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Inadequacies of the Computer Metaphor

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Introduction

One of the most popular tacks taken to explain cognitive processes likens them to the operations of a digital computer. Indeed, the tasks for the cognitive scientist and the artificial intelligence scientist are often seen as indistinguishable: to understand how a machine or a brain "can store past information about the world and use that memory to abstract meaning from its percepts" (Solso, 1979, p. 425). The fact that there are machines that appear to do this, to varying degrees of success, is often taken to imply, almost by default, that cognition would have to embody the same steps in order to achieve the same results. In what follows, we outline our objections to this attitude and briefly consider some alternatives.

A Characterization of Computational Approaches to Cognition

The prototypical embodiment of the computational view is to be found in the early work of A. M. Turing, who, guided by his introspections on how *he* computed, designed a hypothetical machine that could be programmed to compute any function that was computable by algorithm. If an algorithm could be written to describe a particular cognitive function, then the Universal Turing Machine could be programmed to execute that function. On extension, if the machine could be made to "act like a human," that accomplishment was meant to provide insight into how a human acts. Of course, the universality of the Turing machine benefited from its hypothetically infinite memory capacity, its hypothetically perfect reliability, and a computational speed that, hypothetically, could be as fast as the task required. In short, Turing's "invention" was meant to be an ideal device operating under ideal conditions.

Such a device has appealed to students of cognitive phenomena on several fronts. The reason for this allure is obvious if we examine the framework within which most

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cognitive scientists operate. At bottom, it is assumed that the sense data with which a perceiver is provided relate equivocally to their sources in the environment. The input into the brain is so referentially opaque that the meaningfulness must somehow be restored (or recovered) by the perceiver. This restoration is accomplished by means of internalized cognitive procedures that operate on the sense data, combining and transforming them in various ways until, finally, a reasonable facsimile of the world has been constructed. If these cognitive procedures can be captured in the form of algorithms, it means that they can be executed without the intervention of a mystical agent. To construe procedures as a sequence of simple, discrete, deterministic, and finite instructions that can be executed by a machine is presumably to rid cognitive science of the omniscient goblins that too often seemed to creep into accounts of knowing the world.

No doubt, this framework of indirect realism—knowing the world through an internally constructed and stored representation of it—contributes to the vigor with which cognitive science has embraced computational science. When this framework was coupled with the early belief that neurons, which are the substrate of the cognitive machinery, have only the same discrete character as switches (i.e., they either fire or do not fire; they are either on or off), which are the substrate of the computational machinery, the marriage of mind with computer seemed ideal. Unfortunately, ideal properties have little to do with the natural circumstances in which knowers of the real world find themselves. It is from this perspective that we initiate our criticism of computational approaches to cognition.

Failings of the Computer Metaphor

The Misplaced Emphasis on Logic

A Universal Turing Machine is an ideal mathematical object; it represents a formal manipulation of symbols and owes allegiance to criteria of logical consistency but not to physical laws and constraints. Thus, for example, physical variables play no essential role in the concept of algorithm. In reality, however, every logical operation occurs at a minimum cost of KT of energy dissipation (where K is Boltzman's constant and T is temperature) and, in fact, occurs at a much higher cost to ensure reliability.

Of course, a computer instantiation of a formal operation entails the dissipation of energy, but what distinguishes the computer from the animal in this respect is that the computer has a single demand (computation) on relatively unlimited energy resources, whereas the animal has multiple demands on limited energy resources. For sound physical reasons, a formal operation that is logically possible and biologically realizable may not be useful. It is acknowledged among those who would simulate "mind" on a computer (e.g., Marr, 1976) that the construction of an algorithm for some purpose is trivially fettered. Algorithms can be like Kipling's *Just So Stories* (a designation that highlights excessive imaginativeness about causalities, as in "How the Elephant Got Its Trunk") in the absence of a serious attempt to view them in the context of the physical biology of the system for which they are intended.

To be redundant, the mere existence of an algorithm does not constitute an explanation of a phenomenon. That is to say, simply because an algorithm can be written to simulate a given activity of an organism, it does not necessarily follow that the organism uses such an algorithm in performing the activity in question (Cummins, 1977). The algorithm is merely a description of the activity; it may be just one of several alternative descriptions. While we as scientists might need a description in order to talk about a given activity, and an artificial device needs an algorithm in order to simulate that activity, natural systems do not require explicit instructions in order to perform their natural activities. On the contrary, for natural systems, it is largely the free interplay of forces, not *a priori* prescriptions, that realize stationary and transitory states. The significance of considering a system's continuous dynamic processes figures repeatedly in this paper.

The Overvaluation of Discrete Operations

Underlying the equating of cognition with computation and representation is the thesis that intelligence can be accounted for or simulated by discrete happenings in automata. It is claimed that just as continuous functions and variables can be represented by a finite set of discrete symbols and rules, so can intelligent operations of mind. Thus, for any system of sufficient complexity to be ascribed the epithet *intelligent,* one particular type or mode of systemic functioning—the discrete symbolic mode—is advanced as the only aspect of the system's behavior that is significant to an understanding of its intelligence.

This thesis is fundamentally flawed. To anticipate, for any complex system, the label *intelligent* belongs most legitimately to the dynamic mode that *creates* and *interprets* the discrete mode, and less legitimately to the discrete mode, which is (merely) a product (cf. Pattee, 1974).

