Cognition, Simulation and the Problem of Complexity

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OVER a decade ago the great cybernetic theorist, Warren S. McCulloch (1955), posed the following critical challenge to all life scientists:

> To the theoretical question, Can you design a machine to do what a brain can do?, the answer is this: If you specify in a finite and unambiguous way what you think a brain does do with information, then we can design a machine to do it. Pitts and I proved this constructively. *But can you say what you think brains do* (my italics)?

The important contribution of McCulloch and Pitts (1943) was to prove, to the chagrin of the vitalists, that any perceptual or cognitive process believed to be carried out by living a nervous system which could be precisely defined, could be logically simulated by a network of abstract neural modules of considerably simpler structure than living neurons. In later developments of their model, they illustrated this possibility by showing how such networks had the ability to abstract universal properties of simple geometrical figures, to form general functional schemata for recognizing certain patterns, and to store abstract specifications of the patterns presented for future reference. Their work made precise what others had just hinted at and, thus, opened wide the door to mathematical simulation theory. However, they were unable then, as we are now, to say precisely what "brains" do.

More recently, the late John von Neumann, one of the great mathematicians of our day, glimpsed a basic difficulty that he thought explained why simulation models for complex psychological phenomena have failed to develop very far beyond their promising beginnings. He said:

> The insight that a formal neuron network can do anything which you can describe in words is a very important insight and simplifies matters enormously at low complication levels. It is by no means certain that it is a simplification on high complication levels (von Neumann, 1966).

He then illustrates this point with respect to the fact that about one-fifth of the brain is a visual brain, consisting of a network of about two billion neurons. Apparently, this complicated portion of the brain is required to organize and interpret visual analogies (i.e., similarity among patterns).

> It is absolutely not clear *a priori* that there is any simpler description of what constitutes a visual analogy than a description of the visual brain . . . Normally a literary description of what an automaton is supposed to do is simpler than the complete diagram of the automaton. It is not true *a priori* that this will always be so. There is a good deal in formal logic to indicate that the description of the functions of an automaton is simpler than the automaton itself, as long as the automaton is not very complicated, but that when you get to high complications, the actual object is simpler than the literary description (von Neumann, 1966).

In my opinion, McCulloch on the one hand, and von Neumann on the other, put their fingers on the two most important problems facing psychological simulation theory: (1) deciding what the most general psychological function computed by the human brain is, and (2) constructing models, which adequately simulate this surely very complex function, that are themselves not too complicated to be understood.

For sake of argument, although I believe it to be true, let us assume that logico-mechanical models (perhaps, as computer programs) can be designed which adequately simulate simple, or even moderately complex, psychological phenomena. It is tempting to assume that if such models can be successfully achieved, then it automatically follows that *mutatus mutandi* models can be designed to

simulate extremely complex phenomena. Unfortunately, this argument is mere handwaving, for as we shall see, there are numerous arguments to the contrary.

In what follows, I will attempt to show that the most characteristic psychological function computed by higher organisms is quite complicated indeed and, thus, requires of any reasonably adequate simulation model a corresponding degree of structural complication. Moreover, I will also argue that although there may be reason for optimism in assaying the difficulties encountered in constructing simulation models for phenomena of low to moderate structural complexity, there is, on the other hand, much reason for pessimism regarding the possibility of achieving similar successes with respect to extremely complex psychological phenomena.

It should be understood, however, that the arguments are aimed at the logic of complex phenomena, in general, rather than at the logic of simulation models *per se;* that is, complexity not simulation is the logical culprit.

What the Brain Does: A Hypothesis

Intuitively, it is so easy to demonstrate what I believe the most characteristic psychological function computed by our brains is, that I hesitate to do so, for fear of being thought naive. But it is such an obvious, some might even say trivial, datum that many theorists may have overlooked it. Although several theorists, whom I will list later, have implied its existence, none, to my knowledge, have attempted to experimentally investigate it. Perhaps, this is because the function is too general to be tested, or its validity too obvious to require testing. It can be demonstrated by the following exercise.

Look around you. Now, close your eyes and describe aloud what you saw. Open your eyes and check to see how accurate your recall was. Although your recall of detail was by no means total, you probably ceased your description of your immediate environment out of boredom, rather than from lack of recall.

