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Abstract of the original article: The computational view of mind rests on certain intuitions regarding the fundamental similarity between computation and cognition. We examine some of these intuitions and suggest that they derive from the fact that computers and human organisms are both physical systems whose behavior is correctly described as being governed by rules acting on symbolic representations. Some of the implications of this view are discussed. It is suggested that a fundamental hypothesis of this approach (the "proprietary vocabulary hypothesis") is that there is a natural domain of human functioning (roughly what we intuitively associate with perceiving, reasoning, and acting) that can be addressed exclusively in terms of a formal symbolic or algorithmic vocabulary or level of analysis.

Much of the paper elaborates various conditions that need to be met if a literal view of mental activity as computation is to serve as the basis for explanatory theories. The coherence of such a view depends on there being a principled distinction between functions whose explanation requires that we posit internal representations and those that we can appropriately describe as merely instantiating causal physical or biological laws. In this paper the distinction is empirically grounded in a methodological criterion called the "cognitive impenetrability condition." Functions are said to be cognitively impenetrable if they cannot be influenced by such purely cognitive factors as goals, beliefs, inferences, tacit knowledge, and so on. Such a criterion makes it possible to empirically separate the fixed capacities of mind (called its "functional architecture") from the particular representations and algorithms used on specific occasions. In order for computational theories to avoid being ad hoc, they must deal effectively with the "degrees of freedom" problem by constraining the extent to which they can be arbitrarily adjusted post hoc to fit some particular set of observations. This in turn requires that the fixed architectural function and the algorithms be independently validated. It is argued that the architectural assumptions implicit in many contemporary models run afoul of the cognitive impenetrability condition, since the required fixed functions are demonstrably sensitive to tacit knowledge and goals. The paper concludes with some tactical suggestions for the development of computational cognitive theories.

Is the "cognitive penetrability" criterion invalidated by contemporary physics?

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Pylyshyn (1980) advocates and extends a popular view that the model source for the explanatory concepts of cognitive science is the science of formal symbol-manipulating machines. The argument is that the proper vocabulary for constructing adequate explanatory theories of the knowings of animals and humans is the representational-computational vocabulary of computational science and artificial intelligence.

The representational-computational perspective on knowings is far from recent; it has appeared in various forms for over two millennia, being intimately linked with philosophical attitudes variously termed "representational realism," "indirect realism," "idealism," and "phenomenalism." By and large, these attitudes follow from a distinction between the "physical" object of reference and the "phenomenal," or intentional, object that is said to be directly experienced and to which behavior is referred. It has been commonplace over the ages to question the coordination of the two kinds of objects, and it has seemed a simple enough matter to identify slippage between them. In consequence, it has frequently been concluded that the reference object might just as well be excluded from explanatory accounts; there are doubts that it can be known, and even doubts that it actually exists. The representational-computational vocabulary and its allied philosophical postures question or deny that the world is knowable. Animals and humans can only know the phenomena (sense data, representations, etc.) that their brains or minds supply (see Fodor 1980). In sum, philosophy and science have been unable to characterize the animal-environment relation in a way that allows that what animals know is real, existing independently of their knowing it. This state of affairs is curiously tolerated despite its obvious contradiction of the scientific enterprise (see Shaw & Turvey 1980 on Fodor 1980).

Among the many assumptions and intellectual commitments that prohibit a realist posture (see Shaw & Turvey 1981; Shaw, Turvey & Mace, in press) is the assumption that contemporary physical theory is complete. The complete theory's failure to accommodate regularities in biology or psychology gives license to propose new, often special – in the sense of extraphysical – principles. Pylyshyn proposes "cognitive penetrability" as a methodological criterion that is sufficient (but not necessary) to distinguish those phenomena whose explanation requires the privileged vocabulary of representation and computation from those phenomena that can be appropriately described by physical law. Our reading of what is necessary for the "cognitive penetrability" criterion is a good deal more general than Pylyshyn's, but we believe it to be accurate. *The necessary condition is that the behavior of the system in question be nondeterminate, that is, not dominated by boundary and initial conditions.* As we describe below, this necessary condition is met by a broad class of physical systems termed "dissipative structures," systems that are indeed "mere" instantiations of physical law and, therefore, by the criterion, systems that do not entail the representational-computational vocabulary. It seems to us that the criterion is diluted, if not invalidated, by recent extensions of physical theory. Because of this fact, we question its completeness and its propriety for natural phenomena.