To fix this idea of discrete mode, consider a continuous dynamic system such as the motion of a number of particles in a potential field. To describe this process, the physicist uses a few equations relating a small number of symbols. That is, by ignoring most of the details, a rate-dependent process is translated into a rate-independent structure. In expressing an understanding of the continuous process through a discrete set of equations, the physicist is said to be operating in the discrete, symbolic mode. It is universally recognized that this discrete, symbolic mode is essential for clear and exact descriptions, and it would be universally recognized that the physicist exhibited an act of intelligence in arriving at the abstractions in question.

To further fix this idea of a discrete mode, we note that observers of nature may not be alone in its use: biological systems in general may rely on discrete (self-) descriptions for their successful functioning. A prime example is the genetic code, a rate-independent structure (as far as we can tell) that relates the nucleotide symbol vehicles to their corresponding amino acids. This particular example of a discrete description has two notable features. First, the genetic code as description is simple and incomplete relative to the detailed continuous dynamics that it controls. The structure of the amino acids and how they are to fold and operate as rate-controlling enzymes are processes involving tens of thousands of interacting degrees of freedom. Second, the meaning of the genetic code cannot be assessed by transformations or translations into other discrete descriptions. Little headway is made toward interpreting the meaning of the code by transcribing the DNA strings into messenger RNA strings or messenger RNA strings into linear polypeptide strings. One string is as good a description as any other, and all fail to convey the meaning. Rather, the interpretation, or meaning, is in the folding process—a continuous dynamic process—which is not self-described in the cell's code (Pattee, 1974, 1977; Waters, 1981). We can explain the meaning of the DNA string only by reference to the dynamic mode that it complements. Moreover, it makes a lot of sense to argue that we can explain the *origin* of the DNA string only by reference to continuous dynamic processes.

The discrete mode might be characterized, generally, as singularities condensed out of continuous dynamics, a characterization that is consonant with recent attempts to generate biological organizations from the singularities of a dynamic topology (e.g., Thom, 1975; Shaw, 1980). This characterization, however, will be considered incomplete to the extent that one believes that the discrete mode must be structurally embodied (and *a fortiori*, that structure and function are complements). The genetic code is said to be *embodied* in the DNA string, and specific structural embodiment is advanced as a criterial property distinguishing rate-independent rules from rate-dependent laws (Pattee, 1973; Yates, 1980). It is not clear that the occurrences that dynamic topology attempts to portray, such as bifurcations, have a structural embodiment; they do not appear to be associated with symbol vehicles, to use Pattee's terminology. Even granting that the singularities of a dynamic topology might produce embodiments, there would remain unanswered the question of the origin of the privileged status of the genetic code as a suppressor of some select, dynamic degrees of freedom.

The DNA string is the most carefully studied example of the discrete mode of description in a natural context that we can currently lay our hands on. It is illuminating in this respect: *in natural systems, a discrete description can be neither created nor interpreted by the discrete mode*. The strong implication is that the discrete mode of symbolic description that is characterisic of automata models of intelligence is insufficient for the task of capturing natural intelligence. The dynamic mode missing from a putative computer simulation of intelligence is to be found only in the writing of the computer programs and in the reading of the computer outputs.

What kind of machine, therefore, is more suitable for the task of simulating intelligent activity? One answer would be a machine that executes in two complementary modes—the dynamic and the discrete (see the section entitled "Alternatives to the Computer Metaphor"). It would be a mistake to assume that a more accurate simulation of intelligent activity can be achieved by automata that perform parallel, rather than sequential, computations if by *parallel* is meant discrete operations occurring concurrently. Elaborating the discrete mode of functioning is of little avail in the absence of complementary, continuous dynamic processes (Pattee, 1974). It would, of course, enhance the computer as an extension of human capabilities, but that is a very different matter.

The Impossibility of Self-Complexing in the Discrete Mode

As noted in the preceding section, one perspective on the origin of discrete elements is that singularities emerge from extensive changes in an underlying continuum. As long as there is a continuous dynamic process and the possibility of variation in the magnitude of certain dimensions, then new (in the sense of qualitatively different)

discrete events (or observables or descriptions) can emerge. The evolution of structure that is incidental to scale changes in one or more variables affecting an open system is becoming increasingly better understood (e.g., Prigogine, 1980; Soodak & Iberall, 1978). For the present, we wish to recognize that where continuous dynamic processes are artificially suppressed, as in formal automata theory or in a computer model of some aspect of cognition, the intrinsic generation of new primitives is precluded. A system executing *solely* in the discrete mode cannot self-complex. The general argument is that any system whose present competence is defined by a logic of a certain representational power cannot progress *through operations in the discrete mode* to a higher degree of competence (e.g., Fodor, 1975).

Suppose that the operations in the discrete mode are the projection and evaluation of hypotheses. A hypothesis is a logical formula, as is the evidence for its evaluation, and both formulas must be expressed in the discrete symbols of the system's internal language. If the evidence is sufficient to confirm the projected hypothesis, then the fact to which the hypothesis corresponds can be registered in the representational medium. Importantly, however, the range of hypotheses projected and the range of evidence considered are both restricted to the expressive range of the symbols available to the system. Any hypothesis or any evidential source that must be expressed in symbols other than those available cannot be entertained. In sum, a system executing *solely* in the discrete mode cannot increase its expressive power. It cannot develop the capacity to represent more states of affairs at some later date than it can represent in the present. What it can do is to distinguish, within limits, states of affairs that occur from those that do not. The order of complexity achievable by a system executing solely in the discrete mode is frozen; it is determined by the order of complexity with which it began. How is the order of complexity raised in a system with no continuous dynamic processes such as a computer? By coupling it to an external intelligent device (a programmer) that writes in new symbols and discrete rules.

