

MODELING HUMAN MENTAL PROCESSES

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There now exist at least a half dozen computer programs that simulate some of the information processes that humans use to perform problem solving, learning, perceiving, and thinking tasks. These programs constitute theoretical explanations of the corresponding human behavior, and can be tested by comparing the computer traces they produce with the verbal behavior of subjects in the psychological laboratory. This paper surveys this new kind of theory building and theory testing in psychology, and relates it to other uses of simulation as a tool of psychological research.

The use of computers to perform "humanoid" tasks -- which provides the theme for this conference -- falls into a number of distinguishable, though overlapping, categories. On the one hand, the goal may be to learn about human processes by simulating them; this has been the central motivation in simulating neural nets and a good part of the work on simulating human problem solving. On the other hand, the goal may be to find effective machine processes for accomplishing complex tasks -imitating the human processes only when this proves the most efficient way to do the job. This goal of "artificial intelligence" has been perhaps the primary motivation in the fields of information retrieval and language translation. The work to be described in this session falls in the former category: it is aimed at understanding the human mind by imitating it.

Some Kinds of Simulation of Mind

Computer simulations of human thinking can be classified along another dimension: the closeness of the simulation to, or its remoteness from, underlying physiological processes. We can distinguish at least the following broad categories:

1. Abstract simulation of adaptive, goal-seeking, learning mechanisms. Here the primary goal is to understand the nature of organisms in general, rather than the human organism in particular. One set of examples were the "tortoises" of Grey Walter,¹ mobile analogue computers that demonstrated "in the metal" that artifices can be constructed which will behave adaptively in an environment in response to drives, and will improve their adaptation through learning. Another example--also an analogue--is W. Ross Ashby's homeostat,² that shows how learning can be implemented through "Darwinian' mechanisms that cause mutations in the individual organism's program of adaptation to his environment.

2. Simulation of the sensoryperceptual processes by which humans recognize visual and aural patterns and symbols. Mechanical reception and decoding of human speech is a long-time goal of fundamental and applied research that has not yet reached complete success. But much is now known of the cues that humans use to recognize the basic phonemic units of spoken language, and within the past two years some partial successes have been achieved in mechanizing that recognition.^{3,4} Even greater progress has been made with the simpler task of recognizing and decoding hand-sent Morse Code.^{5,6} The classical pattern-recognition experiments of Selfridge and Dinneen7 undertook to simulate some of the basic coding processes employed by the human retina.

3. Simulation of the self-organizing capabilities of neural nets. As in the work mentioned in the previous As category, the problem that has usually been posed is to explain the phenomenon of pattern recognition: how the nervous system, given its known gross characteristics, can learn to classify, say, patterns of light that fall on the retina. The work falling in category 3 is concerned less with the rules by which patterns are classified, and more with the ways in which these rules are acquired by the nervous system. Farley and Clark^{8,9} represented the nervous system as a network of individual elements--schematized neurons--connected in a more or less random fashion, subsequent appropriate organization being induced by learning. A similar scheme, developed independently by Rochester, Holland, Haibt, and Duda, ¹⁰ was aimed at testing the particular

hypotheses about neural organization that had been put forth by the psychologist Hebb.¹¹ Rosenblatt's Perceptrons¹² continue this general line of investigation.

4. Simulation of the symbol-manipulating or information processes employed in learning by rote, in attaining concepts, and in solving problems. This category is most closely related to category 2, but with less emphasis on perceptual processes involving the peripheral sense organs, more emphasis upon non-numerical processes, and more emphasis on the construction of a formal information-processing theory of human mental processes. The research that the other participants in this session will report falls in this category, but before I introduce it, I should like to say something about the methodology involved.

Non-Numerical Computation

Mathematics is the classical tool for formalizing theories, and arithmetic or numerical analysis the tool for testing theories by comparing them with data. Progress toward formal theory in psychology, and the behavioral sciences generally, has been much impeded by the difficulties that are encountered in finding mathematical formulations that capture the significant aspects of the phenomena under study. The difficulty lies not merely in the complexity of the relations among the phenomena; it is even more deeply rooted in the incorrigibly "qualitative" character of the raw data.

How shall we, for example, characterize the data from a laboratory study of human problem solving in order to make these data amenable to mathematical and numerical analysis? We can count the number of problems a subject solves in a given time, and assign scores to batteries of problems on the basis of such counts. We can tally numbers of errors of various kinds. But the numbers we obtain in these ways are pale shadows of the subject's actual behavior--particularly his verbal behavior if he thinks aloud while solving the problem. When we record such behavior, we get data like these:

> S. Well, one possibility right off the bat is when you have just a PvT like that [the problem expression] the last thing you might use is that rule 9. I can get everything down to a P and just add a vT. So that's one thing to

keep in mind ... I don't
know if that's possible;
but I think it is because I
see that expressions (2)
and (4) are somewhat similar.