Again close your eyes and imagine you are a map-maker who must pinpoint exactly where in the world, in the country, in the state, . . ., in the room you are located. What is your present body posture? What is the weather like? The temperature of your room?

Now play autobiographer. Who are you? Where and when were you born? How did you get from there and then to the here and now? What events made you most happy, most sad? Bored you? Are you bored now?

Notice how naturally and quickly you are cognitively geared to answer such diverse and complex questions. We psychologists, who have agonized over theories of rote memory just to explain serial list recall, are understandably annoyed by anyone who reminds us of the immensity of our theoretical problems. But as objective scientists, let us ask ourselves if there are any experiments one needs to run in addition to this simple phenomenological demonstration, to be convinced that the basic psychological function is indeed involved in this exercise. The crucial question which must be answered, however, if this exercise is not to remain trivial, is whether anything precise can be said about the nature of the psychological function implicitly demonstrated.

Minsky (1968) defines one of the main properties of a model as follows: "To an observer B, an object A* is a model of an object A to the extent that B can use A* to answer questions that interest him about A". The significant question for cognitive theory concerns the nature and the organization of the "object" that is neurologically instantiated and that allows man to answer questions which interest him about the current state or history of his environment, of himself and the relation between the two.

Whatever such an object, or model, is, this ultimately, in whole or part, is what must be simulated if we are to make any significant gains toward a theory of perceptual organization, cognition or memory. Given this interpretation, it follows that the task of the cognitive theorist is essentially that of the simulation theorist, namely, to construct a theoretical model which *reproduces* the important features of what I will call the "psychological ecosystem" (i.e., the joint system consisting of the historical interplay of the environment and organism as connected subsystems).

Several other theorists have suggested ways in which higher organisms cognitively reproduce the significant properties of the psychological ecosystem available to them. For instance, Kenneth

Craik (1943), one of the first psychologists to clearly enunciate a cybernetic hypothesis regarding the logico-mechanistic nature of the cognitive reproduction function, stated it this way:

> My hypothesis then is that thought models, or parallels, reality—that its essential feature is not "the mind", "the self", "sense data", nor propositions, but symbolism, and that this symbolism is largely of the same kind as that which is familiar to us in mechanical devices which aid thought and calculation . . . human thought has a definite function, it provides a convenient small scale model of a [natural] process . . .

Some theorists, in essential agreement with Craik, have been bold enough to postulate rather specific cognitive structures by which the organism instantiates its knowledge of the world and itself: For Miller, Galanter and Pribram (1960), the model is called "the image" and is instantiated by a hierarchical organization of TOTE units; according to Hebb (1949) the organism builds up its model by means of "phase sequences" and "cell assemblies"; for Koffka (1935) and other Gestaltists, the model is manifested by a "field of memory traces" which is related to the "environmental field" by a principle of isomorphism; Lashley (1942) postulated "interference wave patterns" and, more recently in the tradition of the field theoretic approach, Pribram (1969) suggested a model based on standing wave patterns governed by holographic principles; in a classical attempt, Tolman (1948), echoed by Bohm (1965) a theoretical physicist, declared for "cognitive maps" and "conceptual maps", respectively; Piaget (1967) sees the child's knowledge as being instantiated in a complex semi-lattice of logically coordinated ideational schemata; and McCulloch and Pitts (1943), as stated earlier, suggest a model consisting of patterns of excitation in a logically simplified neural net. The common core of agreement among these theorists is that higher organisms instantiate their knowledge of themselves and their environments by means of a cognitive reproduction function.

By Neisser's (1965) definition of a cognitive structure as ". . . a non-specific but organized representation of prior experiences" (including, of course, some experiences which are genetically based), all the above theorists can be said to be wrestling with the central problem of cognitive psychology—that of constructing a logico-mechanistic model which is, in principle, capable of simulating the basic cognitive achievement of higher organisms.

Since the basic achievement of the cognitive function is to reproduce the essential features of the psychological ecosystem by representing them in terms of cognitive structures, then an adequate simulation must provide an accurate reproduction of these cognitive structures. But how complex are these structures and how complex must a model be which adequately simulates their functioning?

