INFORMATION PROCESSING AND MEMORY

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1. Introduction

EPAM (Elementary Perceiver and Memorizer) is one of a class of computer simulation models of cognitive processes that have been developed in the last decade. These are models of human information processing in certain learning and problem solving tasks. This paper is not the place to survey this literature. The reader who wishes to become acquainted with a wide variety of research projects in this area is advised to seek out the book *Computers and Thought* [4].

The presentation of this paper at the Berkeley Symposium on Mathematical Statistics and Probability involves a paradox. Neither my work nor the work of my colleagues in the area of simulation of human cognitive processes has much to do with either probability or statistics. The bulk of these models is deterministic, not stochastic. Usually one even searches in vain for a single Monte Carlo procedure in the computer simulation programs that we write. Nevertheless, I will proceed with my story, the paradox remaining unresolved.

In this paper I shall first sketch briefly the history of the EPAM project, without which the remainder of the discussion is not very meaningful. Next, I will attempt to reinterpret the EPAM theory in terms of an emerging three level theory of human memory. In the remainder of the paper, I would like to explore some questions relating to a theory of human long-term associative memory.

1.1. *A brief history of the EPAM project.* Work on the various EPAM models began almost ten years ago. The research has always been a joint effort by myself and Professor Herbert A. Simon of Carnegie Institute of Technology. We have been concerned with modeling the information processes and structures which underlie behavior in a wide variety of verbal learning tasks. These include the standard serial and paired-associate learning tasks, and other not so standard verbal learning tasks.

EPAM I was a very simple model, so simple, in fact, that a mathematical formulation, as well as a computer simulation, was constructed. In EPAM I,

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we postulated a serial mechanism in which the learning of verbal materials took a nontrivial amount of time. We explored the strategies used by subjects to organize their total learning task. The model generated an accurate, quantitative prediction of the well known bowed serial error curve, which plots the percentage of total errors made by subjects at each serial position of a relatively long serially-presented list of words.

EPAM II was a much more comprehensive model. It specified *structures* in which memorized items are stored and retrieved. It specified *processes* for learning discriminations between items; for learning associations among items; and for the familiarization of new items. It specified many other processes for (among many things) responding, attention focusing and the analysis of environmental feedback. The model generated qualitative and quantitative predictions for more than a dozen of the standard and well known phenomena of human verbal learning. EPAM II is described in an article in [3], and also in an article by Newell and Simon in [9].

The EPAM III model was a reconceptualization and generalization of the processes and structures of EPAM II. It attacked the problem of building up very general associative structures in memory (other than word learning); the association of a familiarized stimulus in an arbitrary number of associative contexts; the construction and storage of internal representations of new stimulus experiences by recognizing and bringing together already learned internal representations (that is, already familiar experiences). With this model, we made certain additional predictions about the effects of similarity, familiarity and meaningfulness in verbal learning tasks. These predictions, as well as a brief description of EPAM III, are contained in an article in [14].

Through the references cited, the reader can pursue the structure of the various EPAM models to the depth motivated by his interests. He would be well advised to be prepared to accept and understand the jargon and notation of the nonnumeric symbol manipulating computer languages, especially those that deal with list processing.

2. Information processing and memory

This portion of the paper is adapted from an earlier, unpublished paper prepared for a symposium on Information Processing and Memory, American Psychological Association Annual Meeting, September 1964. It formed the basis for discussion at one of the sessions of the Third Conference on Remembering, Learning and Forgetting, New York Academy of Sciences, Princeton, 1965.

Though the quest for an adequate theory of memory is as old as psychology itself, it has been pursued with significantly increased vigor and success in the last decade. This is due in part to increased sophistication in the art of conducting experiments on memory, at the level of neural processes and at the level of psychological processes. In part also it is due to the desire to explore possible implications for memory theory of the exciting developments in the theory of biological information encoding and storage mechanisms. And, in part, this new vigor is the result of the introduction in the 1950's, and subsequent widespread acceptance of, a new vocabulary of terms and concepts for describing cognitive processes: the language of *information processing* theory. Such terms as buffer storage, coding, retrieval processes, and processing strategy are familiar and commonly used labels, even among those psychologists who do not think of themselves as information processing theorists.