How do we build a mathematical model for such a verbal stream, or for the underlying thought processes that carry the stream along? How much of the process have we captured if we encode the verbal statements and make counts of the numbers of statements of one kind or another?

Psychologists have commonly retreated from one or both horns of the dilemma. Some have steeled themselves against accusations of "softness" from their fellow scientists, and have continued to deal with complex human behavior in all its qualitative, unmathematized, richness and vagueness. This strategy is most evident in clinical psychology, whose norms of clarity and testability are very far from the standards of the natural sciences. But the same characteristics appear, to a milder degree, in the work of psychologists -- notably the Gestaltists and the so-called Wurzburg School -- who have continued to deal with complex human thinking and problem-solving behavior.13 From them we have had valuable insights, but little in the way of testable theory stated in operational terms.

Other psychologists have preserved formal rigor by retreating to simple dichotomous button-pushing choice situations, to the study of reaction times, or to maze experiments with rats. For human and animal experiments involving elementary tasks of these kinds, a considerable body of experimental technique and data and even some formal theory (e.g., stochastic learning theory¹⁴) has developed, but at the cost of leaving a very wide gap between the phenomena that have been treated and the kinds of complex human thinking behavior that we should like to be able to explain.

Computers now open up a third course of action that requires no compromise. We can continue to deal with complex verbal behavior, but use the computer to simulate it without first encoding it or forcing it into mathematical form. For computers, in addition to their arithmetic capabilities, have, of course, quite general capabilities for manipulating symbols: reading symbols, writing symbols; copying symbols, erasing symbols, comparing symbols for identity or difference, behaving conditionally on the outcomes of such comparisons.

The research we are considering in this session exploits the non-numerical symbol-manipulating capacities of computers. Its basic strategy is to use these capacities to formulate programs that simulate, step by step, the nonnumerical symbol-manipulating processes that (if the hypothesis is correct) humans use when they memorize syllables, acquire new concepts, or solve problems. Such a program, once formulated, can be tested by comparing the stream of symbols it generates in a problem situation (the computer trace) with the stream of verbalizations of human subjects in the same problem situation in the psychological laboratory.

Information Processing Theories

The products of this kind of research are programs that purport to explain complex human activities in terms of organized systems of simple information processes--symbol-manipulating processes. In what sense do such programs 'explain' the behavior? Clearly they say little about the underlying neurophysiological and biochemical processes that occur in the central and peripheral nervous systems. How can we have an explanation of the behavior without understanding those underlying processes?

Levels of Explanation

We explain phenomena by reducing them to other phenomena that seem to us, somehow, simpler and more orderly. How did Mendel, for example, explain the relative frequencies of his different kinds of peas in successive generations? He postulated (without any direct observational evidence) underlying dominant and recessive factors passed on from parents to their progeny, whose interaction determined the physical type of the progeny. Only many years later was any direct evidence obtained or microscopic structures in the cell-the chromosomes--that could provide the biological substrate for Mendel's factors." Again, Morgan's studies of fruit fly populations led him to postulate even tinier components of the chromosomes--the genes. These had to await the electron microscope before they could be shown, by direct observation, to exist; and even today, we are still far from an explanation of these biological structures at the next, biochemical level.

The goal, then, in simulating complex human behavior is the same as the

goal in simulating neural nets: We wish to explain the behavior. But the information processing theories approach that explanation in stages. They first reduce the complex behavior to symbol manipulating processes that have not, as yet, been observed directly in the human brain. The hope, of course, is that when we know enough about these processes, it will be possible to explain them at a still more fundamental level by reducing them to systems of neural events.

When this stage is reached, theories in psychology will begin to resemble theories in genetics and in the biophysical sciences in their hierarchical structure. At the highest (but least fundamental) level will be information processing theories of overt behavior. At the next level will be neurological theories explaining how elementary information processes are implemented in the brain. At a still more fundamental level will be biochemical theories reducing the neurological mechanisms to physical and chemical terms. Information processing theories of thinking, neurological theories, and biochemical theories are complementary, not competitive, scientific commodities. We shall need all three kinds, and perhaps others as well, before we shall understand the human mind.

Finally, when we use computers to state and test information processing theories of thinking, we do not postulate any crude analogy between computer and brain. We use the computer because it is capable of simulating the elementary information processes that these theories postulate as the bases for thinking. We do not assert that there is any resemblance between the electronic means that realize these processes in the computer and the neurological means that realize the corresponding processes in the brain. We do assert that, at a grosser level, the computer can be <u>organized</u> to imitate the brain.

