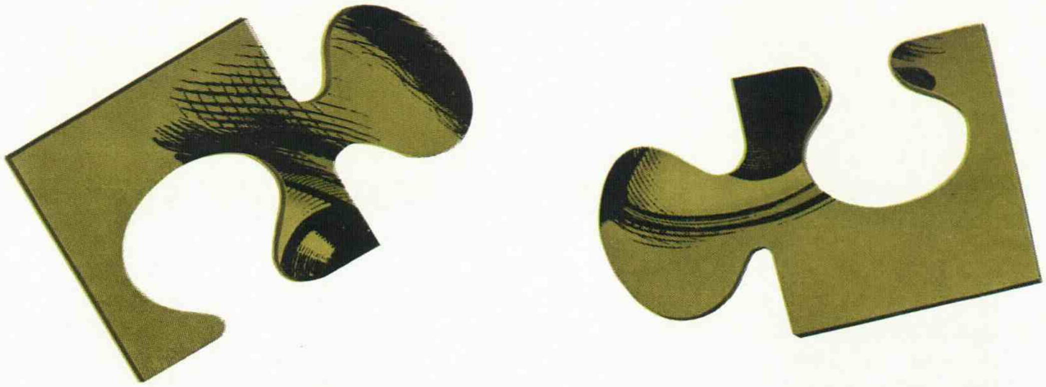

On the mechanization of

The goal of mechanizing certain creative processes in problem solving is attainable, but not in the near future. The problem is to find workable computer procedures for evolving "appropriate" representations in given problem-solving situations. The answer may lie in the extension of ideas that were developed for some elementary theory-formation procedures.

There is no general agreement on the nature of creativity or the characteristics of a creative act. Such an act is often surprising, has elements of a new approach, and is not stereotypic. Beyond these phenomenological properties, one finds that a creative act has a strong element of synthesis. It is usually associated with ill-defined goals or it involves reformulation of externally imposed goals. Some students of the human mind feel that formation of powerful imagery, abstraction to appropriate spaces, flexible associations, and rich generation of analogies are key element sof creative processes. Others feel that, in addition to these elements, some mysterious, unexplainable processes control the genesis of ideas and insights in man's creative process. If we exclude the belief in such unexplainable processes, then it is reasonable to attempt explications of (at least some) creative processes in terms of information-processing models. Explications of this type will essentially amount to advancing operational definitions of creative processes. By studying the implications of such proposed definitions, by testing them versus existing notions of creative behavior, by subsequently improving the proposed definitions, and so on, we can hope to attain a satisfactory understanding of the notion of a creative process. In this manner, there is a chance that we can arrive both at a psychological theory of creative processes and at the logical principles that underlie computer realizations of such processes.

I would like to present here some tentative ideas on an operational definition of creative processes in the general context of problem-solving processes. My comments are restricted to some of the creative processes that occur in the problem-solving activities of the physical scientist, the engineer, and the mathematician.

An important type of problem confronting the physical scientist is the formation of theories that organize empirical knowledge in certain desired ways. A common problem for the engineer is to evolve a design that satisfies desired goals. One of the problems of the mathematician is to prove theorems in a formal system. In the last decade, several procedures have been developed for solving by computer problems of these three types. Much of the present research in artificial intelligence is directed to extending the scope and power of such problem-solving procedures. It is my belief that some of the difficult problems that we are now facing in the design of more powerful problem-solving procedures are related to the problem of mechanizing certain creative processes.

Extending the power of problem-solving procedures

Two central notions are involved in a problem-solving procedure: first, a problem state—a description of a problem situation including goals, available resources, and intermediate results; and second, a set of relevant moves that can be applied from a state to obtain new states. The relevant moves commonly reflect the rules of the game, the rules of inference, the grammar, the available composition, etc., that can be used by a problem-solving procedure in the course of an attempt to construct a solution. In designing problem-solving procedures one must find appropriate descriptions for problem states and for transformation of states via moves. In other words, one must face the problem of defining a problem-state space; I call this the problem of representation. A closely related problem is the problem of evaluation. It involves the choice of concepts and methods for evaluating a variety of measures of progress—as well as estimates of expected search efforts—that can be associated with points in state space and also with transition between points in that space. A third major problem is that of controlling the search for a solution in state space. Here one needs overall strategies and specific decision functions for intelligently selecting problems—solving moves between problem states so that a solution can be found with as small a computational cost as possible. Most of the effort expended on machine problem solving so far has been directed to this third problem; specifically, to the study of a variety of schemes for heuristic search.[1]