Before turning to a description of dissipative structures, let us remark on an aspect of Pylyshyn's argument that we find especially puzzling – the conjunction of Pylyshyn's pursuit of nondeterminacy as the necessary condition for genuine cognitive processes and his advocacy of formal symbol-manipulating machines as the model source for explaining such processes. Pylyshyn wishes to earmark for cognitive science behavior that is not determinately bound to environmental events; such behavior, it is argued, can be accounted for exclusively by the representational-computational vocabulary. However, no suggestion is given of how the various algorithms and representatons are to be nondeterminately selected. Computational devices are all determinate machines in which the output is completely specified by the initial conditions (input) and boundary conditions (algorithms and representations). Oddly, by selecting the formal symbol-manipulating machine as his model source, Pylyshyn, like other proponents of his view, fails to offer any nontrivial distinction between the popular model of cognition and any prototypic behaviorist model, that is, between cognitive science and behaviorism.

Dissipative structures as consequences of conditions on natural law. An analogue to Pylyshyn's "penetrability" condition can be shown to exist in physical systems governed by natural law when such systems are construed as dissipative structures. Although this idea requires careful and complete development, a sketch of the argument can be given as follows: Classical reversible equilibrium thermodynamics describes the thermodynamic behavior of a system only when the system is in or near a state (condition) of equilibrium. In addition, the system may exchange neither matter nor energy with its surrounds. Systems meeting these conditions are referred to as *isolated closed systems*. The behavior of these systems is characterized by a tendency to run down to a maximum state of disorder, zero information, and loss of the ability to do work (Bridgeman 1941). This behavioral state is entropic equilibrium, and once a system is in this state nothing new can emerge as long as the conditions of the system remain isolated and closed. Under these conditions, the thermodynamic analysis is complete. The reversible quality of these systems is evident in the fact that if a perturbation occurs to the system under these conditions, the system responds by going through a succession of states, all of which are at entropic equilibrium. In short, the entire event occurs in a state space in which all points in the space are homogeneous with respect to entropic equilibrium. The concept of reversibility is reflected by the fact that there are no preferred points in the entropic state space: States may reverse themselves and still maintain the condition of entropic equilibrium. Under these conditions the system's behavior is completely determinate and specified by initial and boundary conditions. Such conditions do not allow for the possibility of autonomy or self-organization. While some real events (such as very slow processes in the macroworld) are rather well described by the conditions surrounding classical reversible equilibrium thermodynamics, most interesting events regarding biological and psychological systems are not.

Our suspicion is that Pylyshyn's concept of "natural laws" is based on the above conditions, namely those of an isolated, closed (thermodynamic) system. We would suggest, however, that a model for a biological or cognitive system is poorly represented by the conditions of isolated, closed systems. A more appropriate model might be found in the less familiar conditions of *open* physical systems (that is, systems that exchange energy and matter with their surrounds). While the natural laws pertaining to open conditions are the same as those pertaining to closed conditions, systemic behavior under these two conditions is dramatically different. In particular, when certain conditions manifest themselves, the behavior of open systems need not tend toward a state of thermodynamic equilibrium but more generally toward a steady state regime displaced from equilibrium and maintained by a continual flow of free energy and matter into and out of the operational component of the system (Iberall 1977; 1978; Morowitz 1978; Prigogine, Nicolis, Herman & Lam 1975). The necessary conditions for such behavior are:

1. A reservoir of potential energy from which (generalized) work can arise;
2. A microcosm of elements with a stochastic fluctuating nature;
3. A presence of nonlinear components;
4. A scale change such that a nonlinear component is critically amplified (in the sense that the system's own dimensions now resist the previously dominant effects of the initial and boundary conditions).

If these conditions are present (see Szentagothai's 1978 commentary on Puccetti & Dykes 1978), then the possibility exists for the transition from the stochastic steady-state condition to a spatially structured steady-state condition or a time-dependent limit cycle regime characterized by homogeneous oscillations or by propagating waves. These regimes are stable in virtue of the amplified nonlinear components, and are maintained in virtue of the "dissipation of energy." The manifestation of these *open* systems is hence achieved by drawing spontaneously on potential energy sources, so as to remain stable in the nonlinear sense while dissipating energy (that is, so that there is a greater loss of order in the surround than the gain of order by the system itself - the behavior of such systems is said to be "lossy" with respect to energy). Prigogine (Glansdorff & Prigogine 1971; Nicolis & Prigogine 1978) has termed such systems "dissipative structures" to illustrate that their formation and maintenance require a continuous flow of matter and energy from an outside source. The behavior of dissipative structures is prototypic of thermodynamic engines (cf. Iberall 1977; Yates & Iberall 1973) in that the mean states of the internal variables are characterized by "fluxes" and "squirts" of energy that becomes constrained by nonlinear components so as to behave in a limit cycle manner (Katchalsky, Rowland & Blumenthal 1974; Kugler, Kelso & Turvey 1980; in press; Winfree 1967; Yates, March & Iberall 1972). In this manner such systems resolve the internal degrees of freedom problem which manifests itself so blatantly in formally closed, artifactual systems. Whereas artifactual systems are not capable of self-organization or autonomy, dissipative structures reveal possible insights into such problems.