Information Processing Languages

There has been a strong, and not accidental, interaction between work on the computer simulation of human thinking and research on computer programming. The kinds of processes that computers are called upon to perform when they are simulating thinking tend to be quite different from the processes they perform when they are carrying out numerical analyses. A superficial difference is that the former processes involve little or no use of arithmetic operations. A more fundamental difference is that memory must be organized in quite distinct ways in the two situations.

Within the past five years there have been a number of reports to these conferences on the general characteristics and specific structure of information processing languages specially designed to facilitate non-numerical simulation.¹⁵,¹⁶ I shall not go over this familiar ground again, except to point out that when such languages are used to build psychological theories the languages themselves contain implicit postulates--although rather weak ones-about the way in which the central nervous system organizes its work.

One of the common characteristics of all of these languages is their organization of memory in lists and list structures. By this means there can be associated with any symbol in memory a "next" symbol -- the symbol that follows it on the list to which they both belong. By the use of a slightly more complicated device, the description list, there can be associated with any symbol in memory a list of its attributes and their values. If the symbol, for example, represents an apple, we can store on its description list the fact that its color is red, its printed name is APPLE, and its spoken name, APUL. The incorporation of these two forms of association -the serial order of simple lists and the partial ordering of description lists--in information processing languages permits one to represent many of the associative properties of human memory in a quite simple and direct way. We can use simple lists to simulate serial memory--e.g., remembering the alphabet -- and description lists to simulate paired associations -- e.g., the association between an object as recognized visually and its name.

A characteristic of the list processing languages, which they share with most other compiling and interpretive languages, is that they organize behavior in hierarchical fashion. Routines use subroutines, which have their own subroutines, and so on. This characteristic of the languages again facilitates the construction of programs to simulate human behavior, which appears to be organized in a highly similar hierarchical manner. The fact that most investigators have found it easier to write simulation programs in interpretive list languages than in machine language derives, in all likelihood, from the fact that the former languages have already taken the first steps in the direction of organizing the computer processes to mirror the organization of the human mind.

Heuristic Problem Solving Programs

The Program of Selfridge and Dinneen

The work of Selfridge and Dinneen on pattern recognition,7 which I earlier assigned to the second category of simulation programs--simulation of sensory-perceptual processes--really marks a transition to information processing simulations. The Selfridge-Dinneen program specified a set of processes to enable a computer to learn to discriminate among classes of patterns presented on a two-dimensional "retina." The patterns could represent, for example, English letters like "A and "0" of varying shape, size, and orientation.

In the Selfridge-Dinneen program, recognition was accomplished by using various operators to transform the retinal stimuli -- in general to simplify and 'stylize' them -- and then searching for characteristics of the transformed stimuli that grouped the various exemplars of a given alphabetic letter together, but separated the exemplars of different letters. Although the program made use of the arithmetic instructions of the computer, the operations were basically topological and non-numerical in nature. Appropriate organization rather than rapid arithmetic was at the heart of the program.

The Selfridge-Dinneen program foreshadowed subsequent work in this area in another important respect also. The characteristics used to distinguish patterns were heuristic. They amounted to rules of thumb, selected by the computer over a series of learning trials on the sole basis that they usually worked -that is, made the desired discriminations. In more traditional uses of computers it is usually required that the programs be algorithms -- that they be systematic procedures which guarantee solution of the problem to a desired degree of accuracy. The heuristics generated by the pattern recognizing program provided no such guarantees. Since there are vast ranges of tasks, handled every day by human beings, for which no algorithms in the sense just indicated are known to exist, the admission of heuristics as program components opened the way to simulating the less systematic, but often effective, processes that characterize much garden-variety, everyday human thinking.

Subsequent work has tended to confirm this initial hunch, and to demonstrate that heuristics, or rules of thumb, form the integral core of human problem-solving processes. As we begin to understand the nature of the heuristics that people use in thinking, the mystery begins to dissolve from such (heretofore) vaguely understood processes as "intuition" and "judgment."

Some Other Problem-Solving Programs

In the period 1956 to 1958 there came into existence a number of other computer programs that accomplished complex tasks with a "humanoid" flavor: composing music, 17 playing checkers, 18 discovering proofs for theorems in logic, 19 and geometry, 20 designing electric motors and transformers, 21 playing chess, 22, 23, 24 and balancing an assembly line.²⁵ The primary goal in constructing most of these programs was to enable the computer to perform an interesting or significant task. Detailed simulation of the ways in which humans perform the same task was only a secondary objective--or was not considered at all.