This attempt to bring a reasonable amount of order to the study of memory has been two headed: the search for an adequate description of memory processes and the search for models of the information storage structures that might be involved. The purpose of this part of the paper is to present the elements of an information processing theory of memory incorporating an integrated set of hypotheses about both information processes and information structures of memory. The EPAM model consists of information processes and structures for *learning* and *performance* in paired-associate and verbal serial learning tasks. The job of the EPAM performance processes is to retrieve appropriate responses from the memory structures when the task so dictates. EPAM has two major learning processes: discrimination learning and stimulus familiarization. The former discovers differences between items being learned and those already learned, and builds the memory structure to incorporate tests on these differences, so that storage and retrieval can take place with a minimum of stimulus generalization and confusion. The latter builds internal representations, called *images*, of verbal items being learned. It is an integrative process, in which previously familiarized parts of a stimulus item are first recognized and then "assembled" (according to a strategy) to form the internal representation. As previously mentioned, the EPAM model also contains a number of other mechanisms for attention focusing, organization of the learning task, associative recall, and so forth, which will not be discussed here.

EPAM, as it stands, is a *psychological* theory of certain elementary cognitive processes, framed at the so called *information processing level.* The primitives at this level are primitives concerning elementary symbol manipulation processes. These primitives are not, at this stage of our knowledge, directly translatable into "neural language," that is, statements about how the processes are realized in the underlying neural machinery. Some fruitful conjectures about this have been made [12], however, and more can be expected as increasing confidence in the adequacy of the information processing theory is attained.

2.1. *An information processing theory of memory.* We proceed now to summarize elements of a theory of memory that the work on EPAM has suggested to us. That part of the presentation dealing with permanent storage is, to some extent, conjectural, since these mechanisms have not been precisely defined or rigorously explored, though they have been suggested by shortcomings in EPAM.

2.1.1. *Primitive postulates about process.*

(a) At the information processing level, the central processing mechanism is essentially *serial,* that is, capable of performing one, or at most a very few, elementary processes at any time.

(b) Each elementary information process takes *time* to perform. To carry out a series of processes requires (by 2.1.1a) an amount of time roughly equal to the sum of processing times of the constituent processes. Even for "simple" psychological processes, this processing time may be significantly long when compared with, for example, item presentation rates typically encountered in verbal learning experiments.

These two fundamental ideas are at the root of all EPAM predictions. This is as true of the earliest model, one that predicted only the serial position effect [5] as it is of the later, more comprehensive, models [14]. Neither we nor others have been able to construct an alternate basic formulation that achieves the same results. Postulate 2.1.1b we interpret as identical with the "consolidation hypothesis" suggested by McGaugh [7] and others on the basis of laboratory experiments with animals using electroconvulsive shock and various drug treatments.

The consolidation hypothesis is an empirical generalization. The EPAM theory generates complex and accurate predictions of verbal learning behavior on the basis of an identical postulate inferred from an entirely different empirical base. Taken together, they provide strong confirmation for the basic correctness of the position.

2.1.2. *Hypotheses about structure.* We hypothesize three types of information storage structures.

(a) An immediate memory: a buffer storage mechanism of extremely small size, holding a few symbols. Inputs from the peripheral sensing and encoding mechanisms are held here in a state of availability for further central processing. The immediate memory provides the only channel of communication between the central processes and the sensing processes at the periphery. Central processes may use the immediate memory for temporary storage of internally generated symbols; these then compete for storage with arriving input symbols. The net result of such an immediate memory mechanism is that the total processing system has a very narrow "focus of attention," that is, the central processes can attend to only a minuscule portion of the external stimulus environment at any time.

(b) Acquisition memory: the term is chosen to contrast with long-term permanent store (2.1.2c). It refers to a large working memory for discrimination and familiarization processes in which is built the internal representations of stimulus objects being learned in whose structure is stored the information necessary to discriminate among the learned objects. This memory has a *tree* structure, called the *discrimination net.* At each nonterminal nodal level is stored a testing process, a *discriminator,* which tests some feature of a stimulus object and sorts the object along the appropriate branch to the next nodal level. The termini of the tree are storage locations at which images, assemblages of symbols constituting the internal representation of an external object, are stored.

It is this memory structure upon which most of the EPAM work has been done, and whose structure is best understood.