To summarize, when information used by a system is construed linguistically (that is, ignoring the relationship between symbols and dynamics), it cannot spontaneously increase in expressive power. In order to do so, such a system would have to be endowed with preadaptive foresight, possessing predicates that are currently useless but that will be relevant someday. Since such foresight is not possible, computational models are limited to the order of complexity with which they began. They cannot outperform the control rules that govern their operation (Tomovic, 1978). Natural systems, on the other hand, are open to complexity and require a construal of control information that is self-complexing. Using the fixed hardware of computers to explain brain function is useless because the computer was designed relative to human brains. The symbolic descriptions entailed by the hardware must be tied to the dynamics of the human user.

An Artificial History: No Substitute for a Natural History

For artificial systems, algorithms and data are needed in order to provide an artificial history for a device that has no history in a natural environment (Shaw & Todd, 1980). In other words, there is not a natural relationship between a computer

Animals, however, do have a natural and mutually constraining relationship with their environments by virtue of ontogeny and phylogeny, as well as dynamic laws. They do not need to explicitly embody knowledge about that relationship; the mutuality is a fact of animal–environment systems (for a discussion of animal–environment mutuality, see Gibson, 1979; Michaels & Carello, 1981; Shaw & Turvey, 1981).

The Unprincipled Specification of Representation (and Computational Procedures)

A representation may be defined as an abstract or concrete structure whose properties symbolize the properties of some other structure by means of a relation. As adumbrated in the section on the overvaluation of discrete operations, a discrete, alternative description of some complex process is distinguished, in part, by its limited detail with respect to the detail of the process that it represents. Presumably, wherever representations are realized, it is of little practical utility to represent a thing in other than reduced form. Two closely related questions should be raised: (1) On what grounds and by what means does a particular representation get created rather than another, symbolizing a particular set of properties rather than another? And (2) what determines how much detail a representation should include, given that it does not equal the detail of the reference object? A theory of cognition that abides by the representational/computational point of view must give a principled basis for answering these two queries. No such principled basis has yet been advanced, and it is not likely to be forthcoming.

Let us look at the two questions from the perspectives of physics, the perceiving organism, and the scientist seeking a computer simulation of visual perception. In physics, the two questions press the need for a more profound understanding of dynamics. The second question requires (among other things) an account of how simplicity grows spontaneously from complexity, where complexity is equated with the number of degrees of freedom that can be followed in detail in a dynamic description, and simplicity is equated with the degrees of freedom remaining in the alternative description, given the equation of constraint. As already noted, there are encouraging signs that this account can be given in the coupling of statistical mechanics and nonequilibrium thermodynamics (Morowitz, 1968, 1978: Prigogine, 1980; Soodak & Iberall, 1978). However, understanding how some detail is lost and, thus, how structure can emerge from less structure, or even homogeneity, is not sufficient. Together, the two questions require not just an explanation of how some detail is lost but an explanation of how that loss is special: A continuous dynamic process and its boundary conditions *specify* an alternative description that is *privileged* with respect to the dynamic processes that it constrains. Physics has no choice but to try to understand an alternative description (a representation) as an *a posteriori* fact of dynamic processes. It requires a theory of specification, of how a particular conjunction of dynamic processes and boundary conditions specifies a particular nonholonomic constraint. Again, the recent attempts of Thom (1975) to derive biological organization from the qualitative properties of a dynamic topology may prove helpful in this regard, as might the work of Haken (1977) and others to track mathematically a system's competing nonlinear modes. The point is that physics must pursue a principled account of the specification of alternative descriptions. A similar pursuit, however, does not characterize the representational/computational approach to cognition.

Indirect realism (the philosophical orientation of cognitive science) supposes that the ability of an organism to perceive significant aspects of its environment rests on the ability of the organism to represent those aspects internally. To perceive a thing x that is a token of type X involves a set of descriptors proprietary to X in this sense: they are necessary and sufficient to distinguish X from other types, and they are nearly optimal for distinguishing among X's tokens. Further, given the standard construal, to perceive a token of X requires that the proximal data cast in the internal vocabulary of sensory transducers be recast in the internal vocabulary appropriate to type X. The outputs of transducers are noncommittal on the type X of which x is a token. It is this fact that engenders a well-motivated reservation among orthodox perceptual theorists (e.g., Gregory, 1970) about feature detectors and the like. Admitting to the significance of the discovery for understanding perception, they point to the nontrivial problem that the same featural data can mean any of several alternative things.

There are two implicit acts of specification in the preceding, neither of which is addressed satisfactorily, if at all, by the representational/computational view of mind: (1) the conditions that point to a particular descriptor set as proprietary to X and (2) the means by which noncommittal outputs from transducers or feature detectors point to X's descriptors as being the ones appropriate for describing the *current* proximal stimulation. One might say that both of these are simply matters of induction. But the problem of induction (Goodman, 1965)—here, the problem of why some representations or why some descriptor set should be "projected," rather than others—is resolved, it would seem, only by assuming a noninductive act of (ostensive) specification. In the spirit of the Gestalt proposal of a law of Prägnänz, some scholars posit a benchmark, a simplicity metric, that weeds out *a priori* the unacceptable projections from the acceptable projections (e.g., Fodor, 1975; Hochberg, 1978). To avoid a vicious regress, the origin of this metric must be outside the purview of nondemonstrative inference.