Nevertheless, it was discovered that often the best program for doing the job was a program that incorporated some of the heuristics that humans used in doing such jobs. Thus, the music composition program of Hiller and Isaacson made use of some of the rules of classical counterpoint; the motor design programs and line balancing program were generally organized in much the same ways as the procedures of experienced engineers, and so on. Hence, to a greater or lesser degree, all of these programs have taught us something about the ways in which people handle such tasks--especially about some of the kinds of heuristics they use.

Among these programs Samuel's checker program and the Los Alamos chess program place the least emphasis on heuristics, and hence provide valuable yardsticks for comparison with heuristic programs handling the same, or similar tasks. These two programs make essential use of the computer's capabilities for extremely rapid arithmetic, for their basic strategy is to look at all possible (legal) continuations of the game for several moves ahead, and then to choose that move which appears most favorable (in a minimax sense) in terms of the possible outcomes. In contrast, Bernstein's and the NSS chess programs examine a small, highly selective subset of all possible continuations of the game and choose a move that appears good in the light of this selective analysis.

• Thus, the Los Alamos program, look-ing two moves ahead, will typically examine a little less than a million possible continuations, Bernstein's program approximately 2,500, and the NSS program almost never more than one hundred and more usually only a handful. All three programs play roughly the same quality of chess (mediocre) with roughly the same amount of computing time. The effort saved by the heuristic programs in looking at fewer continuations, is expended in selecting more carefully those to be examined and subjecting them to more thorough examination. Thus, the more systematic, arithmetic programs provide benchmarks against which the progress in developing heuristics can be measured.

The General Problem Solver

All of the programs we have mentioned fell short of human simulation in one very fundamental respect -- apart from failures of detail. They were all special-purpose programs. They enabled the computer to perform one kind of complex task, and one kind only. Only in a few cases (the Checker Player 18 and the Logic Theorist 26) did they enable the computer to improve its performance through learning. Yet we know that the human mind is (a) a general-purpose mechanism and (b) a learning mechanism. A person who is brought into a relatively novel task situation may not handle the situation with skill but, unless it is inordinately difficult, will not find himself at a complete loss. Whether he succeeds in solving the problem that is posed him, or not, he is able, at least, to think about it.

We must conclude that if a computer program is to simulate the program that a human brings to a problem situation, it must contain two components: (a) a general-purpose thinking and learning program that makes no direct reference to any particular task or subject matter; and (b) heuristics that embody the specific techniques and procedures which make possible the skilled and efficient performance of particular classes of tasks. The program must incorporate both general intelligence and special skills.

The General Problem Solver (GPS) was the first computer program aimed at describing the problem solving techniques used by humans that are independent of the subject matter of the problem.²⁷ Since GPS has been described elsewhere, I shall say only a word about its structure. It is a program for achieving the goal of transforming a particular symbolic object (representing the "given" problem situation) into a different symbolic object (the "desired" situation or goal situation). It does this by discovering differences between pairs of objects, and by searching for operators that are relevant to reducing these differences. In the form in which it has thus far been realized on a computer, GPS is not a learning program, hence still falls far short of simulating all aspects of what we would call general intelligence.

In its current computer realization. GPS has solved some simple problems of finding proofs for theorems in symbolic logic (substantially the same task as that handled by the special-purpose Logic Theorist). It has solved the wellknown puzzle of Missionaries and Cannibals--finding a plan for transporting three missionaries and three cannibals across a river without any of the missionaries being eaten. Hand simulation has demonstrated that it can handle trigonometric and algebraic identities. On the basis of other investigations that have not fully reached the programming stage, it appears highly likely that GPS will be able to solve certain tactical problems in chess (e.g., to find a move leading to a fork of a pair of enemy pieces), do formal differentiation and integration, and write codes for simple computer programs in IPL V. Several possibilities for incorporating learning processes in GPS, one of them using GPS in the learning mechanism itself,²⁰ have also been explored.

The adequacy of GPS as a simulation of human problem solving has been examined, primarily in the task domain of symbolic logic, by comparing the computer trace with the thinking-aloud protocols of college students solving identical problems.²⁹ The evidence to date suggests that GPS does indeed capture the principal problem-solving methods used by the human subjects. The detailed comparison of its behavior with the protocols has cast considerable light on the processes of abstraction and on the nature and uses of imagery in problem solving.

Recent Advances in the Simulation of Thinking

The remaining papers to be presented in this session will describe a number of heuristic programs that have been written in the past two years, and which extend very substantially the range of human mental processes that have been simulated with these techniques. I shall not anticipate the content of these programs, beyond indicating what their relation is to those I have already mentioned.