(c) The permanent store: this memory structure considered for practical purposes as being of essentially unlimited size, is the long-term permanent repository of the images. The images are linked together in a highly interconnected web of cross associations. Thus, the structure of this memory is not treelike. However, it is plausible that this structure is "indexed" by a discrimination net like the one described above, for efficient cross referencing and searching.

2.1.3. *Hypotheses about process.* The theory contains a number of hypotheses about memory processing activity, only a few of which will be summarized at this point. Others will be touched on in the discussions below.

(a) Working at the level of the acquisition memory, a matching process scans stimulus encodings and images serially for differences on the basis of which discriminators are constructed. The scan is controlled by a noticing order, an adaptive attention focusing strategy.

(b) Image building in the acquisition memory consists of assembling at a terminal node in an orderly way (that is, controlled by a strategy) *cue-tokens,* which reference other images in the net.

(c) The discrimination net of the acquisition memory over time is elaborated (that is, necessary discriminators and branches are grown) as the task demands finer discriminations for successful performance. The discrimination net is grown in a wholly pragmatic manner, its growth at any stage reflecting what is just adequate for correct performance. There is no attempt at this level to structure or restructure the net for efficiency or logical order.

(d) At the level of the permanent storage, it is hypothesized that a process transfers images, discrimination information, and perhaps even subnets of the acquisition memory to the permanent store, dismantling the structure of the working memory as it processes it. The transferred information is reorganized and tied into the web structure of the permanent store according to an organizational scheme which is more logical and better suited to the long-term retrieval needs of the organism than the pragmatically built structure of the acquisition memory.

Having thus summarized our basic hypotheses about structure and process in a three level memory, we proceed to describe and discuss each of these levels in more detail.

2.2. *Further considerations about immediate memory.* Our theory holds that the immediate memory is a fast access, low capacity storage system whose function is primarily to buffer encoded sensory inputs. We conceive of the immediate memory as being ultradynamic, the average length of time of residence of a symbol therein being of the order of seconds, though the stay can be extended under control of a central process by recycling. At any given moment of time, the set of symbols in the immediate memory is *the* operational stimulus environment of the organism. This position is consistent with and contributory to our fundamental postulate that the central processes are basically serial.

The need for such a buffer storage mechanism is twofold. First, since the performance and acquisition processes consume a significant amount of time, it is necessary to hold on to the inputs lest they vanish before any processing can be done on them. Second, buffer storage provides a necessary decoupling of the central processes from the peripheral processes sensing the external environment. This decoupling, relieving the central processes of the impossible burden of instant-by-instant attention to the environment, is absolutely essential because many of the time-consuming acquisition processes are searching or, what is worse, manipulating memory structure and can not be interrupted at arbitrary times.

It is interesting to note in passing that in large nonbiological information processing machines (any of the modern familiar digital computer systems) buffered data channels are used for reasons identical with the decoupling argument given above. We can not here explain the difficulties encountered in operating the early digital computer systems without buffered information transfer. No modern computer system of which we are aware is built without some input/output buffering.

2.3. *Further considerations concerning acquisition memory.* The acquisition memory is conceptualized as an intermediate level of storage between the ultradynamic immediate memory and the relatively slowly changing permanent store. It is the "working memory" in which the discrimination and familiarization processes classify, and build internal representations of, the current environmental context and the objects thereof. Performance of "current task" is done by referencing the net and images of this memory. In general, we believe that images are not stored in this memory indefinitely but, rather, for times of the order of many minutes to a few hours.

It follows that since the information in the acquisition memory is not yet permanently fixed, and since this memory level stores the recently learned context, it might be possible to disturb this memory, destroying its contents, though this would not be so simple a matter as in the immediate memory, where merely a shift of attention suffices. We conjecture that the retrograde amnesia, affecting the memory of recent learning, observed in animals given electroconvulsive shock shortly after a learning trial is a manifestation of just such a destructive disturbance of acquisition memory before the permanent storage processes have had time to operate.

The discrimination net memory of EPAM is our model of the structure of the acquisition memory. When an object is presented to the acquisition processes for learning, the net is grown to provide a unique terminal location in which to build up the image of the object (that is, to familiarize it), if no such location is already available. *Sorting* an encoded object through the discrimination net will retrieve the stored image of the object for further processing or for response generation. The discriminators used in growing the net to make finer and finer discriminations among the objects entering the learned set are constructed from differences found by *matching* processes that compare objects with previously stored images. *Recognition* of an object is the result of sorting the object to a terminal and finding no differences between the object and the image stored there.

