internal model based upon a series of visual perceptions of that circle as a group of "shaded" lines.

In the model, then, the organism is given a sense of vision which allows the object to be perceived as a colored straight line consisting of points which vary in distance from the organism's eye. This is accomplished through the use of Optical Temporary Memory (OTM) which contains the color and point/distance information of anything in the organism's field of view. The OTM is automatically updated anytime a change occurs in the environment and, therefore, always reflects what-ever is in the field of view. The OTM may be read or stored in the cognitive net by the organism at will. The field of view is defined as a rectangular area of predetermined length which originates at a particular side of the organism and is the width of that side of the organism. For example see Figure 11. The position of the field of view is controlled by an eye movement motor facility.

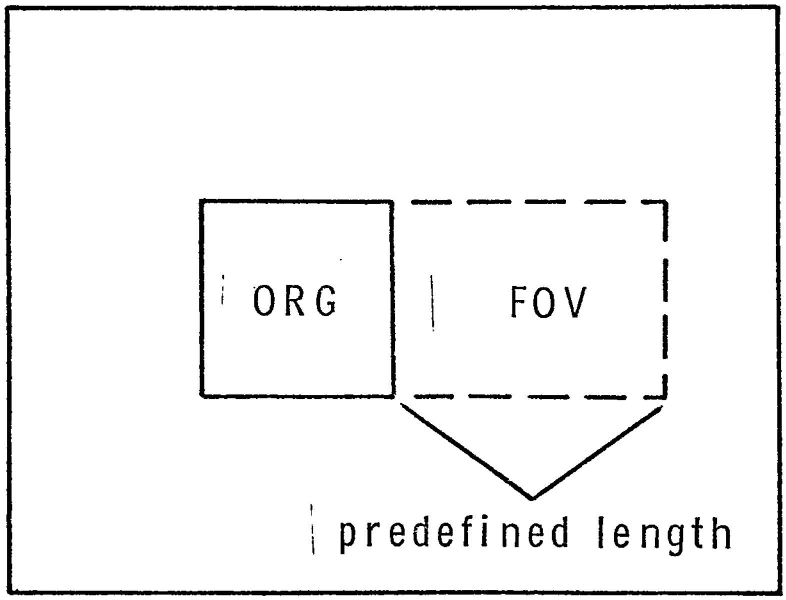


FIGURE 11

FIELD OF VIEW

The organism is also provided with a tactile sense which is much more rudimentary than that discussed by Abbot or provided by Plummer in his program. The sense informs the organism of contact between the organism's hand or body and any object or boundary. No facility is provided (such as Plummer's tactile sense which locates the point of contact on the organism's arm) beyond this. This sense is provided through a Tactile Temporary Memory (TTM) which, like the OTM, is continually updated and can be read or stored at will.

Finally, the organism has a facility which can be considered as a motor-feedback sense. The organism is able to determine the last movement made by each of its motor facilities. A Motor Temporary Memory (MTM) which works similarly to the OTM and TTM fulfills this function.

It should be pointed out that the organism has no predefined understanding of the significance of these senses (or the motor facilities either, for that matter). The three temporary memories are automatically kept updated with no "conscious" effort on the part of the organism. The significance of and the relationship among their contents and the relationship between them and the environment must be learned by the organism through experience and development of cognitive structure.

In summary, then, it is felt that the sensory facilities describe--especially the visual mechanism which does not allow the organism to perceive the environment as it "physically" exists, will provide a model in which the investigation of meaning will be more straightforward than in a system such as Plummer's.

Motor Facilities

The organism is provided with four basic motor facilities. These consist of body movement, hand movement, eye movement, and hand action.

The hand and body movement facilities allow the organism to move its hand or body right, left, forward, or backward at will. The direction of movement is relative to the direction that the organism is facing. The organism's face is considered to be the side of the organism from which the field of vision (FOV) originates. Each time the facility is used, a movement equal to a distance of one environmental cell is effected. Thus, if the organism were to move its body three cells to the right, it would have to perform a "body right" function three times in succession. The hand is carried along with the body, or it can be moved separately.

The eye movement facility allows the organism to move its FOV either right or left from its original position. Each time the function is exercised, the FOV origin changes so that it emanates from the side of the organism indicated. That is, the organism moves its "head." For example consider Figure 12. Thus, the FOV can originate at any side of the organism and can be moved to any other side by the use of the eye movement facility.

The hand action function simply allows the organism to open or close its hand. This gives the organism the ability to grasp an object (or its body) and move that object.

Each time one of these facilities is exercised, the MTM is automatically updated to reflect the last movement of each type made.

To further explain both the sensory and motor abilities of the organism, the example in Figure 13 will be discussed. As shown in Figure 13a, the organism is originally positioned so that its FOV contains nothing. This is indicated by an empty OTM. Its body and hand are not in contact with anything, as indicated by the empty TTM. The organism performs an "eye right" and progresses to the position shown in Figure 13b.

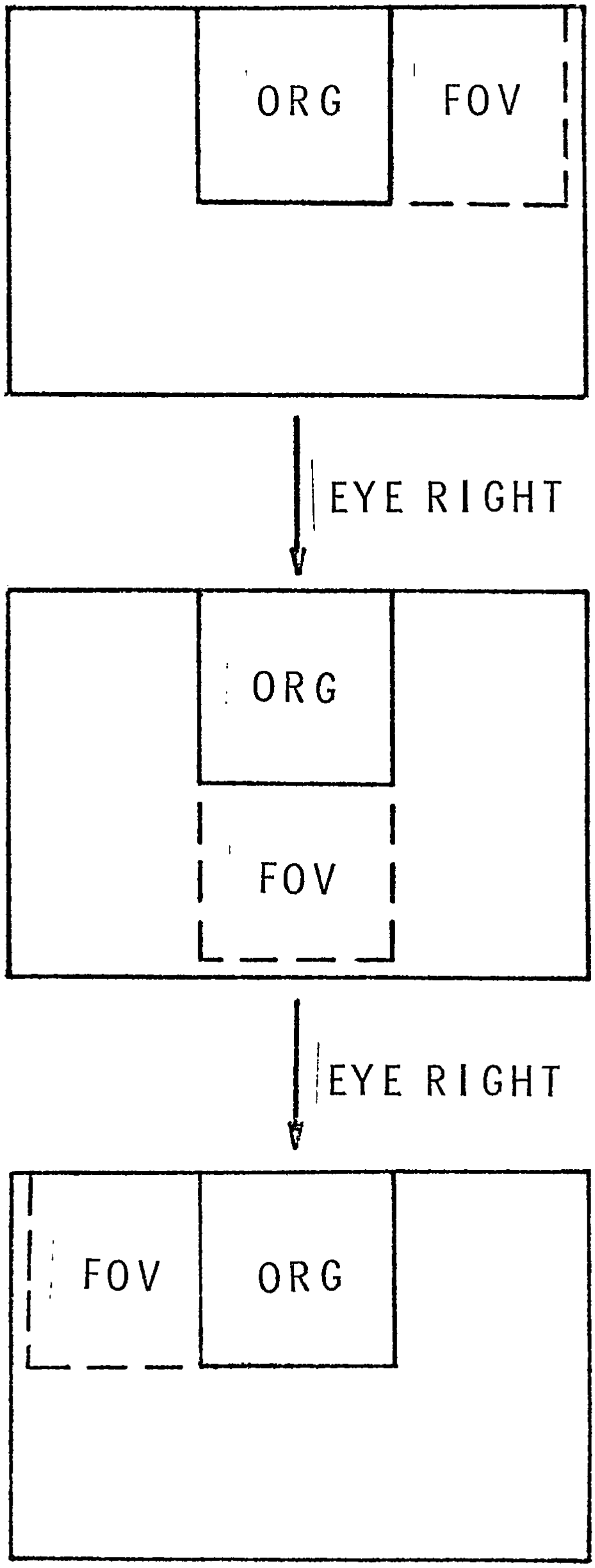


FIGURE 12

EYE MOVEMENT

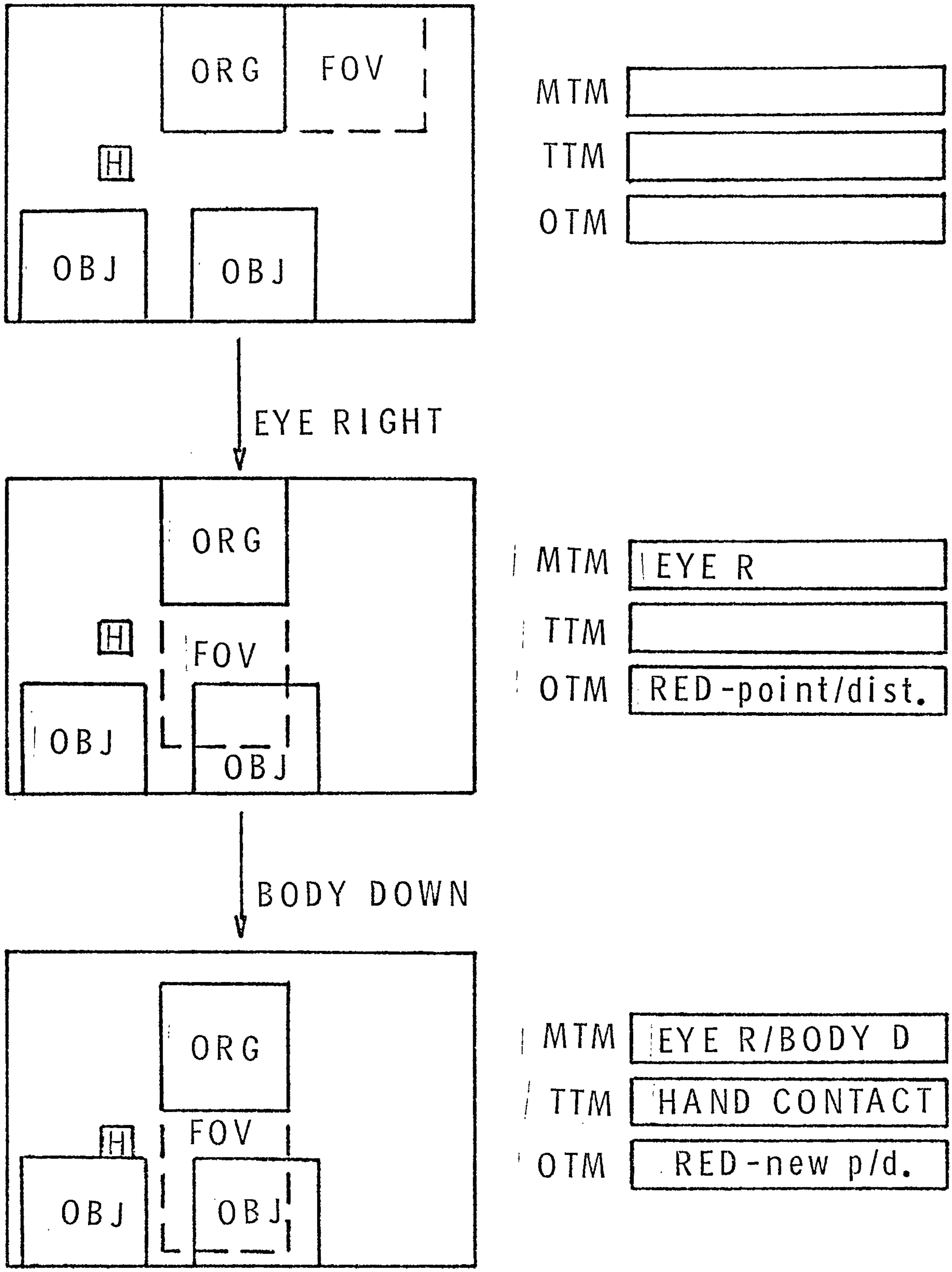


FIGURE 13

EXAMPLE OF SENSORY-MOTOR ACTIVITY

Here the organism has an object in its FOV. The OTM is immediately updated to indicate that an object which is red in color and possesses a certain point/distance characteristic is in view. The MTM is also updated to indicate that the last eye movement performed was an "eye right." The organism then performs a "body down" movement to reach the position shown in Figure 13c. The original object is still in the organism's FOV, but because the organism has moved closer to the object, the point/distance characteristics of the object have changed and the OTM has been consequently updated. The organism has come into hand contact with an object, and this is reflected by the "hand contact" indication in the TTM. As before, the MTM was updated to indicate that the last body movement was "down" and the last eye movement is still "right."

The Basic Structure

The basic structure is an EPAM-like binary tree. An example is shown in Figure 14. The structure consists of two types of nodes linked by "test successful" (+) and "test unsuccessful" (-) branches. The branch taken is dependent upon the outcome of the test applied in the test node. At present

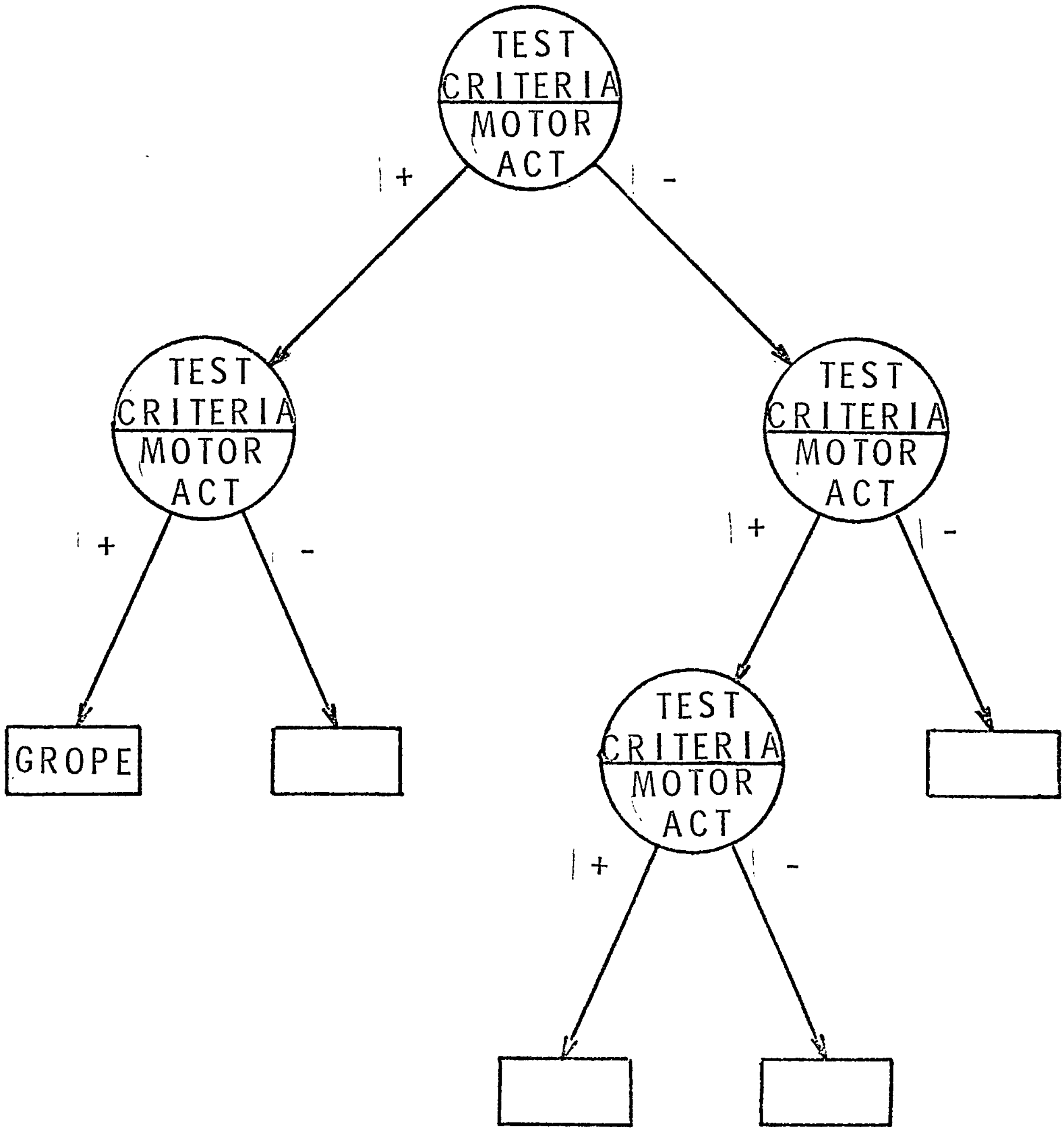


FIGURE 14

THE BASIC STRUCTURE

this test is predefined and is a simple comparison for equality between the test criteria stored in the node and the present contents of the organism's OTM, TTM, and MTM. At present the test criteria stored are simply the contents of the OTM, TTM, and MTM at the time the node was created. The test node also contains a motor action stored when the node was created. This defines what motor function is to be performed when this node is encountered.