Turning to the seeing machines of artificial intelligence, it is tempting to regard some of them as fulfilling what might be taken conventionally as the criterion for a successful simulation of perception (e.g., Marr & Nishihara, 1978). They begin with the description of the retinal mosaic produced by a thing x and they end with a description of x in the vocabulary appropriate to its type. Such simulations, however, are with respect to things of a single type, and the problem of *which* descriptor set to use never arises. The builder of a machine designed to see things of type X addresses only the question of how the transducer output from a given x can be reliably transcribed into the descriptor set S and how a description of x (as the stimulus) in terms of S can be reliably matched to tokens of X in memory, also described in terms of S. The determination of the proprietary set of descriptors S is, of course, an intellectual achievement of the scientist who programmed the seeing machine. No account of how the proprietary set S might arise without intellectual intervention is attempted. Admittedly, the giving of such an account is difficult and is perhaps beyond the pale of current science. Nevertheless, a general theory of specification is logically prior to d perhaps inclusive of a general theory of representation (Shaw, Turvey, & Mace, 82; Turvey, Shaw, Reed, & Mace, 1981): attempts to build the latter in an unprinpled fashion (ignoring specification) seem misguided.

e Nondeterminate Behavior of Natural Cognitive Systems versus the eterminate Nature of Discrete Automata

Proponents of the computational point of view no doubt would agree that where ysical principles can account for a phenomenon they should be allowed to do so. ut they would also contend that where physical principles fail, special, extraphysical inciples (i.e., not contained within physics but compatible with the laws there iden-ied) must be brought to bear. These special principles must be called on to explain gnitive phenomena with, presumably, the privileged vocabulary of representa-n/computation.

Pylyshyn (1980), for example, offered "cognitive penetrability" as the criterion r seeking extraphysical explanations. As interpreted by Kugler, Turvey, and Shaw 982), the underlying necessary condition for cognitive penetrability "is that the havior of the system in question is nondeterminate, that is, not dominated by bound-y and initial conditions." If this reading is correct, then a puzzle arises for those ishing to explain such behavior on the basis of formal symbol-manipulating machines: ear and computational devices are determinate; the output is completely specified the initial conditions (input) and boundary conditions (algorithms and representans). Where is the nondeterminacy that is supposed to characterize cognition?

Moreover, even the condition of nondeterminate behavior does not seem to de-and the privileged cognitive vocabulary. Dissipative structures (Prigogine, 1980) are ysical systems wherein nonlinear components constrain fluxes of energy so that the stem's behavior resists, within limits, the initial and boundary conditions to which is subjected. More generally, living things as members of the class of open systems hibit, to varying degrees, freedom from initial and boundary conditions, a fact ggesting that nondeterminate rather than determinate systems should be the source metaphors for cognition.

Alternatives to the Computer Metaphor

The relationship between computer science and the behavioral and brain sciences s been a symbiotic one in which each domain has effectively raided the other for planatory concepts. But a denial of the exclusive use of the computer metaphor mands a new direction for cognitive science. If not in computer science, then where the model constructs for understanding cognition to be found?

Two alternatives are presented. They are alike in that both try, as much as possible, explain cognitive capabilities without reference to "special" (in the sense of extra-ysical) entities. Both are moves away from the notion that human and animal ellectual abilities require uncommon explanations. The shared strategy is a simple

one: discrete symbol strings (e.g., representations, propositions, and rules) are not to be offered as knee-jerk explanations of those coordinations of organism and niche that constitute the phenomena of knowing. The processing of symbol strings need not be considered as an explanation of cognitive phenomena where physics will suffice. The two alternatives we describe differ with regard to the point at which, or whether, symbol-string processing has to be introduced. In other words, that a good many "privileged" cognitive abilities are more simply understood in terms of underlying physical principles rather than in terms of processing symbol strings is not questioned; whether or not all cognitive abilities are to be understood only in terms of physical principles distinguishes the alternatives described here.

What may be considered the less extreme approach takes issue with standard theories' emphasis on the discrete mode to the neglect of the dynamic mode of a system's behavior in trying to understand that system's intelligence. Rather, our first alternative is an argument (anticipated in the section on the overvaluation of discrete operations) that neither mode alone is sufficient. Intelligence is to be understood only as a *coordination* of discrete symbols and continous processes, with explicit recognition of their incompatibility (Pattee, 1974, 1977, 1982).

The more extreme approach is motivated in part by a reluctance to embrace notions that are consonant with the dualism of mind and body, a dressed-down version of animal–environment dualism (Michaels & Carello, 1981; Turvey & Carello, 1981; Turvey & Shaw, 1979). On this account, the notion of discrete, symbol manipulation and continuous dynamics as formally incompatible, complementary processes is unsatisfactory: symbol–matter dualism (Pattee, 1971) not only is continuous with the classical dualisms, but it is those dualisms in their most unadorned form. But if the complementarity strategy were to be denied, what would remain? Quite simply, it would be the strategy of elaborating continuous dynamics. By this dynamic strategy, the so-called discrete mode would be relieved of an explanatory role and relegated to the status of just one way (out of several or many ways) that a complex system might behave.

The more extreme approach is motivated further (and relatedly) by a concern that indulging the complementarity approach may not be in the best long-term interests of science. Literally interpreted, the complementarity claim holds the discrete, symbolic mode—as control information and as information acquired by measurement (Pattee, 1973)—distinct from physics. This distinction is partly in response to a strategy wherein many physicists have pursued a view of "information" as just another physical variable, like energy or matter (e.g., Layzer, 1975; Tribus & McIrvine, 1971). The objection is that equating "information" with negative entropy or a measure of objective order fails to capture the role that "information" plays in explanations of biological and psychological phenomena. To the criticism that the orthodox physical interpretation of information is too narrow, the complementarity approach (literally interpreted) adds the criticism that it is a category mistake (Ryle, 1949): information in biological and psychological contexts is not reducible to physics. In short, information requires a proprietary, extraphysical explanation.