The Problem of Complexity

In this section, I want to survey some interesting mathematical results which shed light on the following statement by von Neumann (1966):

> It is characteristic of objects of low complexity that it is easier to talk about the object than produce it and easier to predict its properties than to build it. But in complicated parts of formal logic it is always one order magnitude harder to tell what an object can do than to produce the object. The domain of the validity of the question is of a higher type than the question itself.

In just what way von Neumann's remarks are to be taken is somewhat open to question. Unfortunately, he died without clarifying this issue. But it is much too important an issue to ignore, and it would be a mistake to underestimate the importance of von Neumann's thinking along these or any other lines. For this reason it would be well if we seriously pursue the line of argument he suggests. The most important clue has to do with his assertion that "... it is always of a magnitude harder to tell what an object can do than to produce the object. The domain of validity of the question is of *a higher type* than the question itself (my italics)".

The crucial concept here is that of *type*. To those with training in symbolic logic, or set theory, the term "type" most likely evokes the connotation given by Bertrand Russell in his so-called "ramified theory of types", by which he showed mathematicians one way that the paradoxes of Cantor's set theory might be avoided. However, we must look elsewhere to understand what von Neumann apparently

had in mind, since the following quote makes it unlikely that this notion of complexity type was what he meant:

> There is a concept which will be quite useful here, of which we have a certain intuitive idea, but which is vague, unscientific and imperfect. This concept clearly belongs to the subject of information, and quasi-thermodynamical considerations are relevant to it. I know no adequate name for it, but it is best described by calling it "complication". It is effectivity in complication, or the potentiality to do things. I am not thinking about how involved the object is, but now involved its purposive operations are. In this sense, an object is of the highest degree of complexity if it can do very difficult and involved things (von Neumann, 1966).

Not only does this quote serve to show that von Neumann, who understood Russell's type scheme as well as anyone, had something else in mind, but it clearly indicates that von Neumann meant his conjecture to apply generally to the concept of effectivity and not just to biological, or mechanical, self-reproduction as special cases or purposive functioning. In this regard, cognitive reproduction qualifies as another degree of effectivity in complication, that is, as another purposive operation a system can perform if it is sufficiently complicated.

Thus, let us construe the notion of "complexity type" very broadly. Von Neumann surely believed his conjecture that complication is degenerative in effectivity below a certain minimum level, to be robust enough to stand almost any interpretation of the concept of complication. He asserts:

> We do not know what complication is, or how to measure it, but I think that something like this conclusion is true if one measures complication by the crudest possible standard, the number of elementary parts (von Neumann, 1966).

What we need is a scheme by which functions or behaviors, such as self-reproduction, can be categorized in terms of how hard they are to compute. Hartmanis and Stearns (1963) investigated such schemes where the computational complexity of a function is measured by the number of operations a multi-tape Turing machine took to produce a sequence of outputs defining the function. They showed, moreover, that no single class contained all computable sequences (functions), on the one hand, and on the other hand, that every computable sequence is contained in some complexity class. In this way, a hierarchy of complexity classes must exist.

What makes their proofs so important is the somewhat surprising fact that they were able to show that these complexity classes are independent of the time scale or of the speed of the components from which the machines are constructed. Thus, they were able to demonstrate that some computable functions possess an inherent complexity that makes them difficult to compute.

In another paper, Hartmanis (1968) shows the existence of a sharp bound between the time or number of steps it takes for the recognition of regular versus non-regular sequences. Since computation is used to define complexity of sets, it follows that there must be a jump in the structural complexity of machines which are able to compute functions from lower to higher complexity classes. This suggests the interesting possibility that an investigator, who has classified a large number of machines in terms of some additive measure of structural complexity such as number of parts, will see an apparent sharp bound between machines in terms of the functions they can compute. This would appear as the emergence of qualitatively distinct levels of functioning from their increase along a quantitative dimension of complexity. Perhaps this is what is now being observed by biochemists who catalogue those molecular systems too simple to reproduce from those complex enough to do so.

Thus, there is evidence that some functions are inherently more complex than others. Apparently, self-reproduction is a function which is of a higher complexity "type" than others and therefore can only be computed by systems which possess structures of high complications. Still additional support has been found for von Neumanns' conjecture from what may prove to be legitimate interpretation of existing mathematical results.