The second type of node is the "grope" node. This node is automatically placed at the end of both branches of a newly created test node. Whenever that node is reached, the executive program must take the necessary steps to grope. No structure exists beyond that node. The "grope" node signals that something has happened which cannot be handled by the present structure. At this point the organism must adapt by groping for an action and on the basis of that groping must change the structure.

It should be noted that the structure is the whole basis of the model and is the experimental part of the model. That is, development of the model is based on experimentation with structural concepts to determine the best structural concept possible. The best possible concept is that which causes the most human-like behavior. The rest of the organism and the environment are the invariant parts of the experiment.

The structure as described is, in fact, a preliminary version. Discussion of the elaboration of the structure will be deferred until the results of the preliminary version are discussed in Chapter 5.

The Executive

The executive is the program which performs the actions directed by the cognitive structure by exercising all the other programs which make up the model. The executive also provides the groping mechanism which is called into play whenever a "grope" node is encountered. Finally, the executive provides the only "motivation" for the organism. The executive provides the facilities which read, interpret, and manipulate the structure; and then it performs whatever action is indicated by the structure. The executive determines what is to be stored in the test nodes and actually performs the test when it encounters a test node in the cognitive structure. The basic executive is demonstrated by the simplified flowchart shown in Figure 15.

The executive steps through the cognitive structure reading one node at a time. If the node is a "grope" node, the executive performs a grope to determine the next action to be taken from that point. At present, the grope consists of a randomly chosen movement. Based on that grope, a new test node is created to replace that "grope" node. The executive stores

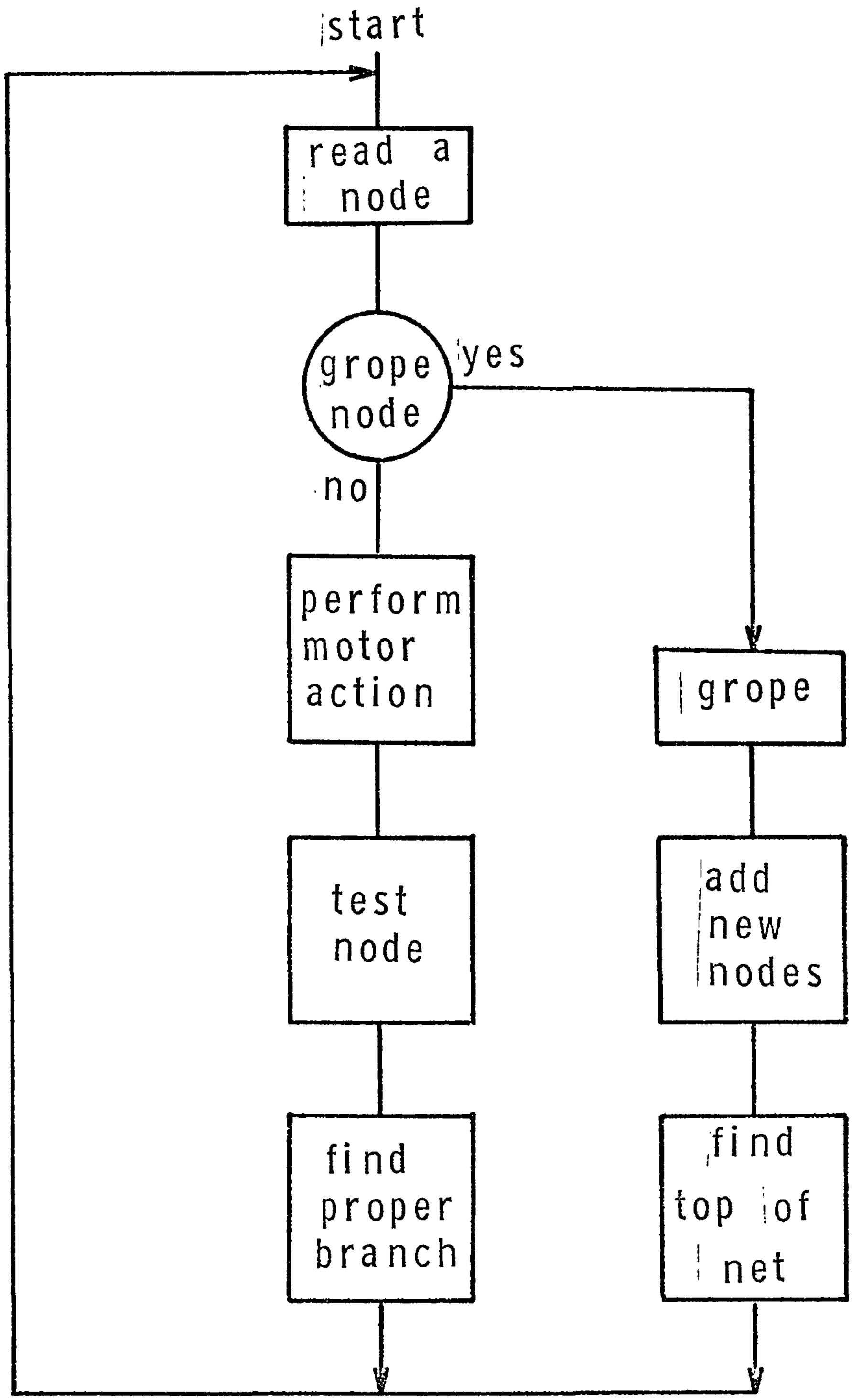


FIGURE 15

SIMPLIFIED FLOWCHART OF THE EXECUTIVE

the contents of the OTM, TTM, and MTM in that node as test criteria and then returns to the first node of the structure. If the node is a test node, the executive updates various parts of the node and then executes the motor function indicated by that node. The executive then compares the OTM, TTM, and MTM to the test criteria stored in the node and from that determines which branch from that node to follow. The executive then locates the proper next node that repeats the same logical process. The executive passes completely through the structure as many times as the experimenter predefines when the run is initiated.

It can be readily seen that the executive and the structure are closely related. Because of this, the executive is also an experimental variable in determining the best structural concept. The basic executive, like the basic structure, is simple and is meant to be changed during experimentation.

Section 4 - In Summary

In summary, the model consists of a set of computer programs and list structures which are intended to provide a two-dimensional simulation of at least part of the human situation. The environment and most of the organism is designed to be constant, while those parts of the organism called the executive and the cognitive structure are designed to be changed based on experimentation. The goals of these changes and this experimentation is the production of an executive and a structure which will allow for the development of a representation of structural meaning in Piaget's sensory-motor sense.

Chapter 5

IMPLEMENTATION AND RESULTS

Section 1 - Implementation--The Basic Model

The basic model as described in Chapter 4 was implemented using the LISP 1.5 language [12] on the Univac 1108 computer [13] at the University of Houston Computing Center, Houston, Texas. LISP 1.5 is a high-level language which is designed for manipulation of symbols, and which provides facilities for organizing symbols into list structures. A minimum mathematical capability is also provided. LISP 1.5 was chosen because the model is concerned with symbol manipulation and requires minimal mathematical capabilities. The list structures available through LISP 1.5 lend themselves nicely to the construction of the cognitive structure required as well as the other structures required to represent the environment, the senses, etc.

The Univac 1108 timesharing system was utilized in the construction of, debug of, and experimentation with the model because of the convenience afforded the experimenter through easy access to terminal equipment at the NASA Manned Spacecraft Center, Houston, Texas.

Implementation of the basic model was felt to be desirable since it would (1) allow for debug of the sensory, motor, and environmental facilities; (2) give an initial idea of the usefulness of structure of the type described; and (3) provide a pragmatic rather than hypothetical base for the anticipated elaboration of the structure.

The basic model consists of a set of thirteen LISP functions which are listed in Appendix B. One hundred "cycles" of the program execute in approximately five and one-half minutes in a time-sharing environment, and require approximately one hour and a half of on-line terminal time.*

The program is designed to run a predetermined number of cycles. This number is specified by the experimenter as a parameter to the executive, which is itself a LISP function. A cycle is defined as one pass through the net from the first node to the first "grope" node encountered. Since new structure is produced at this point, the executive returns to the first node and begins the next cycle after groping is performed. The cycle concept is necessary since there is no other means to determine when the program is through. The program, unlike

*The system used is an interpretive system. The run time would have been reduced if a compiler were available.

most programs, produces no result as such, but simply runs and grows structure. At the end of the number of cycles specified, the program prints out a complete set of all the structures and parameters utilized by the model. This information can be utilized as initial conditions for another run, if continuation of the experiment is desired. The printout of a single one-hundred-cycle run requires an average of one hour of on-line terminal time in a time-sharing environment.

It should be noted that every cycle produces one new test node, which replaces an old "grope" node, and two new "grope" nodes which are automatically placed at the exit branches from that new test node. For each cycle, then, two new nodes are added to the structure. It can easily be seen that the structure grows very rapidly.

In implementing the model, the environment was developed first, and then the associated list structures. The sensory facilities were then developed and verified, using a dummy executive and a test environment which was designed to demonstrate all the possible characteristics of an environment. Next, the motor facilities were designed and debugged, using the same test environment and the sensory facilities. Finally, the initial cognitive structure was specified through the development of an executive. The executive was debugged, utilizing the sensory-motor facilities and the original test environment. The various utilities were produced as the need arose in the development of the model.

The groping mechanism was implemented, utilizing a random method of selecting one of the twelve possible movements or a NIL function which represents an absence of movement. This method was chosen primarily because of convenience and simplicity of implementation. The consistency of a strictly random approach to groping must, like the rest of the executive, be evaluated.

Section 2 - Results--The Basic Model

In general, the results observed were negative. This was to be expected, however, since, as mentioned previously, the initial structure was very simple and intended as a first step in experimentally developing the correct structure. The experiments performed consisted of runs ranging from twenty to one hundred cycles in length. It was made clear from these short runs that serious deficiencies existed in the original structure which would require correction before more complicated and longer experiments could provide any really meaningful results. For this reason, no runs were performed in a batch environment, even though longer runs would have been possible with the printing restrictions inherent in the terminal equipment removed and more data could have been collected through frequent sampling of the model's performance.

After some experimentation, two basic experiments were defined which provided the most information about the model's performance with the minimum of effort and time. These two experiments were centered about two different environments--a sterile and a rich environment.

Both experiments utilized the same initial cognitive structure. This structure was chosen to provide the organism with the minimum predefined direction, while insuring that some activity would take place. The primary requirement for an initial cognitive structure is that a "grope" node must exist somewhere in the structure. This minimum requirement is provided by the structure shown in Figure 16. "Eye right" was chosen as the movement function stored to insure that, at minimum, some visual activity would occur.

Figure 17 shows the sterile test environment. This environment contains only the organism and its hand. The visual sensory stimuli available are therefore limited to that caused by the black environmental boundary and that caused by the flesh-colored hand of the organism. Even the point/distance characteristics associated with each of these is limited

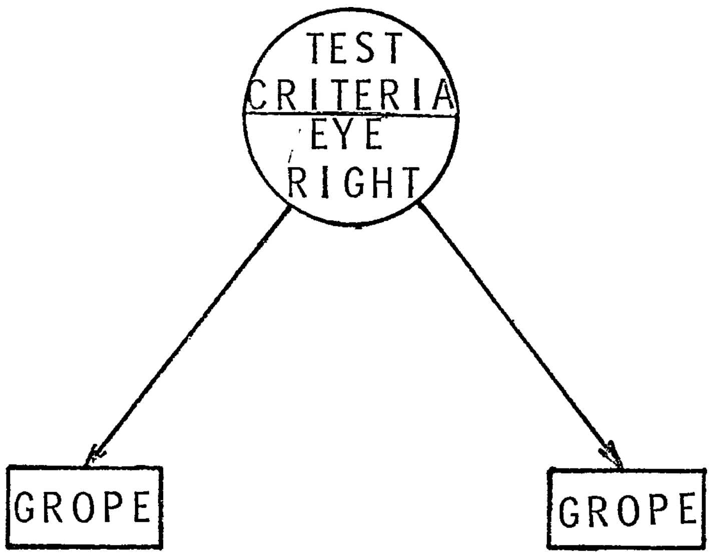


FIGURE 16

INITIAL STRUCTURE

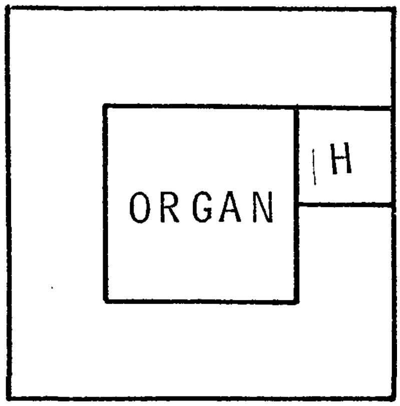


FIGURE 17

STERILE ENVIRONMENT

because of the small size of the environment. Motor activity is limited to a minimum body and hand movement in each direction from the original location. This experiment is designed to force the organism to "concentrate" on the development of sensory-motor coordination schema, schemata which represents models of the characteristics of the environmental boundary, and schemata which represents models of the organism's concepts of itself. In limiting the organism so drastically, it was planned that a stage of relative equilibrium would be rapidly reached because of the small number of things which could be learned, and that analysis of the model's performance would be much simpler. At least a preliminary determination as to the validity of the structure could be made, and the merits of further experimentation could be evaluated as quickly as possible.