Pattee has persistently prodded the scientific community to consider seriously information's ontological status. His impression is that definitive arguments in favor of or against information as a physical variable cannot be constructed because such arguments depend on clear and agreed-upon conceptions of control and measurement that currently elude us (Pattee, 1979). The terms *control* and *measurement* pick out two relations between dynamics (a rate-dependent process) and information (a rate-independent process), and they identify two, as yet unresolved, epistemological issues. Coming to grips with the concept of information, therefore, is not just a matter of more physics. In the meantime, a variety of considerations give the nod to complementarity and not to physical reduction (Pattee, 1979, 1982; Yates, 1980). *Complementarity is advanced as a principle that calls for the simultaneous use of formally incompatible descriptive modes in the explanation of natural phenomena. Rather than attempting to dissolve the dualisms (symbol/matter, mind/body, subject/object, etc.), the advocated strategy is to accept them as fact.*

Unfortunately, an endorsement of information and dynamics as complementary raises the spectre of a scientifically intractable problem, that is, the origin of information, and it is this spectre that the more extreme approach wishes to avoid. The detour can take only one direction—that of elaborating dynamics. It cannot, however, skirt the epistemological terrain carefully mapped out by Pattee. We are sure that Iberall (1977) can be counted among those pursuing a dynamic route to information, and we suspect that it is the route most consistent with the goals of the ecological approach to knowing that was conceived and developed by Gibson (1979).

Each of these approaches—the complementarity approach and the dynamic approach—is discussed in more detail in the next four subsections. While we will align ourselves with the dynamic approach, we nonetheless note a certain kinship with the complementarity approach to the extent that both orientations share misgivings about the discrete mode approach that dominates cognitive science.

The Complementarity Approach

We have identified two modes of system functioning in which the discrete mode s characterized as rate-independent operations on a finite set of symbols and the continuous mode refers to the rate-dependent interplay of dynamic processes. What would it mean to understand cognitive abilities as a coordination of these two modes? One strategy is to look at actual living systems to see how they use symbol strings and dynamics. Beginning at the cellular level, for example, and up through the evoutionary scale, how do strings and dynamics coevolve? Are there universals of string–dynamics interactions that might be appropriate to an understanding of the cognitive functioning of living systems (Pattee, 1983)? Consonant with this strategy, et us return to the problem of enzyme folding (see the section on the overvaluation of discrete operations) for an examination of the complementarity of the two modes.

Recall that this particular example consists of two qualitatively different phases: he genetic code synthesizes an amino acid string, which then folds into a functioning enzyme. The translation of the DNA symbols into amino acid strings is a discrete symbolic process, while the folding of the one-dimensional amino acid string into a hree-dimensional machine is a continuous, dynamic process. The former is a constraint on the latter. To describe the relationship as one of constraint is an important step, for it suggests that the system's meaning—its dynamic ability—does not merely reduce to a symbolic representation. The symbolic mode harnesses the forces responsible for the function, but the symbolic mode is not equated with the function. But neither is the dynamic mode completely autonomous. The folding of the enzyme cannot proceed until the code provides the necessary constraint. In other words, neither mode alone is sufficient for the activity in question.

The effort to ground cognitive abilities in the complementarity of the discrete and dynamic modes is a significant departure from standard computational/representational approaches. The significance lies in the observation that the discrete symbolic mode—the "information" processing—is kept to a minimum in natural systems (Pattee, 1983). Information construed linguistically does not provide all of the details for a given action; it acts as a constraint on natural law, so that the dynamic details take care of themselves. In other words, most of the complex behavior of living systems is essentially self-assembly, which is "set up" by symbol strings but not explicitly controlled by them. This should be no less true of the cognitive activity of biological systems. Complete comprehension cannot be had by appealing to symbol-string processing or physics alone. Both must be used together but in a special way: use physics cleverly so that symbol strings need be used only sparingly in order to ensure the parsimony of the explanation.

The failings itemized earlier with regard to the computer metaphor are addressed by the complementarity approach as follows: (1) by looking at the coevolution of symbols and dynamics, this approach necessarily and pointedly incorporates the constraints that a system's physical biology places on its behavior; (2) in the assertion that neither mode alone is sufficient, the dynamic mode is granted equal footing with the symbolic mode in embodying a system's intelligent activity; (3) by acknowledging that natural systems do not execute solely in the discrete mode, the complementarity approach can, in principle, account for self-complexing where new primitives emerge from the underlying dynamics; (4) the coevolution of symbol strings and dynamics obviates the need for a system's history to be carried, in cumbersome detail, by the symbolic mode and suggests, instead, that the natural history is captured in the complementarity relationship; (5) two principles, parsimony and minimal information, are offered as guidelines for the introduction of and the detail to be carried by a symbol string; and (6) the dynamic self-assembly of natural systems, of which cognitive systems are an example, is constrained but not determined by the symbolic mode.

The Dynamic Approach and Ecological Realism

In the section on computational approaches to cognition, we suggested that it was the framework of indirect realism that made the computer metaphor alluring to the behavioral and brain sciences. A framework of direct or ecological realism, however, does not share the same sympathies. Indeed, direct or ecological realism, as promoted by Gibson (1979) and others (e.g., Michaels & Carello, 1981; Turvey & Carello, 1981), disallows many of the constructs that are part and parcel of a representational/computational orientation and demands a very different class of machine in order to model cognitive activity.