In particular, dissipative structures are associated with a situation called "order through fluctuation" (Prigogine 1976). Under the above conditions, certain structures may arise from the amplification of fluctuations resulting from an instability of a "thermodynamic branch." Because symmetry is broken, new structures are formed. These new structures may possess new functions that correspond to a higher level of interaction between the system and its environment (Prigogine & Nicolis, 1971; 1973). The symmetry-breaking instabilities are dependent on scale factors, and the concomitant bifurcation points in the fluctuation phase provide places where the autonomy of the dissipative structure exerts itself. While the thermodynamic branches themselves are determinately specified by stability and bifurcation theory, the actual choice of which branch (stability mode) the system enters may ultimately be nondeterminately specified by a dimension intrinsic to the system (as opposed to determinately specified, a notion associated with closed systems, or *in*determinately specified, as associated with a randomizing component). If, however, a system is composed of sufficiently small numbers of fluctuating elements, the system's behavior will be dominated by the boundary and initial conditions and can never exhibit autonomy (Nazarea 1974).

It is only when a system is "scaled up" beyond some critical dimension that nonlinearities are able to be sufficiently amplified to lead to some choice between various solutions (thermodynamic branches; Hanson 1974). Only under these conditions do the system's own dimensions become sufficiently influential to resist the previously dominant effects of initial and boundary conditions. It is at this point that the system achieves some autonomy with respect to the outside world and may be said to be nondeterminate. In other words, prior to the scaled-up condition, the system behaves in a determinate fashion; after the critical condition is reached, the system's behavior becomes nondeterminate and autonomous on some dimensions, an autonomy that may be manifested in the macrostructure of the system's behavior.

Under these conditions the behavior of the system is not "causally" linked to the environmental conditions and therefore might be said to come under the so-called penetrability criterion. But should we be willing to say that cognitive factors enter into systems simply because such weak links exist in the causal chain? To answer yes would be tantamount to ascribing the epithet "cognitive" to systems considerably less evolved than humans and not necessarily animate. That cognitive factors might enter is clearly a hypothesis that goes far beyond the mere existence of nondeterminacy in a system's linkage to its environment. For this reason, it seems to us that Pylyshyn has failed to make a cogent case for the usefulness of his "cognitive penetrability" criterion. For, to accept it we would either have to consider the possibility of beliefs, motives, and the like entering into purely physical systems of the dissipative variety, or have to ignore their existence altogether.

Finally, we note that a dissipative system will manifest a stable regularity on certain dimensions of its behavior owing to the nonlinear components that have been sufficiently amplified. This regularity may be disrupted if the system falls below the critical scaling conditions. However, if the system is in the critically stable domain, then any perturbation on the input side of the system will only temporarily disrupt the system's regularity. In addition, the regularities are not necessarily contingent on their material substrates (Thom 1975). Systems sharing the same dimensionality but not necessarily the same substrate will share a common set of stable regularities. (This, we would claim, is the physical equivalent of Pylyshyn's transparency condition.)

A hint at how "cognitive" phenomena might be explained in the nonprivileged vocabulary of physical theory. Here we consider a phenomenon that in its apparent organizational complexity is, on prima facie grounds, not unlike the phenomena of interest to cognitive science. Our purpose is to show how phenomena of this kind might *not* require a privileged vocabulary for their explanation and how a realist perspective on such phenomena might be pursued.