Figure 18 shows the rich test environment. This environment gives the organism the ability to utilize all of its capability. A full gamut of physical characteristics are provided. The objects are different in color, shape, and size. One is fixed and one is movable. The environment is large enough to accommodate such movement. The organism can even be located in a position where it can see nothing. If the model

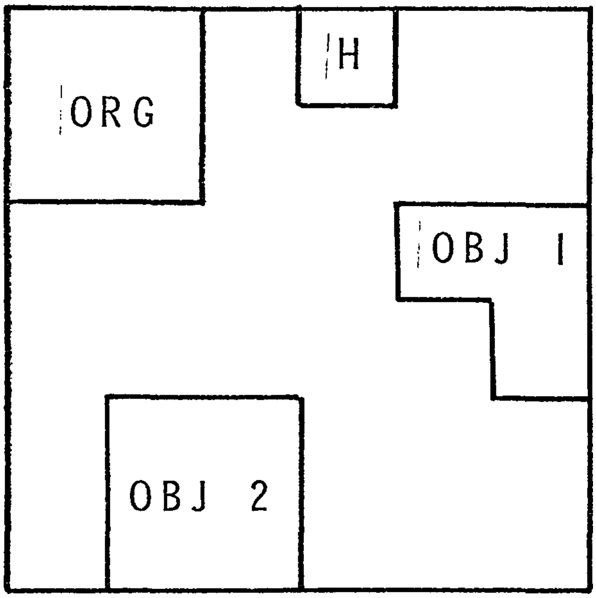


FIGURE 18

RICH ENVIRONMENT

performs adequately in the sterile environmental test, this rich environmental test should start to indicate if more complex intelligent behavior can be achieved.

The basic model was experimented with in both environments even though the results gained from the sterile environmental experiments were adequate to indicate that some significant changes to the structure were necessary.

Three basic problems and deficiencies were encountered. First, the structure can support no generalization. Each situation that the organism finds itself in is treated independently by new structure, even if that situation has been encountered before under somewhat different circumstances. For example, if the organism, through groping, developed a structure which relates body movement towards a wall with the change in point/ distance characteristics experienced in its OTM, that schema can only be accessed by the organism if it finds itself in exactly the same situation as it was in when the schema was created. There is no facility for the organism to utilize that schema in another, slightly different, situation unless that situation were encountered at the same point in the cognitive structure as the original situation. This is not probable. For this reason, the organism must develop this schema anew through additional groping each time a similar situation is encountered. A large amount of wastefully redundant structure is created which serves only to complicate analysis and slow operation of the model.

Related to the first problem is the problem that the executive and the structure are designed so that the structure is required to grow no matter what. Even if all schema are satisfied and the incoming perception is completely assimilated without accommodation being justified, the structure is required to grow. This is the mechanical basis for at least part of the first problem. The executive should be able to either create new structure or provide a branch to existing structure when a "grope" node is encountered. Structural growth is only necessary when existing structure is inadequate.

Finally, a capability provided in the groping facility was also observed to be a problem in that it expended processing resources without providing any observable benefit. The groping facility is capable of creating test nodes which have no motor action stored in them. These nodes only exercise the mental activity involved in testing. When they are encountered, the executive performs the test and chooses an exit branch, based on the stored criteria, but performs no motor function.

It is apparent that these nodes would only be useful if something happened to the environment by some force other than the organism. The nodes could then provide a point for new structure to develop to handle that situation. This at first seems to be a useful feature, but at closer examination does not fulfill any need for the type of experiments planned for the model. The organism is presently the only effector of its environment, and its cognitive development in interacting with its environment is the subject of the model. Although this facility might be useful if the type of experiment planned changes, it presently only serves to complicate the structure unnecessarily, without providing any benefits in performance. What is observed is the growth of strings of test nodes with identical test criteria, none of which can be fulfilled unless the first one of the string is fulfilled, and then they are all fulfilled. Thus the executive must waste time growing and processing multiple, redundant nodes.

Analysis of the structures and overt behavior resulting from the experiments conducted indicated that no truly meaningful or useful schema was developed and no intelligent behavior was produced. A typical result was produced in one run of a rich environment test. In this run the organism was located initially in the upper right-hand corner of the environment (see Figure 19). The organism was facing towards object number 1 and was defined as being the same size as object number 2. Within the first twenty-five cycles of a sixty-cycle run, the organism had moved down the environment until it was positioned under object 2. It remained there for the rest of the run. Although this behavior suggests that some sort of "hiding" schema is being exercised by the organism, this behavior occurred much too early in the development of the structure to be of significance. In addition, hiding implies some ability for experiencing fear or insecurity. Clearly, this is not provided in the model.

In summary, the basic model testing, although it did not produce significant behavior, did provide the opportunity for debugging the fundamental programs, and, as mentioned previously, pointed the way for the creation of the second version of the model.

Section 3 - Implementation--Version 2

The modifications to the basic model to produce version two were made primarily to the executive and, thereby, to the cognitive structure. These were significant changes and required a considerable rewrite of the executive as well as the addition of one more utility program. Specifically, only

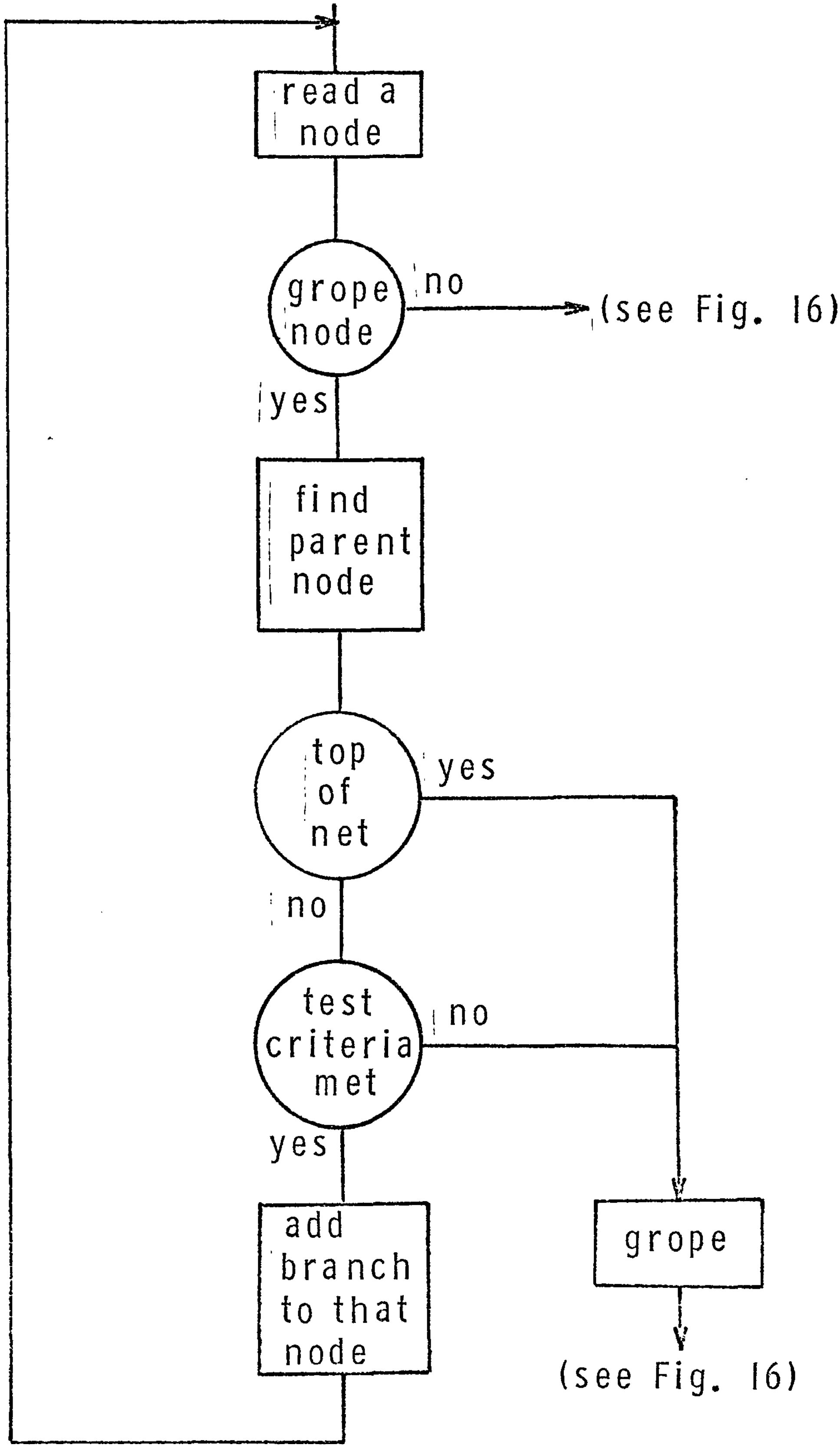


FIGURE 19. FLOWCHART OF EXECUTIVE-VERSION 2

42 per cent of the original executive was retained, while new programming equal to 105 per cent of the original executive was added.

The program runs faster in both computer and terminal time, although the great difference is in the terminal time. Terminal time of thirty minutes and computer time of nine and one-half minutes have been observed for runs equivalent to 200 cycles of the original programs. This will be discussed in detail later in this section.

The first modification made was to the groping facility to remove the capability of producing actionless test nodes (such nodes tended to obscure the performance of the basic model). This capability can be replaced fairly easily in the future if changes in experimental philosophy warrant it. For the present, this action will facilitate implementation of the modified executive and will simplify analysis of the program's performance.

The second modification was to the executive's handling of the "grope" node. This was the primary and most significant of the two modifications made. A facility was added which allows the executive to either create new structure or replace the "grope" node with a branch to an existing node which satisfies the conditions under which the grope would be performed.

The logic associated with this modification is demonstrated by the simplified flowchart in Figure 19, which indicates the changes made to the original logic shown in Figure 15. If a "grope" node is encountered, the executive searches back up the string of nodes which lead ultimately to the "grope" node under consideration. This search is accomplished by following a series of "branch back" paths (added to each node) which lead to the previous node in that string of nodes. The search is continued until the first node in the structure is found. If a node is found which contains a test criterion which would be the same as the test criterion that would be created by a grope, the executive replaces the "grope" node with a branch to that discovered node, and continues processing again at that discovered node.

This modification allows the development of the structures shown in Figure 20. In this much more complex structure, the model is not forced to learn redundantly. To some extent, the model can utilize old schema in new situations through this ability to connect new and old schema. There is no limit, except in computer memory size,to the number of new schema

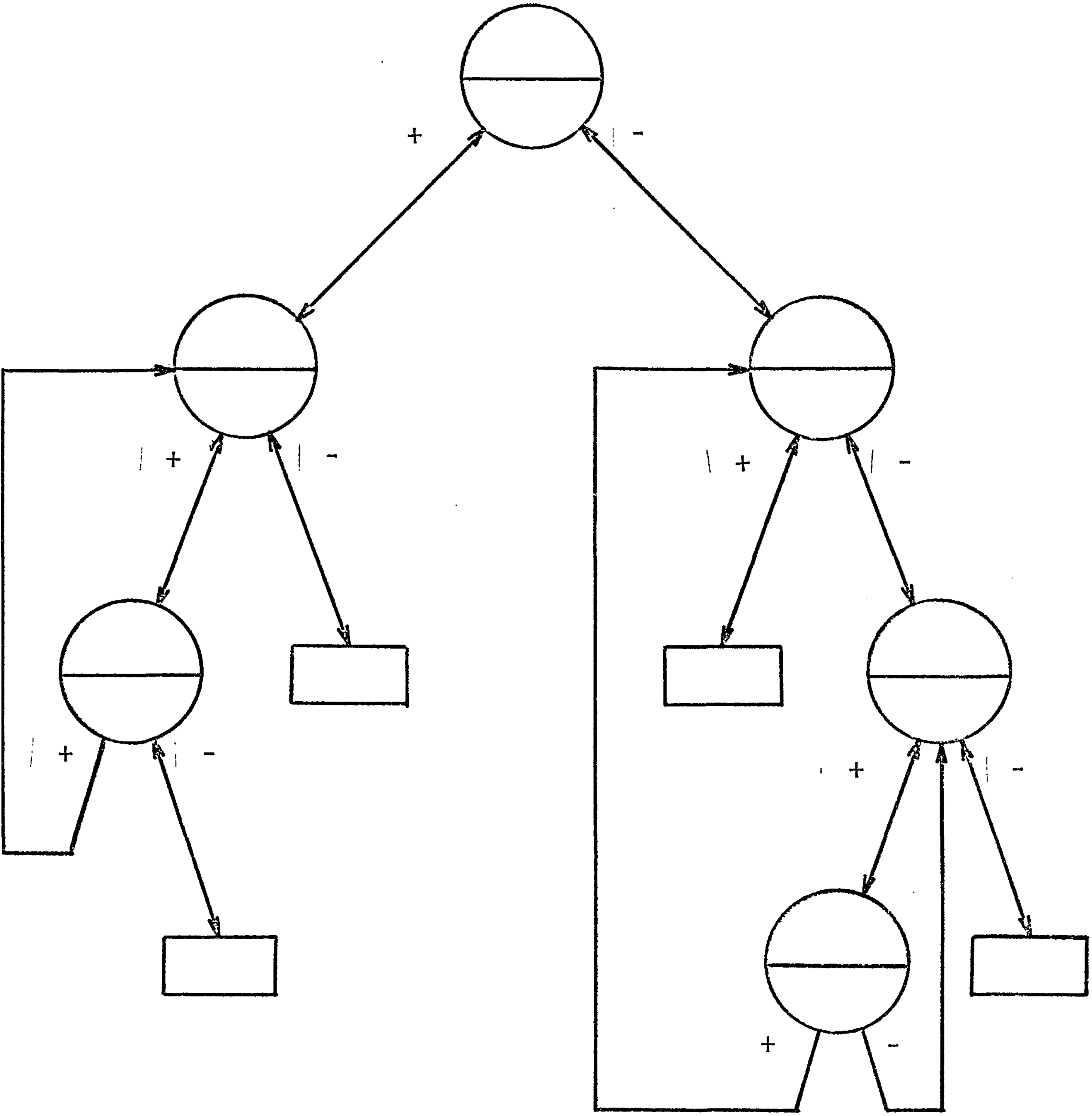


FIGURE 20. EXAMPLE STRUCTURE-VERSION 2

which can branch to the same old schema. This facility provides a measure of generalization lacking in the basic model.

Notice that the generalization is limited. A node can only be connected to another node that lies along the string of nodes that lead to it. This prevents schema from being generalized completely out of context. Completely arbitrary generalization could cause an inability to differentiate properly between completely different situations which have some minor similarities.

Although the idea of branching back to existing structure is suggested by Plummer's work, there is a fundamental difference between his use of the technique and the one discussed here. Plummer's model branches back to structure that fails to apply (i.e., tests that fail to be satisfied), in hopes that intervening actions have adjusted the situation so that the structure will now apply. In other words, the program "knows" it has been in a certain situation before, and it "wants" to be in that situation again. In this implementation, the structure branches back because the model does <u>not</u> "know" if it has been in the current situation before, but it would "like" to find out if it has. The behavior produced by the two models is often similar, but the structural approach is different.

It should also be noted that the facility provided is not the only possible method of providing a generalization capability.* This is simply a first attempt at providing a form of generalization in the model. Experimentation with this capability will be required before the validity of it can be evaluated and any further changes made.

Because of this primary modification, a redefinition of the "cycle" concept was required. It can be seen that with the new structure, it is possible for the executive to progress down a chain of nodes and, through a branch back to the first node of that chain, continue to simply loop through that schema over and over without ever reaching a "grope" node. For this reason, the "cycle" in the second version is defined not only as a pass through the structure until a "grope" node is encountered, but also as a pass through a structure until a branch back to a previous node is encountered.