Consider the following comments of Gibson (1979) in reference to orthodox approaches to perception:

> Adherents to the traditional theories of perception have recently been making the claim that what they assume is the processing of information in a modern sense of the term, not sensations, and that therefore they are not bound by the traditional theories of perception. But it seems to me that all they are doing is climbing on the latest bandwagon, the computer bandwagon, without reappraising the traditional assumption that perceiving is the processing of inputs. I refuse to let them pre-empt the term *information*. As I use the term, it is not something that has to be processed. (p. 251)

> Not even the current theory that the inputs of the sensory channels are subject to "cognitive processing" will do. The inputs are described in terms of information theory, but the processes are described in terms of old-fashioned mental acts: recognition, interpretation, inference, concepts, ideas, and storage and retrieval of ideas. These are still the operations of the mind upon the deliverances of the senses, and there are too many perplexities entailed in this theory. It will not do, and the approach should be abandoned. (p. 238)

The gist of these quotations is plain: perceiving does not involve cognitive in-ermediaries; it does not involve the making of representations or the evaluating of ropositions. The central and fundamental role of explicit symbol-manipulating pro-esses in the orthodox treatment of perception is repudiated by Gibson. For Gibson, formation in the case of vision is optical structure that is lawfully generated by nvironmental structure (e.g., the layout of surfaces) and by movements of the animal oth movements of the limbs relative to the body and movements of the body relative the environment). This optical structure is not similar to its sources, but it is specific them in the sense of being nomically dependent on them. For Gibson, these nomic ependencies comprise an important subset of the laws at the ecological scale that ake possible the control of activity.

By the "perceiving of a thing *x*," Gibson means something very particular, namely, at (1) there is information about the thing *x* in the sense of *specific to* the thing *x*; d (2) the information about the thing *x* is picked up, or detected, by the organism e Turvey *et al.*, 1981, for a more detailed discussion). *It is because of the specificity information identified in (1) that the fulfillment of (2) does not involve interpretive, borative, restorative, constructive, etc., operations*. Considerable confusion sur-unds this assertion. A common misreading is that it denies the organism (or its ntral nervous system) any substantive role in perceiving. In truth, what the assertion nies is the orthodox interpretation of that role. *Information*, in Gibson's sense, does t require *processing* (by epistemically laden operations), *but its pickup does involve cesses*. Gibson (1966, 1967) has given hints that these processes are closer to the cesses identified by physics and systems theory than to the processes commonly ntified by neuroscience, psychology, and computational science. Thus, he has erred, informally, to "resonating," "optimizing," "symmetricalizing," "equili-ting," "orienting," "adjusting," and the like.

Although one could read the foregoing terms as labels for happenings *in the brain*, son has resisted this move. He has ascribed these terms to the states of a perceptual tem, where a perceptual system is defined by an organ and its adjustments at a en level of functioning, and where incoming and outgoing fibers comprise a continuous loop (Gibson, 1966, 1979). And he has intimated that the states to which at least some of these terms refer may well be distributed over the organism and its environment: Do a perceptual system and the information that it picks up comprise a unitary system that "equilibrates"?

The computer provides a metaphor for the processing of information in the orthodox treatment of perceiving, but what kind of machine could provide a metaphor for the pickup of information in Gibson's heterodox treatment of perceiving? We do not believe any such machine currently exists. Nevertheless, some steps can be taken toward its definition.

To begin with, it seems that the machine in question must be of the dynamic sort (governed by law) rather than of the symbolic sort (governed by rule). Second, it seems that the machine in question must be an ensemble of special-purpose dynamic responses to specific dynamic challenges. Gibson's construal of information implies that there are properties of ambient energy distributions that are unique and specific to behaviorally related properties of the environment and to the organism's relationship to the environment (e.g., moving forward rectilinearly, or turning). These ambient energy properties are not replaceable by (putatively) more elemental properties. It has been suggested that if the pickup of an ambient energy property of the kind envisaged by Gibson (also see Lee, 1980, for an established instance) does not, therefore, involve a preliminary decomposition into more molecular properties (followed by a knowledge-guided inference or synthesis), then that pickup must be achieved by a device tailored *to the property* (Runeson, 1977). The notion of an ensemble of special-purpose dynamic solutions raises questions of the physics that molds them and the physics that relates them. Answers are beginning to take shape (e.g., Iberall, 1977, 1978a,b) and will be required if the machine in question is to materialize.

A more disquieting question is raised by the simple recognition that for a dynamic machine to suffice as a metaphor, it would have to be systematically affected by its challenges. It would have to have a history. Gibson (1966, 1979) wrote of perceptual systems' being "attuned" to information in the two senses of (1) becoming able to detect a particular information kind and (2) becoming better at detecting a particular information kind. The disquieting question is how a machine governed solely and strictly by dynamic laws can have a history, given that dynamic laws are ahistorical. On this question it would appear that the dynamic approach must give way to the complementarity approach. Dynamic history in the complementarity approach has a placeholder—the discrete, symbolic mode—but what and where is dynamic history's placeholder in the dynamic approach?

In the next section, we take a look at potential machines as examples of dynamic machines that are necessarily special-purpose. And in the section that follows the next, we elaborate the question of history in dynamics and express some thoughts on how it might be addressed.

The Dynamic Approach and Potential Machines

It is ironic that A. M. Turing, who has been unsurpassed in his contributions activity, should have made a seminal contribution to the explicit understanding of potential machines (Turing, 1952). *Indeed, one might regard the dynamic approach as a call to rally behind the later (1952) rather than the earlier (1950) Turing (and the complementarity approach as a call to rally behind both Turings).*

What is a potential machine? It is any system in which "potentials" (roughly, energy reservoirs) are available for the play of the system's trajectories in state space (or mathematical domain). The "themes" from which the system's trajectories are fashioned include attractors, basins, and separatrices. These themes emerge and dissolve as a function of changes in the layout of potentials. This layout of potentials plays (implicitly) the same organizing role as the governing dynamic equation set plays (explicitly) in the digital computer.