Familiarization of an object is done roughly as follows (though we can not go into all the details of the process here). All images (except the so called elementary images, which are merely stored property strings) are built by listing a set of reference pointers to the net locations of the images of recognized (that is, already familiar) subobjects of the object being familiarized. These pointers are *cue-tokens* of the familiar parts comprising the object. There is only one image for each familiar object in the net, but there may be any number of cue-tokens of this image stored in the context of any number of other images. When an image is processed for some reason, for example, for generating a response, the tokens of subpart images are used to retrieve the subpart images themselves as necessary. Thus, in summary, an object is familiarized in this memory only by the process of listing tokens of already familiar subobjects. If a subobject can not be recognized in the net, it must first itself be made familiar before it can be used in the construction of the image of the higher level object.

The image-building processes of EPAM are essentially recoding or "chunking" processes. No matter how complex a stimulus object may be, after the image of that object has been built a single symbol, its cue-token, will be sufficient to signify its presence as a constituent of any other complex stimulus context being memorized. Thus, all stored images turn out to have roughly the same informational complexity (that is, number of symbols needed to represent them in the storage), though of course the processing that may have to be done to retrieve details of a particular image may be a complex search. We see here operating the trade off, often pointed out by computer scientists, between the complexity of the storage representation and the complexity of the retrieval processes. The EPAM model inclines toward simplicity and homogeneity in the storage representation and complexity of retrieval processing. Thus, for example, the response generation process of EPAM is not a simple find-and-output affair but rather a multilayered recursive *constructive* process (Pribram has called this kind of process "*re*membering, as opposed to *dis*membering").

Two additional observations about the discrimination net will be useful. First, the structure of the discrimination net is the embodiment of all the discrimination learning that has taken place during the acquisition of the items stored in the net. That is, there is no separate storage for the information learned during discrimination learning. Second, the net is built by processes that are under the control of a learning strategy. Among other things, this strategy is responsible for the analysis of the information concerning correct and incorrect performance that is fed back to the subject by the experimental procedure. It decides what is causing incorrect responding and what to do about it. It does this by the application of the following "satisficing" heuristic: an addition or change to the net structure or image information that just works (gets rid of the immediate performance problem) is "good enough." As a result, the net is grown in a pragmatic fashion, no attention being paid to the inherent "logic" of the classification task that the net is performing for the system. This heuristic strategy is useful in the short run in that it allows EPAM to learn experimental tasks with reasonable amounts of processing effort. In general, it will not be the best way to organize information for purposes of long-term storage. We shall return to this argument in the next section. These hypotheses about structure and process in the acquisition memory have many interesting consequences in terms of the learning and performance behavior of EPAM. These consequences constitute the validating evidence for the EPAM theory. In this paper, space does not permit us to survey all of this evidence. We shall mention just one result, a rather startling one since it is a direct consequence of no single process or structure, but is rather a complex consequence of the interaction of many processes and the discrimination net.

The result is this: EPAM exhibits *forgetting behavior* even though there is no destruction or decay of images or tokens stored in the memory. Using traditional labels, this behavior is described as oscillation (in the learning of a single list of items) and retroactive inhibition (in the learning of more than one list).

These two types of forgetting behavior have a single EPAM explanation. The discrimination net must grow to store new items being learned. The cue-token information used by the performance process to retrieve the image of some stimulus item's response associate is generally *just sufficient* to correctly retrieve the response from the discrimination net *at the time the association is learned.* However, as repetitive trials proceed, and the net grows over time to include new items, this cuing information may become inadequate for retrieving the correct response. In this event, what may be retrieved is a subnet of items (all similar to the correct response) which includes the correct response. A random process then selects a response item from this subnet as a guess. (Note that because of the way in which the net is built, this response, if in error, will be an error of response generalization.) When such an error is made, the processes that analyze the informative feedback can correct it by storing additional cuing information. Within the learning of a single list, when S-R pairs learned on later trials interfere in this way with pairs learned on earlier trials, oscillation results. In multilist experiments, when pairs learned in later lists interfere in this way with pairs learned in earlier lists, retroactive inhibition is observed in the test sequences.