Because of this redefinition of cycle, the relative performance of the two models are difficult to compare in terms of computer and terminal time. Experimentation has shown that approximately 2,000 cycles of the new version can produce the

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*Some additional thoughts on how generalization might be accomplished in the model are brought out in Chapter 6.

same number of nodes as 100 cycles of the original program. This is the basis of the performance figures given earlier. Experimentation has also shown, however, that as many as 3,000 cycles of the new version can produce as few as thirteen nodes. Since the number of new nodes produced per cycle in the new version ranges from .45(89/2000) to .004(13/3000), while the old version always produced two new nodes per cycle, the size of the structure and related amount of printing required to output that structure is drastically reduced. This reduced print load accounts for the reduction of terminal time by a factor of four. The less dramatic reduction of actual computer time is due to the fact that basically the same processing is required for each existing node as before, but the additional time for creation of so many new nodes is not required.

Section 4 - Preliminary Observations--Version 2

Initial experimentation with version two has pointed out the existence of a weakness in the model which potentially could be very detrimental to cognitive development. This will be pointed out through a description of the results of a 500 cycle run using the "sterile" environment and a 1,000 cycle run using the "rich" environment.*

Figure 21a shows the initial environment used for the 500-cycle run, while Figure 21b shows the final environment after the run. As can be seen, after the run the organism had moved its body down one cell and its hand down one cell and to the right two cells. This seems to be very little activity for a 500-cycle run. Closer examination of the organism's behavior indicates that the organism reached its final position within ten cycles of the start of the run and then simply remained in that location for the remaining 490 cycles. The only other movement observed was eye movement which occurred only during the first few cycles.

Examination of the cognitive structure developed, shown in Figure 22, indicates the reason for this behavior. It can be seen that the only eye movement function contained in the structure is the "eye right" inputted to the model as the initial structure. The statistics maintained for that node indicate that it was encountered only twelve times by the executive. This accounts for the few observed eye movements.

It can also be observed that only nineteen nodes and

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*Three productive runs with the "sterile" environment and one with the "rich" environment were made prior to completion of this paper.

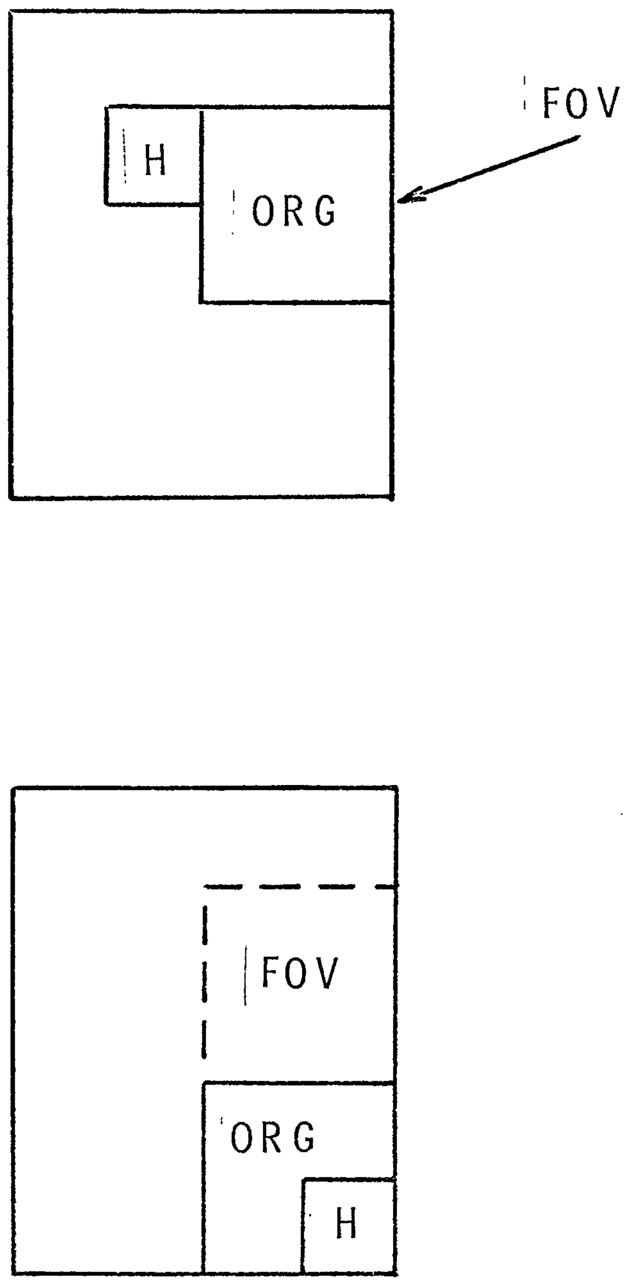

FIGURE 21

STERILE ENVIRONMENT - 500 CYCLE RUN

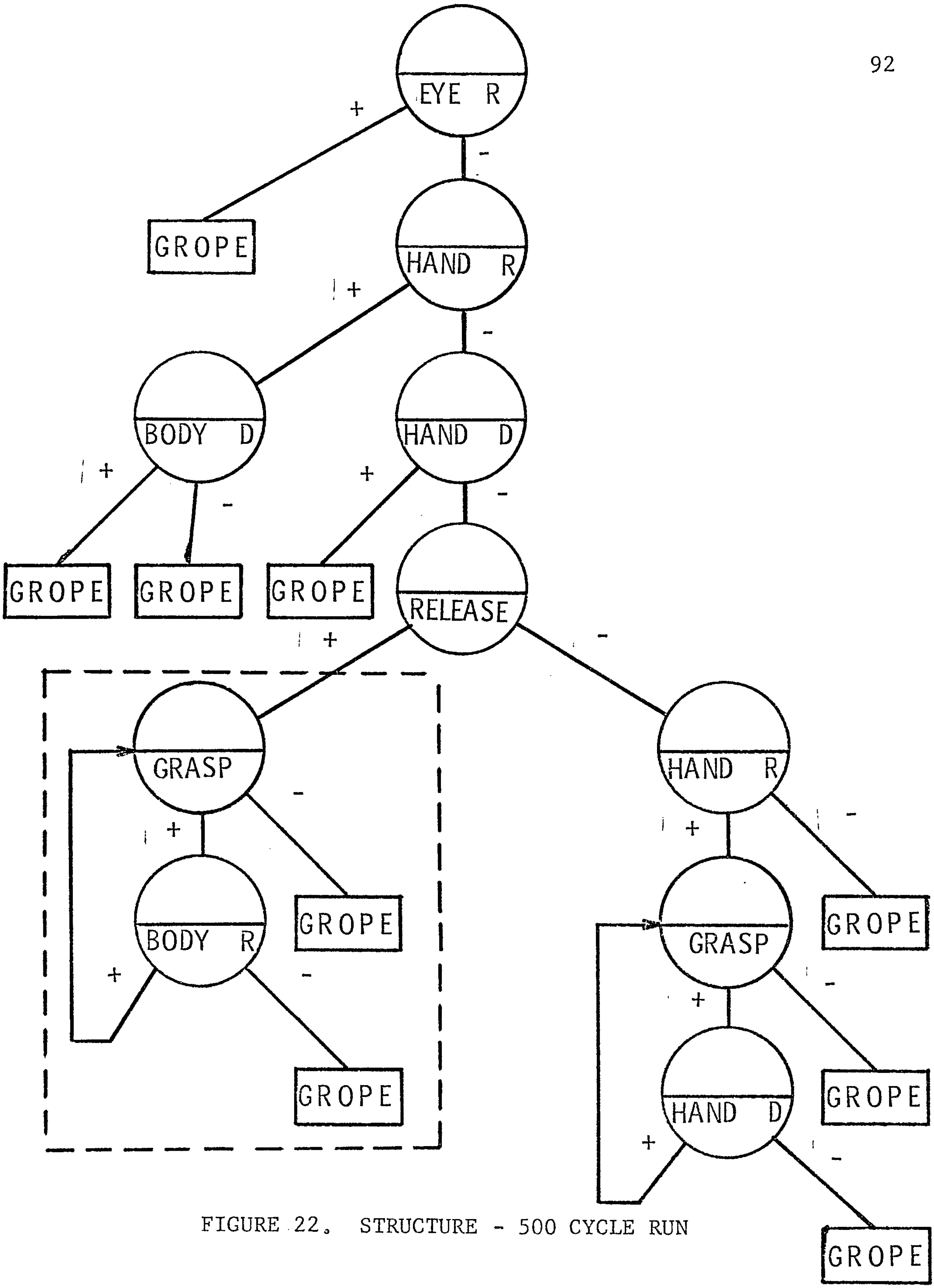

FIGURE 22. STRUCTURE - 500 CYCLE RUN

two branches to existing nodes account for all of the organism's activity and development over 500 cycles. The reason for this small amount of development is indicated in the statistics maintained for the two-node loop enclosed by a broken line in Figure 22. These two nodes represent a schemata which kept the organism trapped in the corner of the environment for so many cycles. These statistics indicate that this schemata was encountered 226 times by the executive. Thus the organism spent the last 226 of its allotted 500 cycles "playing" in the corner of the environment grasping its body and "bumping" against the wall on its right. It should be noted that the word playing used in this discussion is significant. Regardless of how the model's behavior is interpreted, this behavior is produced by predominantly assimilatory functioning which Piaget calls "playing." This will be discussed in Chapter 6.

These observations indicate that it is possible for the organism to develop schema of meaningless activity, which, if developed early in the growth of the structure and exercised under the right (or wrong as far as desired behavior is concerned) conditions, can form "loops" which are impossible for the organism to escape without external intervention. The intelligent organism has a facility which allows it to escape from such "play" when it results in no further stimulation. The intelligent organism can become bored and then exercise some more profitable schema. Notice that Piaget discusses the cognitive need to function in terms of the entire cognitive structure, not just parts of it. Certainly the child is not satisfied by exercising one of his schemata to the exclusion of all others. The model, on the other hand, will continue forever (literally, if the cycle concept were not present) until something external occurs. Therefore, it is apparent that a facility is required in the model which will cause the organism to become "bored" with an unprofitable schemata and escape from the behavioral loop.

Although this type of behavior was observed in the basic model, the organism could eventually escape the corner since the "groping" which always occurs in a cycle could eventually produce a movement out of the corner. In the second version, once the "loop" is established this type of escape is impossible.

It should be noted that this type of behavior is apparently dependent upon the conditions of the environment and is therefore magnified by the "sterile" environment test. The lack of a variety of sensory stimulation in the environment allows the organism to generalize too much. It would seem that a richer environment would reduce the occurrence of "playing" considerably. The 1,000-cycle "rich" environment confirmed this.

Figure 23a shows the initial environment for the 1,000-cycle "rich" run, and Figure 23b shows the final environment. As can be seen, the organism moved its body one cell right and three cells down while it moved its hand one cell down and one cell right to locate itself under the square object. Thus, it exhibited the same overt behavior as the original version in this situation. It took approximately 576 cycles through the structure to produce this total behavior. It should be noted that the movement to the final position was not direct. Many unnecessary movements were made during the run, and, in fact, many movements which counteracted previous movements, such as a "body right" followed by a "body left," occurred. After the first 576 cycles, the organism ceased any observable activity and simply remained in the same position.

The structure produced by this run is shown in Figure 24. Notice that a total structure of thirty-two nodes

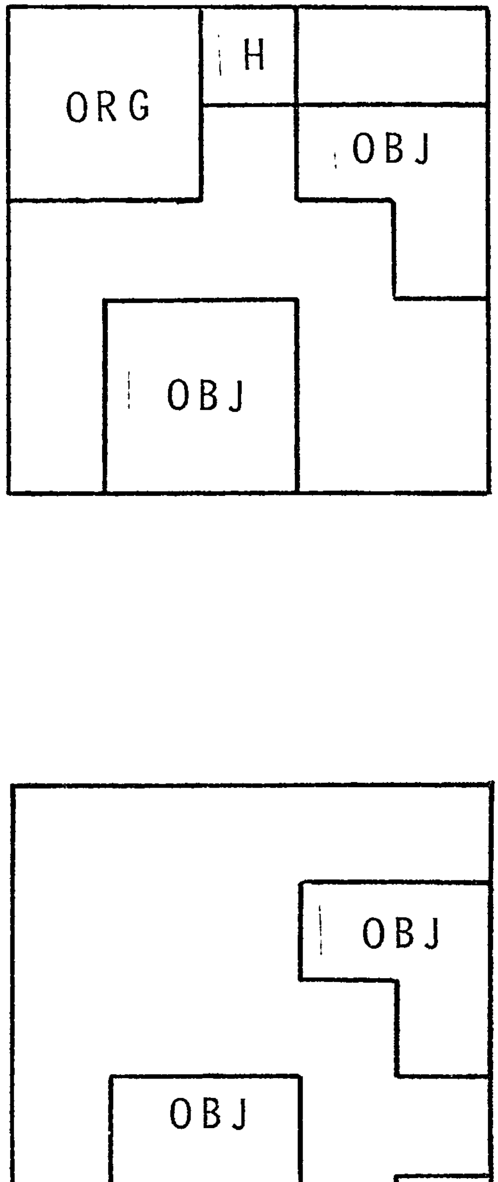

FIGURE 23

RICH ENVIRONMENT - 1,000 CYCLE RUN

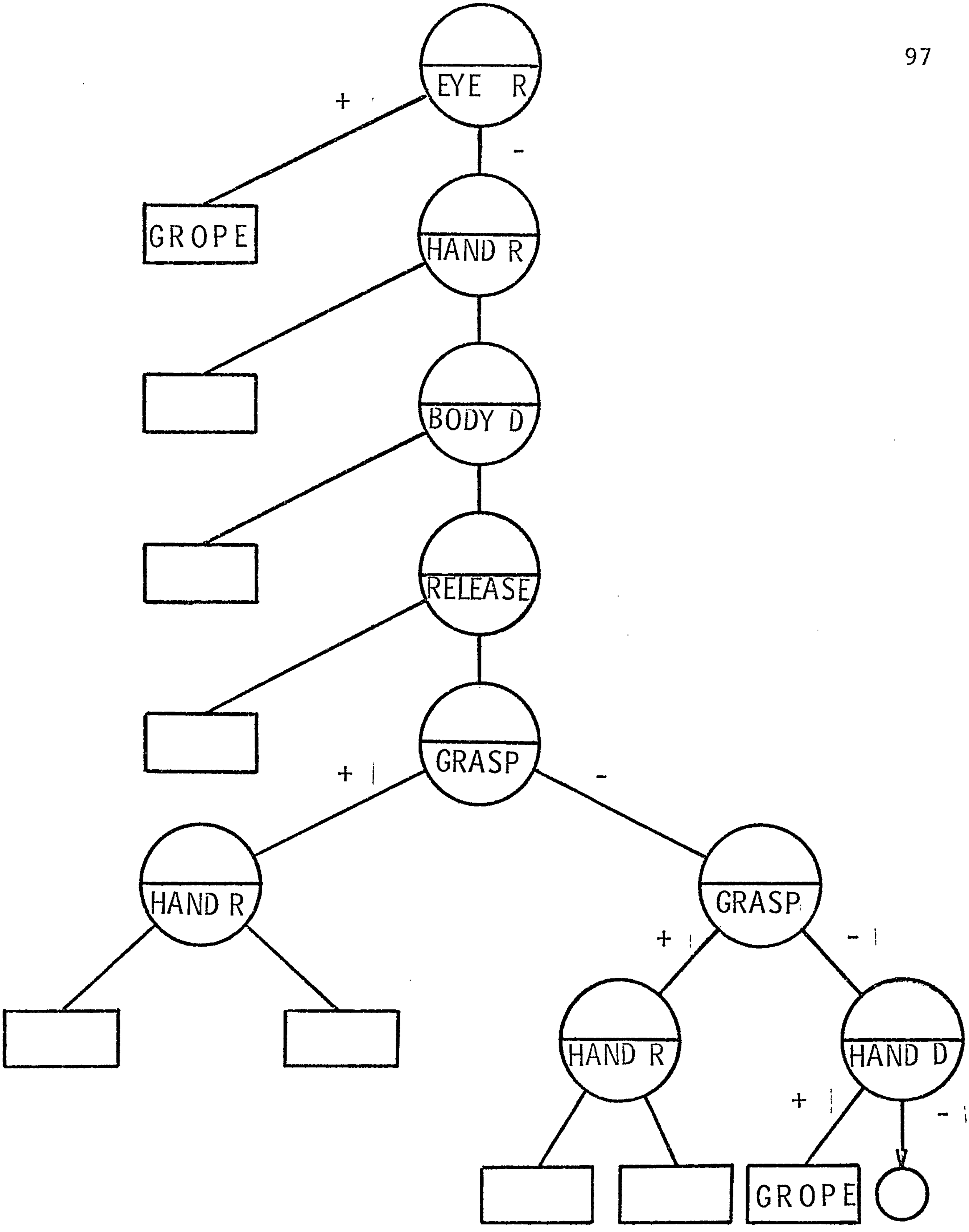

FIGURE 24. STRUCTURE - 1,000 CYCLE RUN

(Continued on next page)