Manuel Blum (1967) successfully demonstrated the existence of a class of functions which require an enormous number of steps to be computed, yet has a "nearly quickest" program. Thus, by the Hartmanis and Stearn's metric of complexity based on time-to-compute, such functions must be considered to occupy a superior position on

the hierarchy of complexity classes. And just as they found, Blum was able to show that any machine program that can compute such complex functions must take practically as many steps as the "quickest program". In other words, if a machine (program) is able to do the complex functions of this type at all, they must all be beyond some sharp bound on the dimension of structural complications. Consequently, if self-reproduction (as well as the dependent concept of evolution) can be shown to belong to such a class for which no simpler program than the nearly quickest program can compute it, then von Neumann's conjecture must be reckoned with. But can we show that reproductive functions belong to such classes of high complexity? The following argument demonstrating the formal analogy between the concepts of simulation of complicated systems and self-reproduction by complicated systems lends support to this claim.

Results by both Tarski (1956) and Gödel (1965) suggest that it may be quite reasonable to conclude that the problems of self-reproduction and the simulation of highly complex systems involve functions which belong to the same order-type complexity class. This conclusion can be stated precisely as a corollary conjecture to von Neumann's conjecture.

Self-reproduction, reproduction and simulation of living systems (i.e., systems of great finite complexity) are semantic predicates of the same logical type since they are special cases of the truth functional property of predicates. For instance, the following statements require test procedures which are essentially of equivalent complexity:

(*a*) System X is a "strong" simulation of the behavior of system Y;

(*b*) System X is a structural reproduction of system Y;

(*c*) System X is self-reproductive;

(*d*) System X is a "true" model of system Y;

(*e*) System X is as complex as system Y.

We will briefly sketch the argument in support of this additional conjecture.

Tarski (1956) was able to show that the truth of a system as a model for another system depends upon the establishment of an isomorphism between the two systems at the appropriate level of analysis called for by the model. In so much as truth is a relationship which subsists by virtue of the correspondence between the state of affairs of one system with another, then truth is not a *local* property of either system. Rather truth must be considered a meta-property of the system of which it is specifically predicated. That is, truth is a *global* property of the pair of systems.

By using Minsky's (1968) definition of a model, it is possible to show that a strong formal analogy exists between the theoretical process of constructing simulation models of natural phenomena and the cognitive process by which humans instantiate their knowledge of their environments and their place in them. If we use Minsky's definition as a formula and substitute the appropriate terms the analogy can be expressed quite precisely:

(*A*) "To an organism B, *the set of cognitive structures* A* is a model of an *ecosystem* A to the extent that B can use A* to answer questions that interest him about A". (i.e., B can use A* to react adaptively to its environment.)

and (*B*) "To a *theorist* B, *the machine* A* is a model of a *psychological phenomenon* A to the extent that B can use A* to answer questions that interest him about A".

The definitions (*A*) (*B*) suggest that the process by which the theorist attempts to explain psychological phenomena is logically the same process used by an organism in attaining knowledge of his world, that is, they both instantiate their knowledge in the form of a model by a process of reproducing the significant properties of the phenomenon in question.

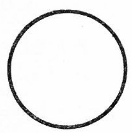
Given the above then, reproduction, as well as simulation, belong to the same complexity class since, like the truth function, they are realized only by procedures which establish an isomorphism between two systems.

Another way of putting this argument, to use the earlier results, is as follows:

Let p be a program executed by some organism o in computing its behavior to a given psychological task. Assume that f is the behavioral function computed by p and that f belongs to the class of functions which are enormously complex and are known to have a "nearly quickest" program. Now assume that p' is a simulation program designed by the theorist to model o's computation of f. By the Hartmanis and Stearn's and Blum's results it follows that p' must be nearly as complex as p.

This conclusion, if valid, portends dire problems for theory construction in psychology. For if f is a function of sufficient complexity, say reproduction, so that von Neumann's conjecture holds, then so must the conjecture hold for p and the would-be-explanatory model p'. The model p' would by necessity be nearly as complex as p and therefore offer no aid to our understanding of the psychological function being computed by the organism. If this is the case then no simulation model for complex organisms can meet the most fundamental criterion of theory evaluation, namely, that the theory be in some significant way simpler to understand than the phenomenon it purports to explain. We would then have two equally complex phenomena to explain (e.g., a human and an android).