In the present state of the artificial intelligence art, the designer of a problem-solving procedure is required to solve without aid from the machine the problems of choosing a state space, a basis for evaluation, and a strategy for heuristic search. The relatively intelligent behavior of the machine that solves problems in accordance with the problem-solving procedure formulated by the designer is therefore circumscribed by the choices of representation evaluation and control that are made by the designer.

Ideas on an operational definition of creative processes in the general context of problem solving are presented—restricted to such processes that occur in the problem-solving activities of the physical scientist, the engineer, and the mathematician

creative processes

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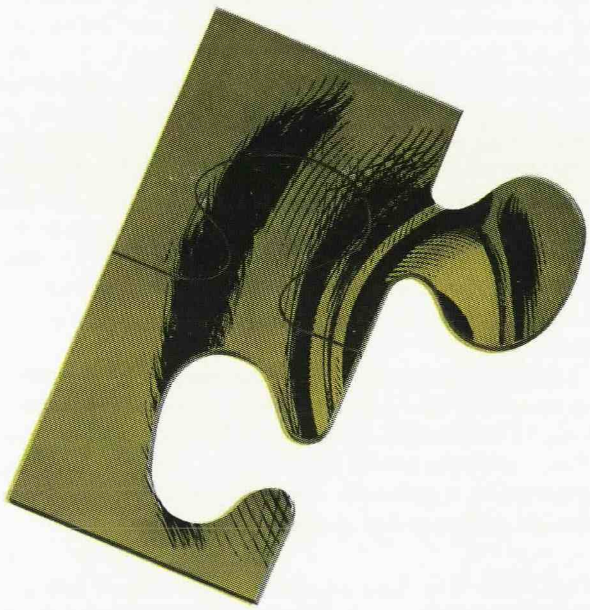

Improvement in the power of problem-solving procedures can be achieved by making appropriate changes in the rules that control search, in the methods of evaluation, and in the modes of representation. Several attempts have already been made to adjust certain parameters automatically in local decision rules that control search, and also in evaluation functions—on the basis of statistical learning techniques.[2] However, no schemes exist as yet for general nonparametric control of the search and evaluation parts of problem-solving procedures.

In our work with proving theorems of the propositional calculus by the method of natural deduction we have developed a sequence of procedures of increasing power in order to evaluate the nature of improvements that occur at different stages of this evolution. The most spectacular improvement was obtained when the problem representation was changed in an "appropriate" way—the shift in representation has transformed the problem to one of finding appropriate closures to certain directed graphs. The new problem representation immediately suggests to human problem solvers a new, more powerful, basis for evaluation and search; the result is a much better goal-oriented, thus less inefficient, problem-solving process. We had similar experience with other relatively simple transportation scheduling problems. Indeed, the importance of "having the right point of view," "casting the problem in the appropriate form," "conceptualizing the problem correctly" has been recognized for some time by students of problem-solving processes.[3]

Finding the "most appropriate" space

I think that creative problem solving is closely related to the notion of directing the search for solution in the "most appropriate" space. More specifically, I would like to suggest that the formation of an appropriate concept of problem space, where a given problem is to be treated—in other words, the solution of the problem of representation—is a creative process. This process could also be regarded as a process of building an appropriate model. While the use of given models in problem solving has already been considered by workers in artificial intelligence,[4] the dynamic aspects of evolving an appropriate model so far have received little attention.

It is commonly asserted that by furnishing a man with convenient graphical displays of appropriate models, he will be stimulated to provide the creative contribution expected from him in his problem-solving partnership with the machine. Clearly, someone has to choose the appropriate models to be displayed in specific situations; I consider this selection of models as demanding the main measure of creativity that enters the problem-solving process. If the man's function in his partnership with the machine is not only to utilize models (that facilitate his search for a solution) but also to form and modify models during the problem-solving process, then he will indeed be exercising his creative powers. This point of view has certain implications regarding the flexibility and power of model-building languages that are needed in a genuine creative problem-solving system involving man–machine interaction. Also, it may provide a test framework for identifying the part that creative processes play in problem solving.