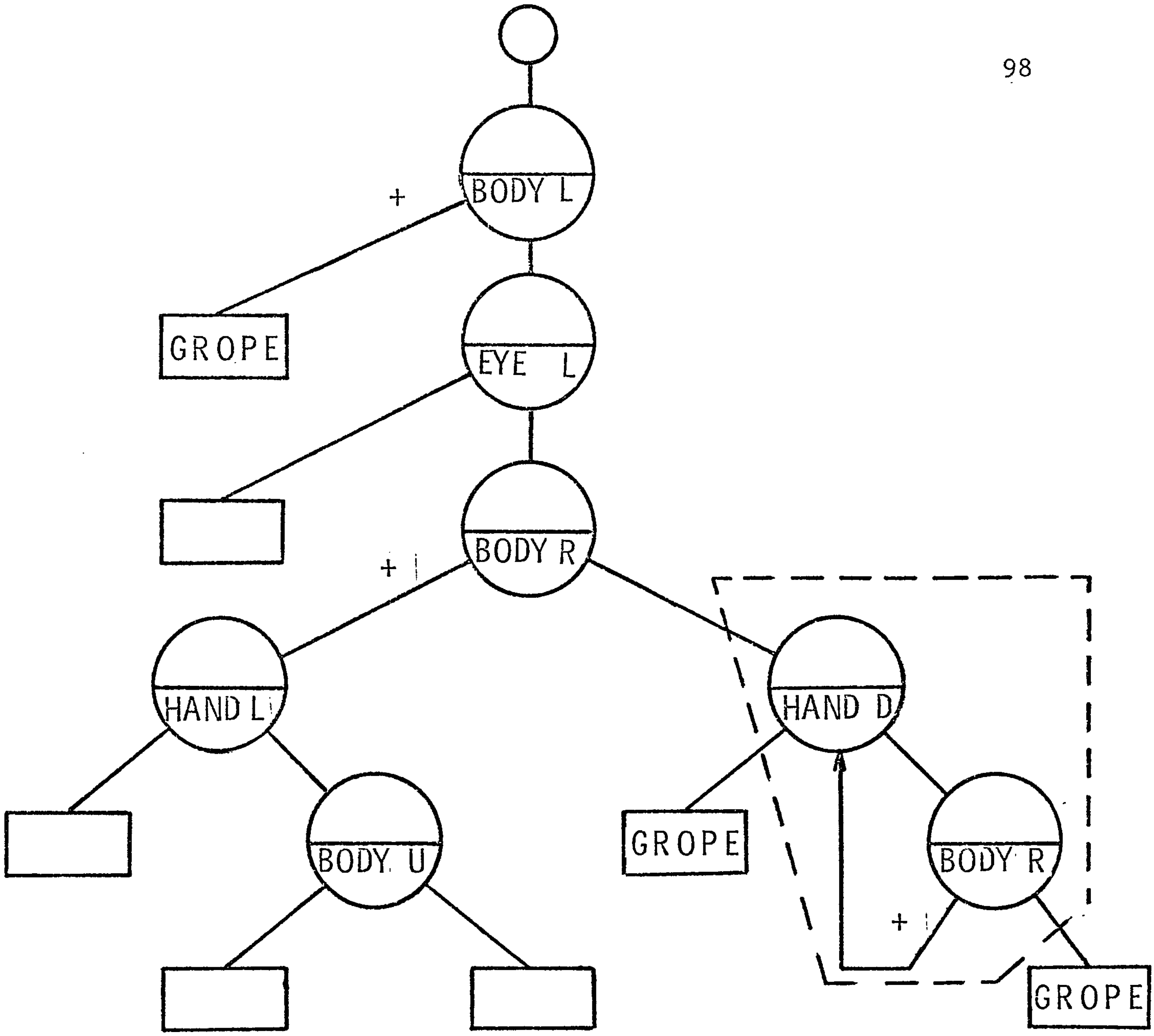

FIGURE 24. STRUCTURE - 1,000 CYCLE RUN
(Continuation)

and one branch back in this case produced the same overt behavior as eighty-nine nodes produced in the original version. This indicates the amount of redundant and unnecessary structure that was produced by the original version, and also indicates that the second version has indeed corrected those related problems.

Analysis of the structure and the statistics maintained concerning the structure indicates that even in this relatively rich environment a "playing" loop occurred. The two-node loop enclosed by the broken line in Figure 24 was encountered by the executive the last 424 cycles of the program. Analysis of that loop shows that the organism could not affect any perceivable change in the environment while in that loop. Both motor functions utilized in that loop would produce no movement because of the organism's location in the environment. The body could not move right because the organism's "hand" was against the right boundary; the organism could not move its hand down because its "hand" was against the bottom boundary. Thus, the organism simply "played" by pushing alternately against the two environmental boundaries with its "hand."

As expected, however, the occurrence of "playing" in the richer environment had less effect on the total performance of the model. This is shown by the greater amount of structure developed before a "playing" loop was created. It would seem reasonable to assume, then, that if the environment were made sufficiently rich, "playing" would not occur. However, it is still quite apparent that the weakness is still a weakness and can have a detrimental effect on the organism's development. It is necessary, then, that the effect felt be consistent with that effect on human behavior, and this necessitates the addition of "boredom" or "fatigue" facilities before completely acceptable use of the generalization facility can be obtained.

It should be noted that the human environment changes by itself, rather than only when manipulated by the organism. Such an environment would not be difficult to program, and spontaneous environmental change would almost always cause the model to exit from a "playing" loop.

Chapter 6

DISCUSSION AND CONCLUSION

Previous chapters have presented a model which is designed as a tool for the investigation of meaning in an artificial intelligence model based on Piaget's psychological theory, have discussed the results obtained from experimentation with the program to date, and have provided the background for this effort. This chapter will conclude the discussion of this model by pointing out the features of the model which are consistent with Piaget's theory and the features of the model which are a departure from those similar programs discussed in Chapter 3, and it will propose some future augmentations to the model and some future experimentation that might be the next logical step in this effort.

Section 1 - Piaget and the Model

It is apparent that the model which is presented is consistent with Piaget's theories. The model interacts with a physical environment and through this interaction develops a cognitive structure which directs that interaction. Cognitive structure development is the basis for cognitive growth. As in

Piaget's theory, two cognitive operators, assimilation and accommodation, act on the dynamic structures to produce structural change which is the basis for the organism's adaptation to its environment. These two operators can be visualized on two different levels of the model's functioning.

The first level of functioning of assimilation is obvious. The sensory-motor information available to the organism is changed into a set of parameters representing the view that each sense has of the environment. This test criterion is then placed into a framework (schema) of test and grope nodes interconnected with branches to produce an addition to the structure. These changes to the incoming information to produce structural growth are produced through assimilatory functioning. Along with this, accommodation is in play in the addition or rerouting of branches, the replacement of "grope" nodes with test nodes, and the appearance of new "grope" nodes. When this first level of assimilation is at work, the structure changes physically. This physical change is affected by accommodation.

There is another level of assimilation and accommodation which is not as obvious as the first. This is the level in play when no structural growth occurs. At this level assimilation affects the same type of change of the sensory-motor information being processed, but in this case those perceptual units are not used in structural growth, but as input to the executive's test as directed by the test nodes. In this form, incoming information is "fitted" into existing schemata and is used by the organism to direct behavior. Along with this level of assimilation is a similar level of accommodation. In this case no physical structural growth occurs. What does occur is that a particular part of the structure is "activated." This selective activation of a substructure is a form of accommodation.

Considering both levels of assimilation and accommodation, it can be seen that there is always some mix of them active. Unlike the first version of the programs, the second version provides the capability for temporary imbalances of assimilation and accommodation to occur in both the "playing" and the "imitative" directions. Whenever a grope is performed and new structure is grown, it is obvious that accommodation is the more active of the two operators. Structural growth implies primarily accommodative functioning in adding new schemata to the structure. This is "imitative" in Piaget's terms. When a branch back to existing structure is taken, no structural growth occurs. This lack of structural growth indicates that a minimum amount of accommodation is active. Assimilation is then much more active than accommodation, and in Piaget's terms "playing" occurs. This type of functioning is quite evident in the results presented in Section 4 of Chapter 5.

As in Piaget's theory, the model has a built-in drive to function. Unlike Piaget's theory, however, the model has no physical drives at all. The only drive provided is the simple facility that the executive will continue to function, returning to the beginning of the cognitive structure whenever the structure runs out and groping is performed, until the number of cycles specified is performed. Piaget indicates that the mental drive is sufficient in itself to cause development. The model is, then, an implementation of an organism in which the mental drive must be sufficient.

Although a stage of equilibrium has never been reached by the model, it is easy to see that the model is equipped to reach such a state. With the second version it has been shown that any combination of assimilation and accommodation is possible. It is certainly conceivable that under the correct environmental conditions and with the structure developed to the proper state, assimilation and accommodation could be in balance. But even in this state, grope nodes will exist, and through their existence the "discontinuity" exists which Piaget says will cause the structure to progress to another "stage." It can also be seen that true equilibrium can be visualized as a complete absence of grope nodes. That is, if the structure ever reached a state where all grope nodes had been replaced with branches to existing structure, there would be no "discontinuities" which would allow the structure to progress to another stage. The structure would be in a state of equilibrium which would prevent any further growth.

It is also apparent that the structure, though not yet the model itself, has the potential to represent internal models of reality. For example, a set of nodes and branches could occur which completely describe an object's shape in terms of sensory-motor perceptions observed from a number of locations around that object. This would be an internal model of that object's shape. The sensory-motor information which the model utilizes is designed to make it impossible for the organism to perceive the entire reality in its true two-dimensional form. The organism can develop a concept of reality only through the development of internal models of that reality made up of interconnected schemata.

Finally, the model is provided with a groping capability. Although the actual movement functions are chosen randomly, the groping activity is directed and is therefore consistent with Piaget's idea of groping. The structure "directs" groping to the level of determining the point at which groping will occur in an overall set of actions. Groping occurs only at a "grope" node, and the location of these nodes is dependent upon the structure itself. The action of groping is then in a sense "directed" by the organism through the cognitive structure.

In conclusion, then, it can be seen that conceptually, the model is firmly based in Piaget's theory, providing facilities which are consistent with the facilities to which Piaget attributes intelligent functioning, and interacting with a physical environment at a level which is analogously consistent with Piaget's definition of interaction by man.

Section 2 - The Model* and the Models

It is clear that the model provides facilities, consistent with many of Piaget's facilities, which the models discussed in Chapter 3 lacked.

The processors, Quillian's semantic memory and ARGUS, were lacking the facility to learn. Related to that was the

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*"The model" is the term used throughout the remainder of this paper to refer to the program described in Chapters 4 and 5.

inability to interact with an environment. Finally, the processors utilized perceptual information at the semantic level. Internal modeling was based on the interconnection of words, rather than on the actual significance of the words to the organism. The model, on the other hand, is designed to interact with an environment and to learn. Further, the model provides the proper level of perception of reality. The model can still handle semantic processing, however, even though no experimentation along these lines has been performed yet. This will be discussed further in Section 3.

The learners, such as EPAM, were lacking in the facility for a two-way interaction with a physical environment. The model, however, provides interaction at the sensory and motor level with a physical environment. The model can build internal models of a physical reality based on the implications of that reality to the model at a physical level.

The model falls into the general category of interactive learner, and the two models discussed in the category in Chapter 3 were Doran's automaton and Plummer's model. Since these programs are of the same type as the model, there are many similarities. It is these differences which are of interest in this discussion.

Doran's automaton was not designed to be a model of human intelligence or designed to explicitly follow a psychological theory. The automaton simulates a much lower level of intelligence and, therefore, differs considerably from the model. First, the sensory-motor abilities of the automaton are much cruder than those provided in the model. Second, the automaton is motivated purely by a physical drive, while the model is motivated strictly by the mental drive described by Piaget.

Plummer's program is the closest to the model presented in Chapter 4. Plummer's program, however, was designed to investigate the sensory-motor learning period, while the model is designed to be more general in nature to allow the investigation of meaning in many stages. Plummer's program's interaction with the environment is different than with the model because of the basic difference in the goals of the two programs. Plummer's organism is outside of the environment and looks down into it, something like an infant looking down on a table covered with blocks. Plummer's organism perceives the environment as it is--as a two-dimensional plane containing two-dimensional objects. Thus Plummer's program allows the organism to perceive objects as they are. The model, on the other hand, is designed to be in the environment and to perceive that environment in a representative way. That is, Plummer's organism sees and moves in the same number of dimensions while the model's organism sees in one less dimension than it moves. The organism cannot see the objects as they exist and must develop a concept of those objects through internal modeling.

Plummer's structure utilizes a branching back to existing structure in order to be in a situation that it "knows" it has been in before, while the model utilizes the branch back technique to try to find out if it has been in that situation before and to apply the structure it created in that situation to the present situation. Finally, Plummer's program has both physical and mental drives, while the model has only a mental drive.

In summary, then, the model presented in Chapter 4 differs to some extent from all the models discussed in Chapter 3. The model provides those facilities which the other programs were lacking to be completely consistent with Piaget's theory, and provides the facilities in such a way as to be useful in the problem of investigating meaning.

Section 3 - Future Work

Several modifications which might be further steps towards developing the model are suggested by the work done to date. Additional experiments also come to mind.

As discussed in Chapter 5, one modification which should be proposed is the addition of a facility which would allow the organism to escape from a playing loop. This could be implemented by either preventing such a loop from occurring by assuring that each new function placed in the cognitive structure causes something to happen in the environment, or by providing a "boredom" facility which would cause the organism to exit from a node through a new "boredom" exit which would lead to a grope node. The point at which the organism exits through this "boredom" branch could be based on the number of times the same action has been performed sequentially without anything happening in the environment. It was pointed out previously that such a facility is consistent with Piaget. The second method provides the ability for the organism to develop playing schemata and also provides for escape from loops which were meaningful when grown but because of environmental conditions have become potential playing loops. This makes it more attractive than the first method. Both methods should be tested through experimentation. In addition, a spontaneously changing environment would be useful in avoiding loops.