3. The long-term permanent store

3.1. *General considerations.* We have been led to the idea of a permanent associative store of very large size for a number of reasons having to do with conceptual problems of the EPAM theory. On these grounds alone, however, the hypothesis of an additional level of memory is not completely convincing, though some of the problems would be resolved neatly under the hypothesis. The existence of empirical evidence that suggests different storage mechanisms for working versus permanent storage is therefore encouraging [2], [7].

The notion of permanence of the storage of symbols in the long-term memory is an assumption for which there is not much empirical evidence. To be more precise about this hypothesis, it is assumed that those symbols upon which a significant amount of processing has been done will never disappear from the long-term storage structure. This hypothesis is not the same as a naive "tape recorder" hypothesis, under which all information sensed is thereby recorded permanently; because of the demands of tasks and the effect of attention focusing processes, some inputs will never receive the processing necessary to qualify them as candidates for long-term storage. The hypothesis regarding permanence is, we think, reasonable at the current state of knowledge. There is no directly controverting evidence, and there is some measure of support from the earlier EPAM modeling efforts, namely, that behavioral evidence of forgetting can be accounted for satisfactorily as *loss of access* to stored symbols caused by dynamic changes of memory structure.

We view the processes of retrieval of symbols from the long-term permanent storage as a problem solving process. By "problem solving" we mean a process that finds an "answer" path through a large maze of possible alternatives using search-limiting heuristics, as has been widely discussed in the literature on computer simulation of cognitive processes and artificial intelligence models [4]. Retrieval times alone would indicate quite a different retrieval process acting in the long-term memory from that involved in the recognition of a familiar object (processes of testing and sorting that are used in EPAM III). Introspection on retrieval episodes, where it is possible to be fairly self-conscious about the underlying processes suggests problem solving—that is, trying out various strategies to guide search, testing hypotheses, exploring particular avenues in depth, piecing together clues in various patterns (as in puzzle solving), a great deal of trial and error searching, and sometimes (as with problem solving programs) the successful termination of search with great suddenness.

Another phenomenon of long-term memory that needs to be explained is the *fluctuating availability* of the symbols stored therein. Sometimes a particular symbol being sought can be retrieved quickly and easily; at other times it may appear irretrievable no matter how much effort is spent trying to recall it, until some circumstances (or merely the passage of time) appear to "bring it to mind." We shall have some comments about this later in connection with the problem solving nature of retrieval processing.

An additional and more subtle question that early influenced our thinking about a level of long-term storage involves an adequate explanation of proactive inhibition, to which we now turn our attention.

The memory of an organism at the beginning of a learning experience, it can be plausibly assumed, contains a large number of symbols stored during past learning. How can this total memory context affect associative *recall* in *current* learning? In the present EPAM model it cannot, that is, EPAM exhibits no proactive inhibition (though there is a "proactive" effect on rate of learning). By the end of the criterion trial the current symbol context is adequately discriminated from previous ones, and no confusion by generalization is possible. In general terms, the problem can be resolved simply by the notion that the recently learned symbols are, over time, assimilated into the total memory context by a transfer process.

Experimental evidence suggests that subjects acquire and use seemingly extraneous features of a stimulus environment in the learning of the task oriented part of the total environment. This information is relevant locally in place and time to the objects of the task. Given a simulated environment enriched with such contextual information, and an augmented list of features for the noticing process to work with, EPAM could learn an experimental task using such local contextual information. The locally relevant information would be used in building discriminators, consistent with the EPAM heuristic that whatever information "works" is satisfactory (for example, the discrimination: "the syllable beginning with the letter *R and* learned 'early' in the experience" versus "the syllable beginning with the letter *R* and learned 'late' ").

Though such information might be useful in speeding up the learning in the experimental session, its utility quickly fades as time passes and stimulus environments change. Local contextual information does not "work" well in discriminating objects and guiding retrieval over the long term.

3.2. *Processes.* Considerations of this kind lead us to suggest a transfer process controlling long-term storage, with these properties.

(a) It "reprocesses" the working memory, copying recently learned images to the permanent store (with the appropriate associative links as determined from the discriminator and cue-token information). In doing so, it makes decisions about temporary versus permanent relevance of the information. It ignores the temporarily relevant information, which thereafter plays no further role. The storage is reused by the acquisition processes in subsequent processing.

(b) It is a *strategy,* in that its decisions concerning long-term relevance may change over time based upon experience with environments or upon instruction.