The governing logic for a potential machine braids topological properties with physical laws (e.g., conservation principles). The end product is a geometrodynamic logic that generically couples physics with geometry (Thom, 1975; Abraham & Shaw, 1982). The geometrodynamic logic is universal for potential fields; that is, the design logic is independent of the material composition. Because of the generalizable nature of dynamic patterns, it is possible to use the layouts of attractors, basins, and separ-itrices of one material substance to study the dynamic properties of a materially lifferent system with the same or similar layouts. In other words, a substitute geo-netrodynamic field can be used to study the unfolding (or evolution) of trajectories or a wide class of dynamic systems (many of which defy direct experimental manip-ılation). Several examples of the machines are (1) the photoelastic machine (Frocht, 1941); (2) the Hele-Shaw parallel-plate machine (Lamb, 1932); (3) the Chladni-Faraday ibrating machine (Faraday, 1831; Waller, 1961); (4) the Rayleigh-Bernard simmering nachine (Fenstermacher, Swinney, Benson, & Golub, 1979); and (5) the Covette-Taylor stirring machine (Koschmeider, 1977). An example of a potential machine in iology is the piezoelectric effect in bone growth—a transduction of mechanical stress atterns to electric voltages to bone growth.

Each of the above is a physical machine that simulates the behavior of some ystem without any symbolic representation of that behavior. The simulations or "so-utions" are not the result of formalisms entailing some form of recursive function heory; rather they are the result of equilibrations occurring within competing processes f energy flow systems. For these machines, the *field* "solves" its own self-defining quation sets. Whereas dynamic modeling with a digital computer may provide ac-ounts of single-trajectory solutions, it does not provide accounts of the continuum ield properties. This limitation is the reciprocal of that of potential machines; that is, potential machine can exhibit properties of a continuum-field nature, but it cannot olate a single-trajectory solution nor precisely identify the initial conditions of an quation set. We briefly describe two potential machines and an unsuccessful pro-rammatic attempt to build *general*-purpose potential machines.

Photoelasticity: A Photoelastic Analogue for Solving Problems in Field Mechanics. The theoretical similarity between field problems in Hamiltonian ray mechanics and Newtonian particle mechanics can be experimentally realized by means f photoelastic components to model the field dynamics of stress properties in mechanical systems (Frocht, 1941; Love, 1944; Sommerfeld, 1934). The photoelastic field's *similarity* in character to the Hamiltonian ray-mechanics field properties allows for its use as a dynamic simulator for problems in Newtonian continuum mechanical problems. In this sense, an electromagnetic field can be used to generate solutions to problems involving a continuum mechanical field. Analogue machines can be designed that simulate or "model" the stress fields arising in continuum mechanical fields. There is reciprocity in simulation, allowing for the inverse possibility of a continuum mechanical field's being used to "model" or "simulate" an electromagnetic field. The photoelectric simulator involves a piece of stressed plastic through which a polarized light field is passed. The index of refraction generates a patterned field of stress contours that is proportionally similar to the stress contours of a related mechanical field. These simulations are not analytic. Rather, they are dynamic simulations involving no explicit processing of symbol strings. The problems are solved dynamically within the field; that is, the system's trajectories are powered by the available potentials and constrained by their geometrical layout in accordance with the conservation principles. As long as potentials provide a source of energy to the system, equilibrating trajectories will be defined.

Hydrodynamics: The Hele-Shaw Simulator. The Hele-Shaw simulator (Shaw, 1980; Lamb, 1932) was designed to solve a limited set of problems in fluid mechanics. The machine is a hydrodynamic device in which a two-dimensional liquid flow is established between close parallel plates. Various obstacles can be inserted into the flow stream so as to create new source–sink layouts associated with consequent changes in the field's kinetic patterns. For the most part, those results could be generalized to *any* two-dimensional flow field whose structure was constrained within the laminar domain.

An Attempt at a General-Purpose Electrodynamic Computer: The Gutenmakher Enterprise. Digital and potential machines are different on the issue of self-organization: potential machines self-organize; digital machines (as yet) do not. A digital machine's set of trajectories (output state space) is formally closed and explicitly restricted by limits defined in the equation set. A potential machine's set of trajectories is open and can evolve as a function of ranges and domains of accessibility for the operational parameters. Whereas the digital machine is a general-purpose device that can be designed to instantiate an indefinitely large number of rules, a potential machine is a special-purpose device that is successful in specialized circumstances by virtue of a particular geometry linked to a particular subset of physical laws. This restriction on potential machines has severely limited its applicability as a general-purpose computer. Gutenmakher (1963) detailed the most extensive programmatic attempt to use a potential machine as a general-purpose computing machine. The Gutenmakher laboratory was Russia's braintrust set up to compete with the digital computer evolution in the West. The Russians sought an "electrological, chemicological, mechanicological device" in the belief that it would prove to be a more general-purpose (and powerful) device than the discrete automaton. Their attempt failed for two major reasons: (1) it was premature, and (2) dynamic logic is necessarily special-purpose, unlike digital logic, which can be general purpose. The machine pursued by Gutenmakher could olve classes of problems untouchable by the digital machine; the economic needs, owever, were for a general-purpose device. (In part, the failure of the Gutenmakher roject accounts for the present inferiority of Russian computer technology.)

he Dynamic Approach: Duality rather than Complementarity?