Another possible future modification involves the idea of generalization. Although a form of generalization is provided by version two of the model, additional generalization might prove valuable. This generalization involves the creation of the test criteria. At present, this test criteria is predefined as a complete set of all sensory-motor information available at the point groping occurs. This requires that the organism have a full set of identical information in order to recognize the same situation. This is not consistent with human behavior. It is apparent that man can generalize test criteria to the point that recognition is possible with a very limited set of meaningful information. A facility which should be provided and evaluated in the model is one which would allow the test criteria to consist of only the significant subset of all the information available.

Finally, one other possible modification is implied in the problem of generalization discussed above. This modification would be to provide a facility which would allow the organism to "consciously" choose test criteria based on other stored schema. At present test criteria are chosen by a predefined function. This facility would allow the organism to determine, based on the schema that it has developed, what test criteria are the significant test criteria for the particular grope being performed.

Several future lines of experimentation are also possible. Once a model version has performed properly in a "sterile" environment (i.e., has reached a stage in which it has developed a structure which provides some measure of sensory-motor coordination, some internal model of the organism itself, and some internal model of the basic laws of the environment), experimentation with a very rich environment should provide further insights into the model's strong and weak points. Once the organism has developed a structure in a "sterile" environment, the organism and its structure could be placed into a rich environment to allow investigation of the values of those old schema in a new situation. Comparison with this behavior and the behavior of an organism which was "raised" in the rich environment would be interesting.

One other line of experimentation is towards semantic processing and learning. The model can participate in a series of experiments which will evaluate its ability to handle semantic information in a way similar to the processors and learners discussed in Chapter 3. This requires that some alphabet be developed which will be consistent with the organism and its environment. It can be seen that in a three-dimensional environment, the alphabet consists of a set of two-dimensional figures which can be perceived in their entirety. The perception of these symbols is as they exist, and these completely perceivable symbols can be related to some reality which cannot be completely perceived. In the environment provided in the model, then, the alphabet must be a set of one-dimensional symbols which can be perceived in their entirety in their actual form and can be related to physical reality which cannot be completely perceived. The alphabet proposed here is an existing alphabet which has these characteristics--the international Morse code [14]. This language represents the alphabet in terms of dots and dashes which can be thought of as long and short one-dimensional lines. Since they are all one-dimensional lines, they can be viewed directly by the organism. Consider Figure 25. Here the environment has been constructed with small enough environmental cells that the organism can hold a large number of the cells in its field of view. A single, black environmental cell is defined as a "dot," and three consecutive black environmental cells define a "dash." One empty environmental cell separates the "dots"

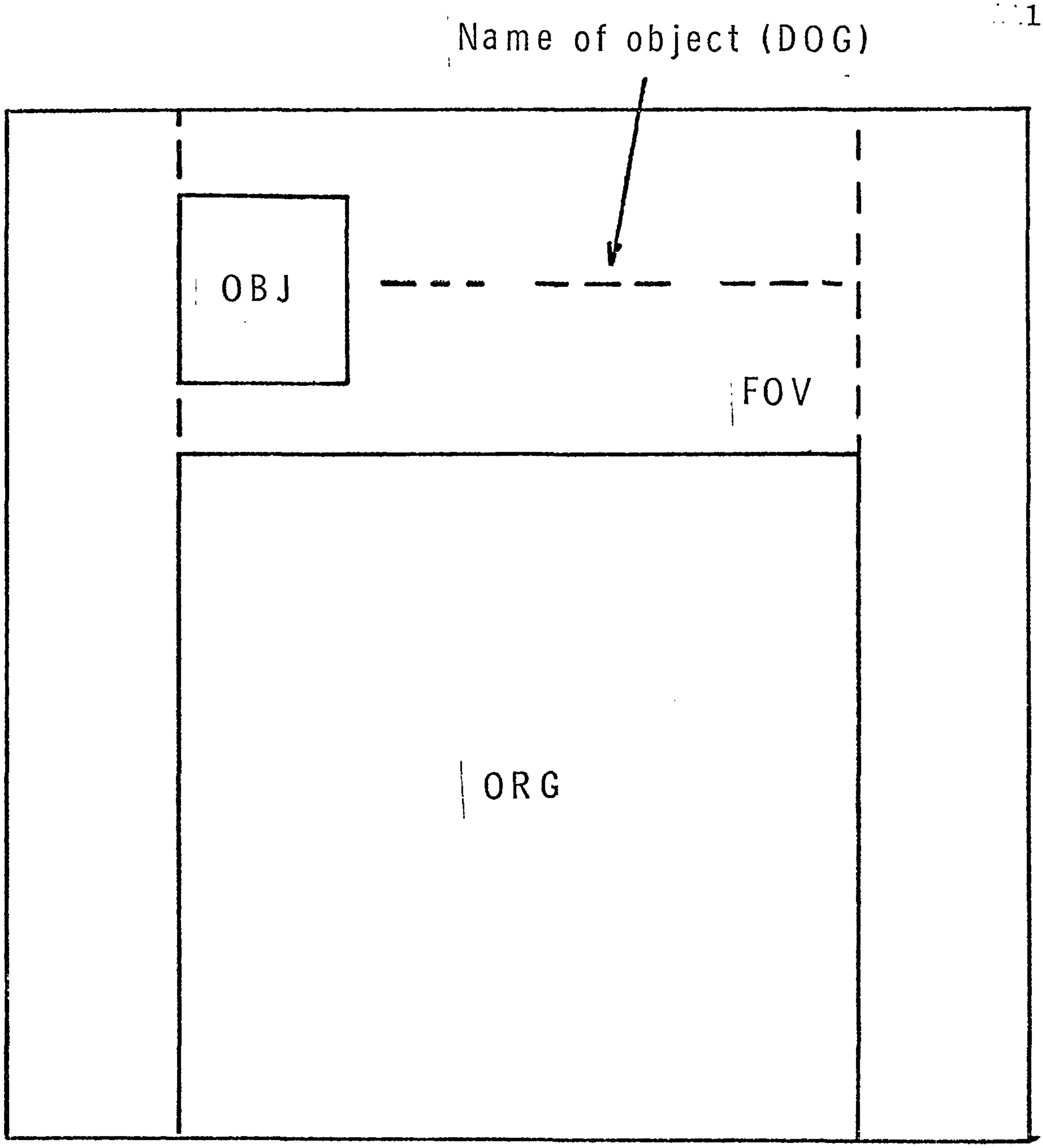


FIGURE 25

SEMANTIC ENVIRONMENT

and "dashes," and three empty environmental cells separate the groups of "dots" and "dashes" which make up a single letter. A set of six empty environmental cells can be used to separate words. In Figure 25, for example, the word "dog" is shown represented by a series of black and empty cells. The word can be placed in the FOV of the organism each time it observes the object. The organism would eventually assimilate that word to the existing structure which defines the object to the organism. The result would be, hopefully, the production of the same behavior by the organism towards the word as towards the object. In this way words could come to have meaning in the terms of what the object represented by the word means to the organism in a sensory-motor way. Once a large vocabulary was built up, the words would be related to one another through the interrelationship between the schema which defines those words, and semantic definitions would be formed through those connected paths.

Section 4 - Conclusion

Although the results observed in the experiments conducted to date were for the most part negative, they were the type of results which direct further development of the model towards ultimate success. The model is successful because it is consistent with Piaget's theory and because in that consistency it does produce behavior and develop cognitively. This indicates that the basic model is a tool that can be used in continued experimentation with different structural concepts, and that psychological theory is a useful tool in the creation of artificial intelligence programs.

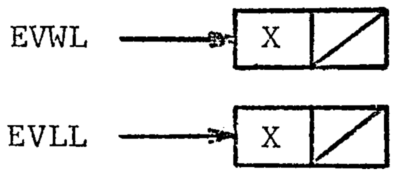
A P P E N D I C E S

APPENDIX A - STRUCTURES

I. Structure Used by the Executive

A. Environmental width and length vectors

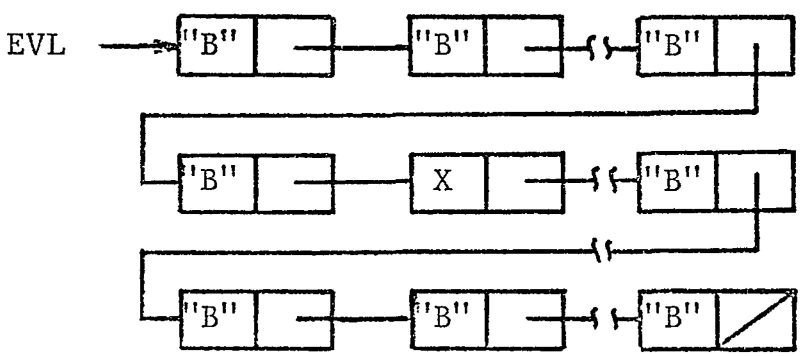
(EV<u>W</u>L and EV<u>L</u>L)--



X = number of cells in width of environment

X = number of cells in length of environment

B. Environmental Description List (EVL)--



First row of cells ("B" = border cells)

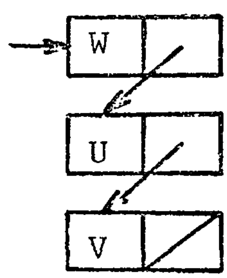
Second row

Last row

X =

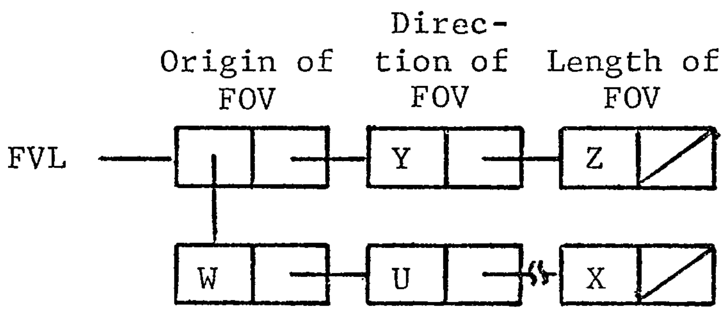
- "H" if the hand is in that cell
- "NIL" if the cell is empty
- "ORG" if the organism occupies that cell
- Object name if an object occupies that cell

or



Where; W is either "H" or "NIL"
U is either "ORG" or "NIL"
V is either Object name or "NIL."

C. Field of View List (FVL)--

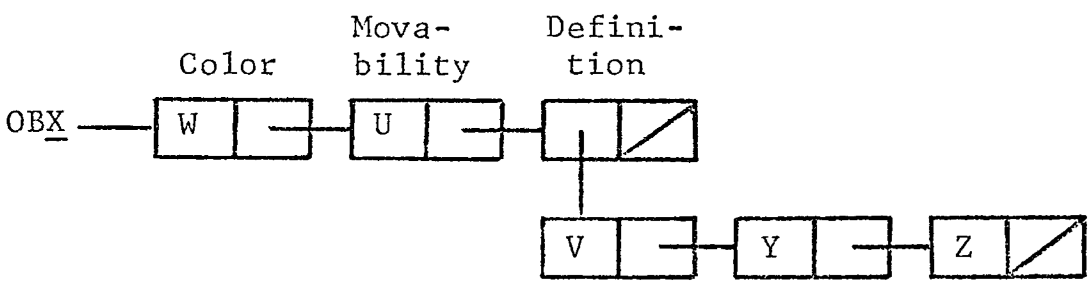


W, U, and X = cell numbers which define the origin of the FOV; must be one side of the organism

Y = North / South / East / West

Z = number of cells from origin to horizon of FOV

D. Object Definition List (OBL)--



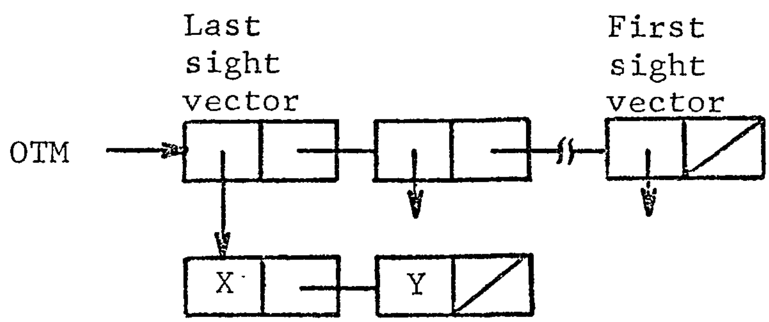
W = any color ("red,""blue," etc.)
X = identification of object (number)
U = (M = movable
(IM= fixed
V, Y, Z = cell number which make up object

E. OBL Index List (OBLL)

X, Y, Z = identification numbers of all objects in the environment

II. Structure Available to Organism and Executive

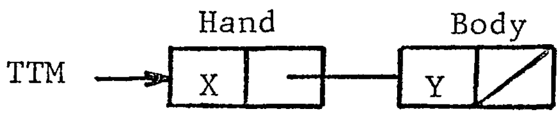
A. Optical Temporary Memory (OTM)--



X = color viewed by sight vector

Y = distance to object in sight vector

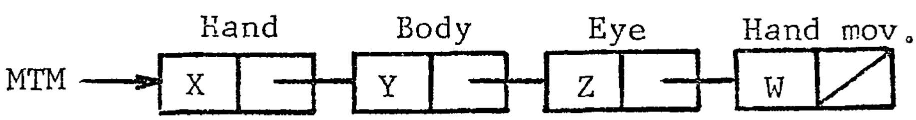
B. Tactile Temporary Memory (TTM)--



X = "NC" if hand is not in contact with something
"C" if hand in contact

Y = "NC" if body is not in contact with something
"C" if in contact

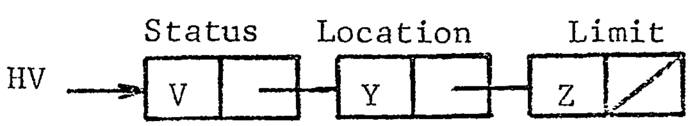
C. Motor Temporary Memory (MTM)--



X = "G" if hand is grasping
"R" if hand is released

Y, Z, W = last direction moved ("right," "left," "forward," or "back")

D. Hand Vector (HV)--

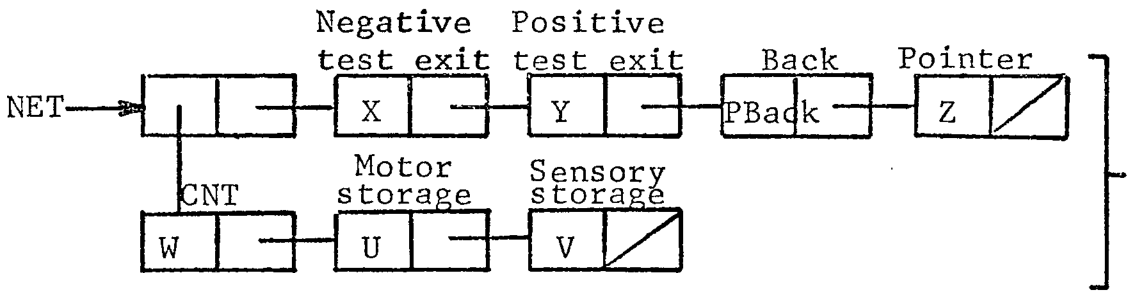


V = "NIL" if no object grasped
= object ID if object grasped

Y = number of EVL cell at which hand is located

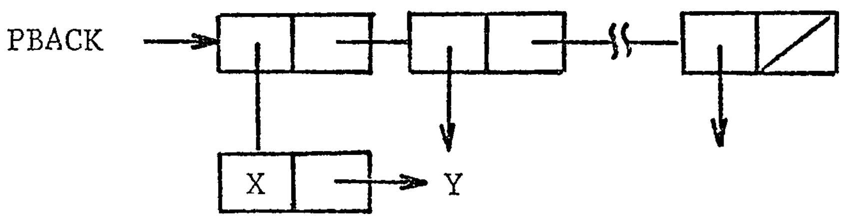
Z = number of cells from body that hand may move