(c) It is a *low priority* process. The high priority processes are those that attend to the demands of the environment and the acquisition of the task. Since it must share with these the processing time of the serial mechanism we have just postulated, and since it must grow a memory structure which is good (useful and relevant) for long-term processing, not merely "just adequate" we conclude that the so called "consolidation" of the long-term storage will extend over a considerable elapsed time. This time may be of the order of hours, or even days (as suggested by some drug studies), depending upon the activity of the organism and the other information processing demands it is satisfying, and depending also upon the complexity of the learned task.

It may be that the permanent storage process is slow for another reason, namely that the underlying biological permanent storage process is intrinsically a very slow process. One sees this, for example, in some of the nonbiological memory models that have been constructed. To cite two extremes, the chemical thread-growing memory built by Pask ([11], pp. 105–108) stores information thousands of times more slowly than the fastest magnetic memories of present day computers. Indeed, within a computer system itself, the data rates of the main "working" memory are many times faster than the data rates of the huge "bulk" memories used for secondary storage.

In this connection Chorover's result [1] showing very fast consolidation is disturbing but not totally at variance with our position, at least for very simple learning tasks. McGaugh, in personal communication, indicates that his experiments suggest big differences in consolidation speed between simple tasks and complex tasks. On the other hand, Chorover's result is at variance with many previous results in the experimental work on consolidation.

Such a process suggests the solution to the questions posed earlier about the mechanism needed to account for proactive inhibition. It merges the recently learned context with the total symbol context of the permanent memory, and in so doing, throws away some of the discrimination information that was responsible for perfect performance during the criterion phase of the recent learning. The consequence of this is generalization with the symbols of the total memory context, typically for some, but not all, of the recently learned items.

3.3. *Structure.* The structure of long-term memory is viewed here as an extension of the EPAM III (acquisition memory) structures, not as an entirely separate level of organization. The primary memory structure of EPAM III is the discrimination net, described earlier. The images stored at the bottom of the discrimination net are richly interconnected so that they form an usually large and complicated graph. An image is built at the bottom of the net as a collection of "tokens" for already learned subimages; the subimages are themselves built up in this general way; and so on. In this graph of interconnected images, those that are connected to the discrimination net are said to be in the acquisition memory. Others connected into the graph but not directly accessible through the discrimination net are said to be in the long-term store.

Thus, the nodes of the memory graph are the familiar images of objects. Connections between nodes are either attribute-value links defining relations between images at nodes, or specifically the whole-part relations that are "built in" by the way EPAM constructs images.

Space here does not allow a detailed examination of this structure. However, there is a simple way of looking at it. If the capacity of the long-term store is very great, and if symbols stored permanently therein are to be retrieved without very great information processing penalties and long search times, there must be multiple entry points to the store. These might be thought of as index points to a large file. The discrimination net of the acquisition memory is, in essence, the *index* to the long-term memory. Under our present conception of storage processes acting in the long-term memory, the discrimination net grows and contracts—grows during discrimination learning thereby increasing the number of points at which the net accesses the long-term memory graph, and contracts as the net is reprocessed by the transfer process described above.

The search for images in the long-term store need not be restricted to merely a movement from node to node using whole-part or attribute value relational structure. The discrimination net is always available as an indexing device for selecting a new entry point. Search strategies can be constructed that make use of this fact, thereby adding an additional "dimension" to the search.

3.4. *Retrieval from the long-term store by problem solving.* Stimulus events set up retrieval problems. In the laboratory situation, they are part of the task that the subject is called upon to master. In performance mode, he accesses symbols stored during present and past learning activity. In learning mode, he accesses previously stored symbols to build up higher level images. In our present conception, retrieval of information is either *direct* or by *problem solving.*

Direct retrieval is accomplished in the discrimination net: a path of the net links directly to the image being sought. In the sense described earlier, this directly retrieved image is in the acquisition memory.

If the image being sought cannot be retrieved directly in this fashion, then a problem solving search for the item is conducted in the neighborhood of the "entry point" given by sorting through the discrimination net the stimulus situation that gave rise to the search. Usually entry to the graph will be obtained at a region containing information similar to the information being sought, since this is how the net and long-term memory graph is built up in the first place.