Although the potential machine is the model that seems better suited to the amework of ecological realism, we can identify two related problems that must be solved in order for such a machine to be minimally adequate for modeling cognitive henomena: (1) complementarity is continued, and (2) time—and therefore history—lays no role in dynamic law. In this section, these problems are identified, and a amework in which the resolution might be found is sketched.

The two types of machines—the potential and the symbol-manipulating—can be istinguished as being law-governed and rule-governed, respectively. In the language f the complementarity approach, these would correspond to the dynamic and symbolic odes. With regard to problem (1), then, the two classes of machines continue the stinction between the two modes and enforce the distinction between those aspects phenomena that each can be said to describe: phenomena *per se*, in uninterpreted rm, favor the common bases established in potential machines, while formal simations of phenomena favor the representative forms provided in symbol-manipulating achines. We have not yet resolved, therefore, the paradoxical relationship described Pattee (1982):

> Complementarity is not to be confused with tolerance of different views. It is not a resolution of a contradiction, as if you were to agree that we are simply "looking at the problem from different perspectives." . . . Rather, it is a sharpening of the paradox. Both modes of description, though formally incompatible, must be a part of the theory, and the truth is discovered by studying the interplay of the opposites. (pp. 27–28)

Potential machines and symbol-manipulating machines are considered opposites ofar as the former are law-governed and the latter are rule-governed. But is this elf the criterial distinction, or does it merely create the critical property by which two classes of machines are necessarily distinguished? If the latter, what might s property be? One important feature of dynamic laws in traditional (Hamiltonian) ysics is that time is an extrinsically imposed state label. As a consequence, the ure state of the system can be predicted only on the basis of current state information d the law. In other words, the history of dynamic systems cannot be reclaimed.

With regard to problem (2), then, a potential machine under classical, quantum chanical, or relativistic dynamical law would be a machine whose history would y no role in its future. (In contrast, symbol-manipulating machines are equipped h a history by a program.) There is clearly something lacking in potential machines en applied to humans and animals with learning histories to guide them. Bertrand ssell (1921) suggested that the omission is one of *mnemic* determination: current straints must be augmented by historical constraints that produce a tendency. But lassical laws are not time-bound, how can dynamic models (potential machines) dequate models for psychological (mnemic) phenomena? The answer depends on possibility of introducing mnemic relations into the laws that govern potential machines. It is our contention that this possibility is currently being accomplished through the efforts of contemporary physicists such as Prigogine (1980), Iberall and Soodak (1978), Haken (1977), and others to make time an intrinsic part of dynamic law so that history is no longer an alien concept.

If these attempts are successful, how are "opposites" such as mnemic (past temporal) constraints and physical (future-pending) constraints to be construed? Complementation enforces dualism, which is not countenanced by ecological realism. Yet, these opposites are not simply symmetrical perspectives. Rather, we suggest that the relationship is one of *duality* (a mathematically defined relationship as opposed to dualism, a philosophically defined position), wherein there exists a class of potential machines *PM* governed by future-pending laws and a dual class of potential machines *PM′* governed by past-dependent laws. We can only speculate about the possibility that there exists a class of machines, *DM*, with a generalized dynamics that incorporates *PM* and *PM′* as coordinated (dual) submachines. (Shaw and Todd, 1980, provided a formal description of an analogous pair of dual abstract machines.)

Because the complementarity approach finesses many of the failings of the computer metaphor simply by acknowledging the role of dynamics in natural systems, the solutions from the dynamic approach are not appreciably different. Rather than itemizing them again, therefore, we will identify the issue on which the two approaches differ significantly. That issue is the specification of representations.

The computer metaphor was criticized because there is no principled basis for specifying (1) which representations are created and (2) how much detail a particular representation should include (see the section on "The Unprincipled Specification of Representations"). The complementarity approach does not address point (1) specifically, but it does address a related point, namely, when a representation should be created by putting a premium on parsimonious explanations—if the physics is getting too complex, a symbol or symbol string should be allowed to restore simplicity. And, given the conviction that cognitive systems should be consonant with other natural systems, point (2) is answered with the stricture that the detail carried by a representation should be minimal. We are not at all convinced, however, that such a tactic solves the problem satisfactorily. It seems to be a tactic for the scientist trying to explain nature rather than a tactic of nature itself.

In denying the equation of information with representation, and in promoting the equation of information with specification, the dynamic approach, tempered by Gibson's ecological realism, substitutes the question of how representations are specified by questions of the kind: how optical structure is specific to what activity can be done (by an organism of a particular type in a particular setting), how the activity can be done, and when it can be done. For example, how is optical structure specific to a place that permits stepping down (rather than, say, falling off), specific to how the stepping down is to be conducted, and specific to when the stepping down should be initiated?

Our impression is that answering questions about the nomic dependence of optical structure on facts of the animal–environment system will illuminate, in a very general way, the specificational perspective on information emphasized by the dynamic approach. One might say that, in contrast, the complementarity indicational or injunctional perspective on information, preserving the qualitative tenor of formal information theory. Not surprisingly, Gibson (1979) sees the latter as a misplaced emphasis:

> There is a vast literature nowadays of speculation about the media of communication. Much of it is undisciplined and vague. The concept of information most of us have comes from that literature. . . . we cannot explain perception in terms of communication; it is quite the other way around. We cannot convey information about the world to others unless we have perceived the world. *And the available information for our perception is radically different from the information we convey.* (p. 63)

The indicational sense of information is not exclusive. It is distinct from the specificational sense and is predicated on the specificational sense. In short, understanding information as specific is logically prior to understanding information as indicative (compare with "The Unprincipled Specification of Representations). Explicit recognition of this priority distinguishes the dynamic approach from the complementarity approach.

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