E. Cognitive Structure - Version 2 (NET)--



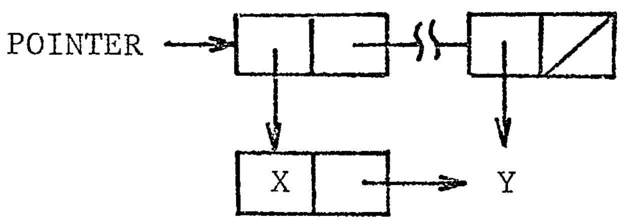
XY = branch to a following node, "grope" or identification (ID) of branch back to a previous node
Z = identification (ID) of branch to "parent" node
W = number of times executive has encountered this node
U = motor function stored when node was created
V = concatenated list of TTM, OTM, and MTM stored when node is created

F. Point Back Table (PBACK)--



X = ID of pointer to "parent" node
Y = Actual pointer to "parent" node

G. Pointer Table (Pointer)--



X = ID of pointer to some existing previous node
Y = actual pointer to node in NET

APPENDIX B - LISTING

```
(CSETQ HMØVE(LAMBDA(X Y)(PRØG(T1 T2 T3 T4 EVLN T5 T6 T7 ØBLLT)
(SETQ ØBLLT ØBLL)
(SETQ T7 ØBL)
(CØND((EQUAL X 'UP)(GØ U)))
(CØND((EQUAL X 'DØWN)(GØ D)))
(CØND((EQUAL X 'LEFT)(GØ L)))
(SETQ T1 9)
(GØ A1)
U(SETQ T1(MINUS EVWL))
(GØ A1)
D(SETQ T1 EVWL)
(GØ A1)
L (SETQ T1(MINUS 1))
A1(SETQ T2(CADR HV))
(SETQ T2(PLUS T1 T2))
(SETQ EVLN EVL)
(SETQ T3 0)
A2(CØND((NØT(LESSP T3(SUB1 T2)))(GØ A3)))
(SETQ T3(ADD1 T3))
(SETQ EVLN(CDR EVLN))
(GØ A2)
A3(CØND((EQUAL(CAR EVLN)'B)(RETURN NIL)))
A4(CØND((NULL T7)(RETURN NIL)))
(SETQ T3(CAR T7))
(SETQ T7(CDR T7))
(SETQ T5(CADDR HV))
A4A(CØND((ZERØP T5)(GØ A5)))
(CØND((EQUAL(PLUS(CAR T3)(TIMES T5 1))T2)(GØ A6)))
(CØND((EQUAL(ABSVAL(DIFFERENCE(CAR T3)(TIMES T5 1)))T2)(GØ
A6)))
(CØND((EQUAL(PLUS(CAR T3)(TIMES T5 EVWL))T2)(GØ A6)))
(CØND((EQUAL(ABSVAL(DIFFERENCE(CAR T3)(TIMES T5 EVWL)))T2)
(GØ A6)))
(SETQ T5(SUB1 T5))
(GØ A4A)
A5
(SETQ T3(CDR T3))
(CØND((NULL T3)(GØ A4)))
(SETQ T5(CADDR HV))
(GØ A4A)
A6(CØND((NØT(NULL(CAR HV)))(GØ A8)))
A7(CSETQ HV(LIST(CAR HV)T2(CADDR HV)))
(CSETQ XIM(LIST(CAR XIM)(CADR XIM)(CADDR XIM)X))
(CØND((NØT(EQUAL Y 'T))(NEWL)))
(RETURN T)
A8(CØND((NØT(EQUAL(CAR HV)'ØNG))(GØ A9)))
(CØND((EQUAL Y 'E)(GØ A7)))
(RETURN NIL)
A9(CØND((EQUAL(CAR HV)'E)(RETURN NIL)))
(CØND((EQUAL(CADDR (GET ØBL(CAR HV)))'IM)(RETURN NIL)))
(CØND((ATØM(CAR EVLN))(GØ A10)))
(CØND((NØT(NULL(CADDAR EVLN)))(RETURN NIL)))
```

```
A10(COND((EQUAL(CAR EVLN) ORG)(GO A11)))
(COND((EQUAL(CAR EVLN) H)(GO A11)))
(COND((NULL(CAR EVLN))(GO A11)))
(RETURN NIL)
A11(SETQ T3 NIL)
(SETQ T4(CADDDR(GET OBL(CAR HV))))
A12(COND((NULL T4)(GO A15)))
(SETQ T5(CAR T4))
(SETQ T4(CDR T4))
A13(SETQ T6(APPEND T6(LIST(PLUS T5 T1))))
(GO A12)
A15(COND((NULL OBLLT)(GO A19)))
(COND((NOT(EQUAL(CAR OBLLT)(CAR HV)))(GO A16)))
(SETQ OBLLT(CDR OBLLT))
(GO A15)
A16(SETQ T3(CADDDR(GET OBL(CAR OBLLT))))
(SETQ T5 T6)
A17(COND((NOT(NULL T5))(GO A18)))
(SETQ OBLLT(CDR OBLLT))
(GO A15)
A18(COND((MEMBER(CAR T5)T3)(RETURN NIL)))
(SETQ T5(CDR T5))(GO A97)
A19(SETQ T3 EVWL)
(SETQ T5 T6)
A19A(SETQ T7 0)
A20(COND((EQUAL(CAR T5)(MINUS T3 T7))(RETURN NIL)))
(SETQ T7(ADD1 T7))
(GO A20)
A21(SETQ T7 1)
A22(COND((EQUAL T7 EVLL)(GO A23)))
(COND((EQUAL(CAR T5)(TIMES T3 T7))(RETURN NIL)))
(COND((EQUAL(CAR T5)(ADD1(TIMES T3 T7)))(RETURN NIL)))
(SETQ T7(ADD1 T7))
(GO A22)
A23(SETQ T7 0)
A24(COND((EQUAL T7(SUB1 EVWL))(GO A25)))
(COND((EQUAL(CAR T5)(DIFFERENCE(TIMES EVLL EVWL)T7))(RETURN NIL)))?

(SETQ T7(ADD1 T7))
(GO A24)
A25(COND((NULL T5)(GO A26)))
(SETQ T5(CDR T5))
(GO A99A)
A26(PUT OBL(CAR HV)(LIST(CAR(GET OBL(CAR HV)))
(CADR(GET OBL(CAR HV)))(CADDR(GET OBL(CAR HV)))T6))
(GO A7) )))
(CSETQ BMOVE(LAMBDA,X)(PROG(T1 T2 T3 T4 T5 T6 OBLT)
(SETQ T6 OBL)


(SETQ T4(LIST))
(COND((EQUAL X 'UP)(GO U)))
(COND((EQUAL X 'DOWN)(GO D)))
(COND,(EQUAL X 'LEFT)(GO L)))
(SETQ T1 1)
(GO A1)
U(SETQ T1(MINUS EVLL))(GO A1)
D(SETQ T1 EVLL)(GO A1)
L(SETQ T1(MINUS 1))
A1  (SETQ T3 (LIST))(COND((NULL T6)(GO A4)))
(SETQ T2(CAR T6))
(SETQ T6(CDR T6))
A2(COND((NULL T2)(GO A3)))
(SETQ T3(APPEND T3(LIST(PLUS T1(CAR T2)))))
(SETQ T2(CDR T2))
```

```
A4(SETQ T3 T4)
A5(COND((NULL T4)(GO A7)))(SETQ T1(CAR T4))
(SETQ T4(CDR T4))
A6(COND((NULL T1)(GO A5)))
(SETQ T2(CAR T1))
(SETQ T1(CDR T1))
(SETQ T5 EVL)
A6A(COND((ZEROP(SUB1 T2))(GO A6C)))
(SETQ T5(CDR T5))
(SETQ T2(SUB1 T2))
(GO A6A)
A6B(COND((NOT(ATOM(CAR T5)))(GO A6)))
(COND((EQUAL(CAR T5) 'B)(RETURN NIL)))
(GO A6)
A7( SETQ ODLT ODL)(CSETQ ODL T3) (COND((HAOVE X 'B)(GO A8)))
(CSETQ ODL ODLT)
(RETURN NIL)
A8
(CSETQ MTM(LIST(CAR MTM)X(CADDR MTM)(CADDDR MTM)))
(REVL)
(RETURN T) )))
(CSETQ GRASP(LAMBDA()(PROG(CNT TEMP)
(SETQ CNT 0)
(SETQ TEMP EVL)
(COND((EQUAL GN(CAR MTM)-(RETURN NIL)))
(CSETQ MTM(CONS GN(CDR MTM)))
A1(COND,(EQUAL CNT(SUB1 (CADR HV)))(GO A2)))
(SETQ TEMP(CDR TEMP))
(SETQ CNT(ADD1 CNT))
(GO A1)
A2(COND((ATOM(CAR TEMP))(GO A4)))
X(COND((NULL(CADDAR TEMP))(GO A3)))
(CSETQ HV(CONS(CADDAR TEMP)(CDR HV)))
(PUT OBL(CADDAR TEMP)(APPEND(LIST(CAR(GET OBL(CADDAR TEMP)))
GN)(CDDR(GET OBL(CADDAR TEMP)))))
(GO A4)
A3(CSETQ HV(CONS 'ORG(CDR HV)))
A4(TOUCH)
(RETURN T) )))
(CSETQ RELEASE(LAMBDA()(PROG(Z)
(CSETQ GN 'R)
(COND((GRASP)(GO A1)))
(SETQ Z NIL)
(GO A2)
A1(SETQ Z T)
A2(CSETQ GN 'G)
(CSETQ HV(CONS NIL (CDR HV)))
(RETURN Z) )))
(CSETQ EYE(LAMBDA(X)(PROG(T1 T2 T3 T4)
(SETQ T2 ODL)
L(COND((EQUAL X 'RIGHT)(GO R)))
(COND((EQUAL(CADR EVL) 'SOUTH)(GO E)))
(COND((EQUAL(CADR EVL) 'NORTH)(GO W)))
(COND((EQUAL(CADR EVL) 'EAST)(GO S)))
(GO N)
R (COND((EQUAL(CADR EVL) 'NORTH)(GO E)))
(COND((EQUAL(CADR EVL) 'SOUTH)(GO W)))
(COND((EQUAL(CADR EVL) 'WEST)(GO S)))
S(SETQ T1(CAR T2))
(COND((NOT(NULL(CDR T2)))(GO S1)))
(CSETQ EVL(LIST T1 'SOUTH (CADDR EVL)))
(GO OUT)
```

```
W (SETQ T3(LIST  ))
W1A(COND((NULL T2)(GO W1)))
(SETQ T3(APPEND T3 (LIST(CAAR T2))))
(SETQ T2(CDR T2))
(GO W1A)
AW1(CSETQ FVL(LIST T3 'WEST(CADDR FVL)))
(GO OUT)
E(SETQ T3 (LIST  ))
E1A(COND((NULL T2)(GO E3)))
(SETQ T4(CAR T2))
E1(COND((NOT(NULL(CDR T4)))(GO E2)))
(SETQ T3(APPEND T3 (LIST (CAR T4))))
(SETQ T2(CDR T2))
(GO E1A)
E2(SETQ T4(CDR T4))
(GO E1)
E3(CSETQ FVL(LIST T3 'EAST(CADDR FVL)))
OUT(CSETQ MTM(LIST(CAR MTM)(CADR MTM) X (CADDDR MTM)))
(LOOK)
(RETURN T) )))
(CSETQ TOUCH(LAMBDA()(PROG(TEMP)
(SETQ TEMP EVL)
(CSETQ TTM(LIST 'NC 'NC))
A1(COND((NULL TEMP)(RETURN T)))
(COND((NOT(ATOM(CAR TEMP)))(GO A2)))
(SETQ TEMP(CDR TEMP))
(GO A1)
A2(COND((NULL(CAAR TEMP))(GO A4)))
A3(CSETQ TTM(CONS(QUOTE C)(CDR TTM)))
(COND((NOT(NULL(CADAR TEMP)))(GO A5)))
(SETQ TEMP(CDR TEMP))
(GO A1)
A4(CSETQ TTM(LIST 'NC 'C))
(SETQ TEMP(CDR TEMP))
(GO A1)
A5(CSETQ TTM(LIST 'C 'C))
(RETURN T) )))
(CSETQ LOOK(LAMBDA ()(PROG(T1 T2 T3 TC CNT CNT2)
(CSETQ OTM NIL)(SETQ CNT 1)(SETQ CNT2 0)
(COND((NULL FVL)(RETURN NIL)))
(SETQ T2(CAR FVL))
(COND((EQUAL(CADR FVL)'SOUTH)(GO S)))
(COND((EQUAL(CADR FVL)'NORTH)(GO N)))
(COND((EQUAL(CADR FVL)'WEST)(GO W)))
(SETQ T1 1)
(GO A1)
S(SETQ T1 EVAL)
(GO A1)
N(SETQ T1(MINUS EVAL))
(GO A1)
W(SETQ T1(MINUS 1))
A1
(SETQ CNT 1)
(COND((NULL T2)(RETURN T)))
A2
(SETQ TC(CAR T2))
(SETQ T2(CDR T2))
A2A
(SETQ T3 EVL)
(SETQ CNT2 0)
A3(COND((NULL T3)(RETURN NIL)))
A5(SETQ CNT2(ADD1 CNT2))
```

```
(CSETQ ØTM(CØNS(LIST CNT 'BLACK)ØTM))
(SETQ T1(QUØTIENT T1 CNT))
(GØ A1)
A6(SETQ T3(CDR T3))
(GØ A3)
A7(CØND((ATØM(CAR T3))(GØ A8)))
A4(CØND((NØT(NULL(CADDAR T3)))(GØ A4B)))
A4A(CSETQ ØTM(CØNS(LIST CNT 'FLSH)ØTM))
(SETQ T1(QUØTIENT T1 CNT))
(GØ A1)
A4B(CSETQ ØTM(CØNS(LIST CNT(CAR (GET ØBL (CADDAR T3))))ØTM))
(SETQ T1(QUØTIENT T1 CNT))
(GØ A1)
A8(CØND((NULL(CAR T3))(GØ A9)))
(CØND((EQUAL(CAR T3) 'H)(GØ A4A)))
(CØND((EQUAL(CAR T3) 'ØRG)(GØ A4A)))
(CSETQ ØTM(CØNS(LIST CNT (CAR(GET ØBL (CAR T3))))ØTM))
(SETQ T1(QUØTIENT T1 CNT))
(GØ A1)
A9(SETQ T1(QUØTIENT T1 CNT))(CØND((EQUAL CNT(CADDR FVL))(GØ A10))) (SETQ

        CNT(ADD1 CNT))
(SETQ T1(TIMES T1 CNT))
(GØ A2A)
A10(CSETQ ØTM(CØNS(LIST NIL)ØTM))
(GØ A1) )))
(CSETQ ASSØC(LAMBDA(E L)(CØND((NULL L)NIL)((EQUAL E(CAAR L
))(CAR L))(T(ASSØC E(CDR L)))))))
(CSETQ ABSVAL(LAMBDA(X)(PRØG()
(CØND((MINUSP X)(RETURN(MINUS X)))(T(RETURN X)))
)))
(CSETQ CREE(LAMBDA()(PRØG(T1 T2 TCNT)
(SETQ T1 0)
(SETQ T2 EVL)
(SETQ TCNT 0)
A1(CØND((NØT(NULL T2))(GØ A2)))