Areas of Psychological Experimentation

The simulations mentioned so far all fall in the area that psychologists call "higher mental processes." As I indicated earlier, these processes have tended to be underemphasized in American experimental psychology until quite recently because we did not have tools for investigating them in an objective and rigorous way. If computer simulation has shown itself to be a powerful tool of research in an area as difficult as the study of higher mental processes, we might expect this tool to prove even more powerful if applied to the simpler phenomena with which experimental psychologists have been largely concerned. The papers of this session report some of the first evidence that this expectation is justified.

What are the kinds of tasks and processes that have been most thoroughly studied by psychologists? Perception--the interaction of sensory organs and central nervous system in the discrimination and recognition of stimuli--has been the subject of extensive investigation. A second, very active, research area has been learning, and particularly the rote learning of serial material and of stimulus-response pairs. A third area has been simple choice behavior, especially choice among a small number (usually two) of alternatives with systematic or intermittent reward. Animal and human maze learning experiments have been used to study both rote learning and simple choice behavior. Finally, there is a rather varied assortment of work that is usually classified under the heading of "concept formation" or "concept attainment.'

No one supposes that the topics I have mentioned--perception, rote learning, simple choice behavior, maze learning, and concept formation--are mutually exclusive and exhaustive categories. They are simply pigeon holes that psychologists have found convenient for classifying experiments. It is almost certain that the mechanisms required to perform tasks in one of these areas are called into play in some of the others. Hence, we would have reason to hope that as heuristic programs are constructed to handle one or another of these tasks, the mechanisms employed in the several programs will begin to show distinct resemblances--and resemblances also to the mechanisms used in problem-solving simulations. Such resemblances and common mechanisms are already beginning to appear.

Long-Range Goals of Simulation

The long-term research strategy would again be gradually to replace a multitude of special-purpose programs with a more general program aimed at simulating the whole man--or at least the cognitive aspects of his behavior. Although enormous gaps of ignorance still separate us from that goal, the goal itself no longer seems entirely Utopian to the active researchers in the field.

Perhaps the largest single gap at present--and one that is not filled by any of the work to be reported today--is in programs to explain long-range human memory phenomena. I will venture the personal prediction that filling this gap will soon become crucial to progress in the whole field of information retrieval.

Another important gap that also has significant practical implications lies in the area of simulation of natural language processes. Here, interest in language translation and in the improvement of computer programming languages has already led to exciting progress--as illustrated for example, by the work of Chomsky³⁰ and Yngve.³¹

Heuristic Programs in New Areas

The areas of rote learning, simple choice behavior, and concept attainment are represented in the programs to be described by Mssrs. Feigenbaum, Feldman, and Hunt, respectively.

Rote Learning. The Elementary Perceiver and Memorizer (EPAM) is a theory to explain how human subjects store in memory symbolic materials that are inherently 'meaningless." The typical learning materials are "nonsense syllables"--spoken or printed syllables that do not correspond to English words. By studying rote learning, we hope to understand, for example, how humans learn to associate names with objects, and learn to read by associating printed words with their oral counterparts.

Binary Choice. In the so-called partial reinforcement or binary choice experiment, the subject is instructed to guess which of two events will occur next. In variants of the experiment, the actual event sequence may be patterned, or it may be a random sequence. The binary choice experiment has been one of the principal situations used to test the stochastic learning models that have been developed in psychology over the last decade.^{14,32} Mr. Feldman's Binary Choice program offers an alter-native theory to explain these phenomena, hence provides an interesting example for comparing and contrasting heuristic programs with more traditional mathematical models.

Concept Formation. In the simplest form of the concept formation task, a rat is given a choice of two gates, one of which is labelled, say, with a large triangle, the other with a small circle. If the experimenter's aim is to test the rat's attainment of the concept "triangle," he places a reward behind the gate labelled with the triangle. On succeeding trials, the symbols change in shape, size, or color, but the gate labelled with a triangle always leads to the reward. Within the past year, several computer programs have been written that simulate slightly more complex concept learning behavior in humans. One of these programs, the Concept Learner, will be described by Hovland and Hunt.

Conclusion

I have tried to outline the development over the past decade of the use of computers to construct and test nonnumerical information-processing explanations for human thinking and learning. Such programs, which are beginning to be validated by behavioral evidence, are providing embryonic theories for these phenomena in terms of underlying information processes. Hopefully, the elementary information processes that are postulated in the theories will, in turn, find their explanation in neurological processes and mechanisms. The papers in this session describe a few of the programs of this kind that have been constructed to date, and provide some basis for judging the prospects for this approach to understanding the human mind.

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118

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