Creative processes and theory formation

If we start with the assumption that the function of a creative process in problem solving is the formation of an appropriate problem representation (the growth of appropriate symbolizations or of suitable models), then the mechanisms that come into play in a creative process will have much in common with theory-formation mechanisms. In the theory-formation problem of the physical scientist the objective is to construct efficiently an information structure, in terms of existing linguistic and conceptual resources, that would summarize "elegantly" and "explain" a set (usually large) of empirically obtained relationships in a given area. The information structure, because of its mode of construction, expresses the empirical knowledge in terms of existing theoretical constructs, thus incorporating the new empirical information in the main body of theoretical knowledge. It also provides an appropriate basis for solving problems and answering questions in the given area. In the model-formation problem of the problem solver the objective is to construct a theory in terms of appropriate linguistic and mathematical constructs that expresses in a convenient manner to the problem solver the properties of the problem state space.

In our work on theory-formation processes we have studied specifically procedures for the automatic formation of computer programs in a given programming language that have to satisfy a given set of computational correspondences.[5] Candidate programs are represented in the system in terms of a language of program descriptions. The system generates program descriptions, it evaluates them over the given set of correspondences, it modifies the program descriptions, and so on, until a description with the desired computational properties is found. The crucial problem for us is to find strategies of formation that direct in an efficient way this search in program-description space. After working with certain heuristic formation procedures, where considerable "blind search" takes place, we have found that basic improvements in the power of the formation procedures can be obtained if appropriate representations of the problem-state space (in this case this is the space of program descriptions) are available to the system.[6,7] Given an appropriate mathematical model of formation space, it is possible to have a formation process that is much more efficient. Note that in the present case we are discussing the importance of using models for efficiently building models (a model of formation space is used to evolve a model for a certain computation). Hence, it is again natural to ask how it is possible to evolve in a machine an appropriate model that would guide the machine formation of another appropriate model.[4] Again, I consider the construction of such a model as involving a creative process.

Mechanization of creative processes

In general, I think that many of the ideas used in theory-formation procedures can be transferred to the mechanization of processes for evolving appropriate representations (or for recognizing that a certain formal system provides an appropriate model) in given problem-solving situations. If we agree that such representation selection processes are creative processes, then we can already envision an approach (through theory-formation ideas, which, admittedly, are still at a very early stage of development) to the mechanization of creative processes in problem solving. However, even if a general approach using theory-formation ideas is considered, the question still remains as to how to solve representation selection problems efficiently with computers. Efficient solution of representation selection problems at a certain level may necessitate the solution of representation selection problems at a higher level (as we found out from our experience with theory-formation problems); the logical complexity of the required programs and the requirements of storage and computation time may well be beyond realistically attainable systems.

In general, I think that by mechanizing the process of selecting appropriate representations for problem-solving situations we will be taking an enormous step toward advancing artificial intelligence. Furthermore, I think that the notion of creative processes in problem solving is closely related to such representation selection processes. I believe that the goal of mechanizing certain creative processes in problem solving can be achieved; but we are a long way from it now. I think that the following quotation from E. Post's diary[8] is relevant to my comments: "The creative germ seems not to be capable of being purely presented but can be stated as consisting in constructing ever higher types. These are as transfinite ordinals and the creative process consists in continually transcending them by seeing previously unseen laws which give a sequence of such numbers. Now it seems that this complete seeing is a complicated process mostly subconscious. But it is not given till it is made completely conscious. But then it ought to be constructable purely mechanically."

I find this statement remarkable because it associates the notions of visualization (symbolization or representation), of a hierarchy of such visualizations, and of conscious self-reflectiveness with the creative process; furthermore, it ends with a note of confidence about the possible mechanization of creative processes.

This article is an expanded version of the author's points of view as expressed in a panel discussion on the mechanization of creative processes that took place on May 28 at the 1965 IFIP Congress in New York, N.Y. The panel was chaired by E. A. Feigenbaum; other panelists were J. McCarthy, V. Neisser, A. Newell, G. Pask, and L. Uhr. The research discussed in this article is sponsored by the Air Force Office of Scientific Research, of the Office of Aerospace Research, under Contract No. AF49-(638)-1184.

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