(CSETQ EVLL,QUØTIENT (ADD1 TCNT) EVWL))
(RETURN T)
A2(SETQ TCNT(ADD1 TCNT))
(CØND((NØT(EQUAL(CAR T2) 'B))(GØ A3)))
(SETQ T2(CDR T2))
(GØ A1)
A3(CØND((NØT(EQUAL  T1 1))(GØ A4)))
(SETQ T2(CDR T2))
(GØ A1)
A4(CSETQ EVL (SUB1(SUB1 TCNT)))
(SETQ T1(ADD1 T1))
(SETQ T2(CDR T2))
(GØ A1) )))
(CSETQ NEVL(LAMBDA()(PRØG(CNT T1 T2 T3 TCNT)
(SETQ CNT 1)
(SETQ T1 EVL)
(CSETQ EVL (LIST 'B))
(SETQ T1(CDR T1))
A1(CØND((NULL T1)(RETURN T)))
(SETQ CNT(ADD1 CNT))
(CØND((NØT(EQUAL(CAR T1) 'B))(GØ A3)))
(CSETQ EVL(APPEND EVL(LIST 'B)))
A2 (SETQ T1(CDR T1))
(GØ A1)
A3
(SETQ T2 ØBL)
A4(CØND((NULL T2)(GØ A8)))
(SETQ T3(CADDDR(GET ØBL (CAR T2))))
```

```
A6(CØND((EQUAL CNT(CAR T3))(GØ A7)))
(SETQ T3(CDR T3))
(GØ A5)
A7(SETQ TLIST(LIST(CAR T2)))
(GØ A9)
A8(SETQ TLIST(LIST NIL))
A9(SETQ T2 ØDL)
A10(CØND((NØT(NULL T2))(GØ A11)))
(SETQ TLIST(CØNS NIL TLIST))
(GØ A15)
A11(SETQ T3(CAR T2))
A12(CØND((NØT(NULL T3))(GØ A13)))
(SETQ T2(CDR T2))
(GØ A10)
A13(CØND((EQUAL CNT(CAR T3))(GØ A14)))
(SETQ T3(CDR T3))
(GØ A12)
A14(SETQ TLIST(CØNS 'ØRG TLIST))
A15(CØND((EQUAL CNT(CADR HV))(GØ A20)))
(SETQ TLIST(CØNS NIL TLIST))
(CØND((NULL(CADR TLIST))(GØ A18)))
(CØND((NULL(CADDR TLIST))(GØ A17)))
A16(CSETQ EVL(APPEND EVL(LIST TLIST)))
(SETQ T1(CDR T1))
(GØ A1)
A17(CSETQ EVL(APPEND EVL(LIST 'ØRG)))
(SETQ T1(CDR T1))
(GØ A1)
A18(CØND((NULL(CADDR TLIST))(GØ A19)))
(CSETQ EVL(APPEND EVL(LIST(CADDR TLIST))))
(SETQ T1(CDR T1))
(GØ A1)
A19(CSETQ EVL(APPEND EVL(LIST NIL)))
(SETQ T1(CDR T1))
(GØ A1)
A20(SETQ TLIST(CØNS 'H TLIST))
(CØND((NØT(NULL(CADR TLIST)))(GØ A16)))
(CØND((NØT(NULL(CADDR TLIST)))(GØ A16)))
(CSETQ EVL(APPEND EVL(LIST 'H)))
(SETQ T1(CDR T1))
(GØ A1) )))
(CSETQ RANDØM(LAMBDA()(PRØG()
(SETQ LRAN(TIMES LRAN 20613))
(CØND((MINUSP LRAN)(SETQ LRAN(PLUS LRAN 34359738367))))
(SETQ RAN(TIMES LRAN 0.29103830E-10))
(CØND((LESSP(ABSVAL(ENTIER(TIMES RAN 10)))1)(GØ A1)))
(RETURN(ABSVAL(ENTIER(TIMES RAN 10))))
A1(CØND((LESSP(ABSVAL(ENTIER(TIMES RAN 100)))1)
(GØ A2)))
(RETURN(ABSVAL(ENTIER(TIMES RAN 100))))
A2(CØND((LESSP(ABSVAL(ENTIER(TIMES RAN 1000)))1)(GØ A3)))
(RETURN(ABSVAL(ENTIER(TIMES RAN 1000))))
(CSETQ EXEC2(LAMBDA(LCNT IRAN ILRAN)(PRØG (T1 T2 NØDE PC MCNT
T3
ØTMT)
(CLEAR)
(CSETQ PØINTER (LIST (LIST 0 NIL)))
(CSETQ FBACK(LIST (LIST 0 NIL)))
(CSETQ CN 'G)
(SETQ PC 0)
(CØND((NULL IRAN)(CSETQ RAN 0))(T(CSETQ RAN IRAN)))
(CØND((NULL ILRAN)(CSETQ LRAN 4097))(T(CSETQ LRAN ILRAN)))
(SETQ MCNT 0)
START
```

```
T2(SETQ NODE(ASSOC(CADR(CAAR LOCP))(CDAAR LOCP)))
(SETQ MCNT(ADD1 MCNT))
(COND((EQUAL MCNT ECNT)(GO END)))
(SETQ OTMT OTM)
(SETQ T2(LIST NIL))
(RPLACD T2 LOCP)
(SETQ T2(CADR T2))
(RPLACA T2 NODE)
(EVAL (CADR NODE))
(COND((NOT(EQUAL(CAR TTM)(CAADDR NODE)))(GO F1)))
(COND((NOT(EQUAL(CADR TTM)(CADADDR NODE)))(GO F1)))
(COND((NOT(EQUAL(CAR MTM)(CADDADDR NODE)))(GO F1)))
(COND((NOT(EQUAL(CADR MTM)(CADDDADDR NODE)))(GO F1)))
(COND((NOT(EQUAL(CADDR MTM)(CADDDDADDR NODE)))(GO F1)))
(COND((NOT(EQUAL(CADDDR MTM)(CADDDDDADDR NODE)))(GO F1)))
(CSETQ NN(CDDDDDDADDR NODE))
(COND((NULL NN)(GO F1)))
E3 (COND((NULL OTMT)(GO E4)))
(SETQ T1(CAR OTMT))
(SETQ OTMT(CDR OTMT))
(SETQ T3(CAR NN))
(SETQ NN(CDR NN))
E3A (COND((NULL T1)(GO E3)))
(COND((NOT(EQUAL(CAR T1)(CAR T3)))(GO F1)))
(SETQ T1(CDR T1))
(SETQ T3(CDR T3))
(GO E3A)
E4 (COND((EQUAL(CADDAR LOCP) 'GROPE)(GO E5)))
(COND((EQUAL(CAADDAR LOCP) 'POINTER)(GO P1)))
(RPLACA LOCP(CADDR T2))
(GO E2)
E5 (SETQ T2(LIST NILL))
(RPLACA T2(CAR LOCP))
E5A (COND((EQUAL(CADDDAR T2)0)(GO E5X)))
  (COND((EQUAL(CADDDDR(ASSOC(CADDDAR T2)PBACK))0)(GO
E5X)))
(RPLACA T2(CDR(ASSOC(CADDDAR T2)PBACK)))
(COND((NOT(EQUAL(CAR TTM)(CAADDAAR T2)))(GO E5A)))
(COND((NOT(EQUAL(CADR TTM)(CADADDAAR T2)))(GO E5A)))
(COND((NOT(EQUAL(CAR MTM)(CADDADDAAR T2)))(GO E5A)))
(COND((NOT(EQUAL(CADR MTM)(CADDDADDAAR T2)))(GO E5A)))
(COND((NOT(EQUAL(CADDR MTM)(CADDDDADDAAR T2)))(GO E5A)))
(COND((NOT(EQUAL(CADDDR MTM)(CADDDDDADDAAR T2)))(GO E5A)))
(CSETQ NN(CDDDDDDADDAAR T2))
(COND((NULL NN)(GO E5D)))
(SETQ OTMT OTM)
E5B (COND((NULL OTMT)(GO E5D)))
(SETQ T1(CAR OTMT))
(SETQ OTMT(CDR OTMT))
(SETQ T3(CAR NN))
(SETQ NN(CDR NN))
E5C (COND((NULL T1)(GO E5B)))
(COND((NOT(EQUAL(CAR T1)(CAR T3)))(GO E5A)))
(SETQ T1(CDR T1))
(SETQ T3(CDR T3))
(GO E5C)
E5D (SETQ PC(ADD1 PC))
(SETQ T3(LIST PC NIL))
(RPLACD T3(CAR T2))
(NCONC POINTER (LIST T3))
(SETQ NN(LIST 'POINTER PC))
(RPLACA(CDDAR LOCP) NN)
(GO E1)
E5X (SETQ T1 (GENSYM)) (CSETQ NN(LIST(LIST 0 T1 (APPEND TTM(APPEND MTM OTM
```

```
'GROPE 'GROPE 'PBACK MCNT))
(SETQ T3(LIST MCNT NIL))
(RPLACD T3 (CAR LOCP))
(NCONC PBACK (LIST T3))
E5Z (RPLACA (CDDAR LOCP) NN)
(GO START)
E6 (SETQ T2(LIST NIL))
(RPLACA T2(CAR LOCP))
E6A (COND((EQUAL(CADDDAR T2)0)(GO E6X)))
  (COND((EQUAL(CADDDDR(ASSOC(CADDDAR T2)PBACK))0)
(GO E6X)))
(RPLACA T2(CDR(ASSOC(CADDDAR T2)PBACK)))
(COND((NOT(EQUAL(CAR TTM)(CAADDAAR T2)))(GO E7A)))
(COND((NOT(EQUAL(CADR TTM)(CADADDAAR T2)))(GO E6A)))
(COND((NOT(EQUAL(CAR MTM)(CADDADDAAR T2)))(GO E6A)))
(COND((NOT(EQUAL(CADR MTM)(CADDDADDAAR T2)))(GO E6A)))
(COND((NOT(EQUAL(CADDR MTM)(CADDDDADDAAR T2)))(GO E6A)))
(COND((NOT(EQUAL(CADDDR MTM)(CADDDDDADDAAR T2)))(GO E6A)))
(CSETQ NN(CDDDDDDADDAAR T2))
(COND((NULL NN)(GO E6D)))
(SETQ OTMT OTM)
E6B (COND((NULL OTMT)(GO E6D)))
(SETQ T1(CAR OTMT))
(SETQ OTMT(CDR OTMT))
(SETQ T3(CAR NN))
(SETQ NN(CDR NN))
E6C (COND((NULL T1)(GO E6E)))
(COND((NOT(EQUAL(CAR T1)(CAR T3)))(GO E6A)))
(SETQ T1(CDR T1))
(SETQ T3(CDR T3))
(GO E6C)
 E6D (SETQ PC(ADD1 PC))
(SETQ T3(LIST PC NIL))
(RPLACD T3 (CAR T2))
(NCONC POINTER (LIST T3))
(SETQ NN(LIST 'POINTER PC))
(RPLACA(CDAR LOCP)NN)
(GO E1)
E6X (SETQ T1 (GENM)) (CSETQ NN(LIST(LIST 0 T1 (APPEND TTM(APPEND MTM

OTM))) 'GROPE  'GROPE 'PBACK MCNT))
(SETQ T3(LIST MCNT NIL))
(RPLACD T3 (CAR LOCP))
(NCONC PBACK (LIST T3))
E6Z (RPLACA(CDAR LOCP) NN)
(GO START)
F1 (COND((EQUAL(CADAR LOCP) 'GROPE)(GO E6)))
(COND((EQUAL(CAADAR LOCP) 'POINTER)(GO P2)))
(RPLACA LOCP(CADR T2))
(GO E2)
P1 (RPLACA LOCP(CDR(ASSOC(CADADDAR LOCP)POINTER)))
(GO E2)
P2 (RPLACA LOCP(CDR(ASSOC(CADADAR LOCP)POINTER)))
(GO E2)
END (PRINT 'RAN=)(PRINT RAN)
(PRINT 'LRN=)(PRINT LRN)
(PRINT 'CYCLES=)(PRINT MCNT)
(PRINT 'EVL=)(PRINT EVL)
(PRINT 'NET=)(PRINT NET)
(RETURN 'RUNEND) )))
(CSETQ GENM(LAMBDA ()(PROG(  RANDOMS RANDOMT)
E5(SETQ RANDOMS (RANDOM))
(COND((NOT(EQUAL RANDOMS 0))(GO E6)))
(EYE 'RIGHT)
```

```
(RETURN '(EYE 'LEFT))
E7(COND((NOT(EQUAL RANDOMS 4))(GO E8)))
(GRASP)
(RETURN '(GRASP))
E8(COND((NOT(EQUAL RANDOMS 5))(GO E9)))
(RELEASE)
(RETURN '(RELEASE))
E9(COND((NOT(EQUAL RANDOMS 2))(GO E19)))
E10(SETQ RANDOMT (RANDOM))
(COND((NOT(EQUAL RANDOMT 0))(GO E12)))
E11(HMOVE 'UP NIL)
(RETURN '(HMOVE 'UP NIL))
E12(COND((EQUAL RANDOMT 4)(GO E11)))
(COND((NOT(EQUAL RANDOMT 1))(GO E14)))
E13(HMOVE 'DOWN NIL)
(RETURN '(HMOVE 'DOWN NIL))
E14(COND((EQUAL RANDOMT 5)(GO E13)))
(COND((NOT(EQUAL RANDOMT 2))(GO E16)))
E15(HMOVE 'RIGHT NIL)
(RETURN '(HMOVE 'RIGHT NIL))
E16(COND((EQUAL RANDOMT 6)(GO E15)))
(COND((NOT(EQUAL RANDOMT 3))(GO E18)))
E17(HMOVE 'LEFT NIL)
(RETURN '(HMOVE 'LEFT NIL))
E18(COND((EQUAL RANDOMT 7)(GO E17)))
(GO E10)
E19(COND((EQUAL RANDOMS 3)(GO E10)))
(COND((NOT(EQUAL RANDOMS 8))(GO E21)))
E20(GO E5)
E21(COND((EQUAL RANDOMS 9)(GO E20)))
E21A(SETQ RANDOMT (RANDOM))
(COND((NOT(EQUAL RANDOMT 0))(GO E23)))
E22(BMOVE 'UP)
(RETURN '(BMOVE 'UP))
E23(COND((EQUAL RANDOMT 4)(GO E22)))
(COND((NOT(EQUAL RANDOMT 1))(GO E25)))
E24(BMOVE 'DOWN)
(RETURN '(BMOVE 'DOWN))
E25(COND((EQUAL RANDOMT 5)(GO E24)))
(COND((NOT(EQUAL RANDOMT 2))(GO E27)))
E26(BMOVE 'RIGHT)
(RETURN '(BMOVE 'RIGHT))
E27(COND((EQUAL RANDOMT 6)(GO E26)))
(COND((NOT(EQUAL RANDOMT 3))(GO E29)))
E28(BMOVE 'LEFT)
(RETURN '(BMOVE 'LEFT))
E29(COND((EQUAL RANDOM 7)(GO E28)))
(GO E21A) )))
```

R E F E R E N C E S

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