For this purpose, an adequate problem solving model is the General Problem Solver (GPS) due to Newell and Simon [10]. Stated very briefly, GPS solves problems that can be put in the following general form. Given descriptions of an initial problem state and a target state, and given a set of operators for transforming states by reducing differences between problem states, find a sequence of operators that will transform the initial state into the target state.

In the memory retrieval problems being discussed, the initial state is the entry node given by the discrimination net. Some of the extrinsic information that gave rise to the retrieval problem is used up in accessing the appropriate "local" portion of the memory graph. The remainder is available as a description of the target state (the image being sought). This description is the basis for recognizing the target node when it is encountered. Upon encounter, a cluster of symbols is accessed (those associated with the target image), one or more of which may be the sought after symbol(s), for example the *name* associated with the target image. The operators, the means by which states are transformed, correspond to the various ways of moving from one node to another in the graph.

We wish to conclude this section by looking again at the problem of explaining fluctuating availability of stored symbols in the light of the proposed problem solving nature of the memory retrieval process. GPS, or the Logic Theory Program that was its forefather [8] or any one of a number of programs (such as

Slagle's SAINT [15]) that are cousins to the Logic Theorist, are fairly powerful heuristic problem solvers in the sense that, over the domains of their applicability, they solve problems about as complex as people can solve. Yet all of these problem solving efforts (programs or people) appear to have a common characteristic: the average number of steps in the solution derivations, and in the means-ends reasoning chains, is not large. The longest proof generated by LT was eight steps deep; the average perhaps half that. The average number of steps in GPS means-ends chains for the tasks that have been explored is probably about six. In the well known Checker Playing Program and in some chess playing programs, analysis proceeds four half moves deep in the "look ahead" search.

Suppose that in memory retrieval problems, under a GPS-like regimen, comparable limits on "solution complexity" were to be encountered (a reasonable assumption). Then on some particular retrieval attempts, searches may be unsuccessful (subjectively, frustratingly so) because the item being searched for is not within the "span" covered by the problem solver from the entry node given it by the index, that is, the discrimination net. In other words, the selected entry node was not "close enough" to the target node for the "path length to solution" to be within the bounds of average depth of search. The sought for item is thus inaccessible unless a better entry node is selected.

One way to achieve a better solution is to postpone the retrieval problem for some time, awaiting the circumstance (testing periodically) that the contact nodes of the discrimination net with the memory graph will be more favorable. This is a possible solution because in the normal course of events the discrimination net is expanding and contracting under the impact of the changing environment, as described earlier. Thus, we have here a possible explanation for fluctuating response availability, even in the absence of a conscious retrieval strategy.

However, deliberate strategies are also ways of inducing shifts of entry nodes. Some strategies, for example, might employ early or intermediate products of search in various arrangements as inputs to the discrimination net for new entry node selections. Another strategy which appears to be commonly used is the systematic generation of "stimuli" (produced and used internally), which we would interpret as a search for an appropriately "local" portion of the memory graph in which to search for a particular item. A common example of this is the trick of "going down through the alphabet" when trying to remember the name of some object. This strategy is very much a trial-and-error process, like most other heuristics, but it often works. Here we have another piece of the explanation for fluctuating availability of stored symbols, this time strategy-directed.

There are other general inferences one could make from a model of the type that views memory retrieval as a problem solving process, but discussion of these is best postponed until after a computer simulation of the model is written and tested.

4. Conclusion

In this paper, we have proposed a three level theory of memory:

(a) an immediate memory of very small size, in which information is stored for very brief intervals, which acts as a buffer storage to decouple the input (peripheral encoding) processes from the central processes and as a temporary storage for central processing;

(b) an acquisition memory, a working memory with the structure of the EPAM discrimination net, in which discrimination learning takes place and in which the internal representations of stimulus objects are built;

(c) a permanent storage in which the internal representations are organized and stored for long-term retrieval.

The EPAM model is a precise formulation of the immediate and acquisition memories, and we have been able to demonstrate and validate the consequences of these parts of the theory. The theory of the permanent storage is a logical extension of EPAM suggested to the theorist as a resolution of certain difficulties with the present model. Since it has not been precisely described or tested by means of computer simulation, it is offered in a tentative spirit.

The discrimination net of the acquisition memory is viewed as an index to the permanent storage. Retrieval of information from the permanent storage is viewed as a problem solving process, along the lines of the General Problem Solver model.

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