Still another line of argument suggests that the above conclusion is indeed valid, that is, that simulation and cognitive reproduction are very complex functions. Minsky and Papert (1967) suggest another interesting measure for the complexity of structures. They introduce the concept of the "order-type" complexity of a structure. The *order-type complexity index* of a geometric property is essentially determined by the relative degree of complexity of the structures reuqired to define the property. For instance, consider the algorithm for determining whether a figure is *convex*. Figures A and B offer examples of forms which do and do not have the property of convexity respectively. The test for convexity requires the determination of whether a pair of points x and z, which define a line segment, can be selected such that if they are both contained in the same form then so must be their midpoint y. A form for which it is the case that the midpoint lies outside the form while the end points are contained by the form is said to lack convexity. A simple test of all point triples on Figure A fails to find a case in which the midpoint of a line segment falls outside the form unless one of the end points does also. However, the same test applied to Figure B shows, in fact, that a line segment can be placed across the pie-shaped slice so that the midpoint of the segment lies outside the boundaries of the form containing the endpoints.



A

B

The *order-type index k* of the property of convexity is therefore at most $k = 3$. This illustrates how the order type index is determined by the cardinal number associated with the minimal structure required to define the property. It is especially interesting to note that some properties of structures are of an indeterminate order type, that is, are defined over minimal structures whose associated cardinal number is indeterminately large. For instance the property of *connectivity* (i.e., of a form consisting only of connected parts) is an example of such a property of indeterminate order-type. Minsky and Papert (1969) contrast the two properties by introducing the distinction between "local" and "global" properties.

It can be decided whether or not a figure has the property of convexity by simply testing to see if all point-triples meet the requirements defined earlier. Since a single test of a triple can decide the negative case then the tests are independent, but since a sum of all tests is required to determine the positive case then the test must agree unanimously. Thus a point triple as a *local* property is sufficient for determining whether the property of convexity holds for the figure or not. By contrast, however, connectivity is such a property that no procedure which tests less than all the points in the figure can determine whether the property holds. Thus connectivity requires the test of the whole figure or a *global* property while convexity only requires a test on a local property.

In other words, there are "global" properties like connectivity which are inherently more complex to define than other properties,

local ones like convexity. Moreover, any test program which determines the global property must be of an indeterminate order of complexity in the sense that as the finite size of the figure grows the test increments proportionately. What happens when the object to be tested becomes astronomically complex, say in case of determining the connectivity of a neural net with several billion synaptic junctures?

This result poses a plethora of problems for theoretical psychology since it suggests that there may be "global" structural properties of organisms which the psychologist must determine if he is ever to understand complex human behavior. But unfortunately such properties would require an indeterminate number of parametric experimental tests. Since reproduction is a function (property) which by definition involves an operation that duplicates every significant point of a given system then, like connectivity, it too must be global and therefore, of an indeterminate order type. In order for a test to decide whether one system (the model) is a true reproduction of another system (the phenomenon) an isomorphism must be established between the sets of elements supporting the structures of the two systems. Thus, it would seem that any science like psychology, which desires formal models of highly complex systems, like organisms, will have to consider von Neumann's conjecture a threat to the fulfillment of its explanatory goals.

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An Experimental Study of Medical Diagnostic Thinking*

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THE staff of the Medical Inquiry Project of the Office of Medical Education Research and Development is engaged in a long-term program of studies of the medical diagnostic process. Through our investigations, we hope to generate a model of the diagnostic process as a form of inquiry and decision-making which will lead to improvements in methods for teaching these complex skills to medical students.

Three simulated cases, drawn from actual clinical records, are used to study physicians' reasoning. Actors simulate the patients and the clinical encounter is video-taped in a room designed to resemble a physician's office. In two cases, the actor-patient is interviewed for the history of the present illness and the functional inquiry. Data from the physical examination are available upon questioning a medical student who serves as a "data bank". In the third case, an actress has been trained to simulate the physical findings so a physician can conduct both a physical examination and an interview. In all three cases, the physician may order any laboratory tests he wishes. After the workup is completed, a "recall" session is held in which the physician views the videotape of the workup he performed. He has a stop-start switch with which he can

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