Representations and algorithms, while introduced as a convenient way to inquire into the organization of systemic activity, very often assume ontological reference apart from inquiry (Dewey & Bentley 1949). With this assumed status, it is tempting to put such "between things" that coordinate animal and environment into the role of explanatory first principles. For example, if one says that the relation between aspects of a system's input and aspects of its behavior is programmatic, then one is tempted, with regard to the input aspects, to attribute the systematicity of the system's behavior to the systematicity of a program, and in the case of biological systems, to assign this new object a location somewhere in the animal's nervous system. To equate a program with the causal basis of a behavior is not only to introduce sui generis a special explanatory principle, but is, additionally, to subscribe to a view in which the orderliness of a phenomenon is said to be owing to an explicit, a priori description of that orderliness. In summary, a program or representation is conceived as an ordering of details that *precedes* a behavior and is causally responsible for the ordering of behavioral details.

The goal of the realist's style of inquiry is to minimize first principles: By rigorously considering the reciprocity among complementary components as a global property, many "between things" sui generis may prove unnecessary to account for the animal-environment relationship (Kugler et al., in press; Shaw & Turvey 1981). Under the constraints of this style of inquiry, the orderliness of a systemic phenomenon - such as a behavior - is not owing to an a priori prescription *for* the system but rather is an a posteriori fact *of* the system - that is to say, a property that arises from within the system during the course of the system's existence. Any explanation of a natural systemic relation that appeals to some a priori embodiment of that very relation would be rejected by the above perspective; for such an explanation is a step toward phenomenalism and a step away from realism and, in consequence, a step away from a unified view of physical explanations regarding natural phenomena. By the precepts of a realist's view the appeal to a mediating factor, or a "between thing," as an a priori source of behavioral order arises from an incorrect perspective on the phenomenon.

To illustrate this point, let us apply the dissipative structure story developed above to the phenomenon of insect architecture. Consider, for example, the early phase of termite nest building, in which pillars and walls are constructed sufficiently close together to permit the formation of arches. The construction proceeds in two stages: In the first stage building materials are randomly deposited. In the second the termites tend to aggregate and to accumulate material at far fewer sites than the number of original deposits.

An individual termite relates to its surroundings chemotactically, moving on a local chemical gradient. The attractant is a scent the termites contribute to the building material during their manipulations. When the accumulation of building material through random deposits is low and the number of deposits relatively few, the diffusion of the scent is homogeneous over the area in which material is being deposited. This means that as far as the individual termite moving on local gradients is concerned, any locale is as good as any other. Imagine now a termite moving through the building area after some amount of random depositing has occurred. The greater the number of random deposits, the greater the likelihood that an individual termite will pass in the neighborhood of *a* deposit. In terms of the attractant's diffusion in the air, the place of a deposit defines a local maximum, a place where the density of pheromone molecules is at its greatest. In the neighborhood of a deposit, therefore, chemotaxis is biased toward the coordinates of the deposit. In consequence, a place where a deposit has been made is a place which "invites" further deposits to be made. Speaking formally, the latter identifies an autocatalytic reaction - the accumulation of material at X is increased by the very presence of material at X. The criticalness of this autocatalytic component rests with an appreciation of the fundamentals of nonequilibrium, irreversible thermodynamics, that is, with the fundamental character of open systems. A further exposition of open systems will permit us to take the next step toward an understanding of the architectural achievement of termites as a necessary a posteriori fact.

For an open system there must be a source of high potential energy and a low potential energy sink such that in the drawing of energy from the higher order form and relegating it to the lower order form, work is done in a generalized fashion. More commonly, we say that across the boundaries of an open system matter and energy are continuously in flux. As described above, open systems are consistent with familiar thermodynamic law in that, being dissipative, their operations lead to a net increase in entropy on the global scale. At the same time, however, these very operations generate negentropy or structure on a local scale. The emergence of a (new) structure depends on the presence of nonlinearities in the system and a sufficient change of scale in one or more system dimensions.

Fluctuations, understood as spontaneous deviations from some average macroscopic behavior, will always occur in an open system with many degrees of freedom. When the fluctuations, and hence the deviations, are not large - such as might be the case at low fluxes of energy - the response of the system is usually to restore the original state, that is, to move as close as possible to maximum entropy and hence away from structuralization. However, the presence of nonlinearities, combined with a scaling upward of, say, energy flux, allows for a pronounced amplification in fluctuations, such that the system is driven to a new average state of fewer degrees of freedom. In short, where an open system with nonlinearities is at a critical distance from equilibrium, a new structure emerges.

Returning to termite architecture, the autocatalytic reaction, by which the presence of material at a site stimulates the depositing of more material, is a nonlinear contributor to the dynamics of the termite-nest system. As the random depositing proceeds, some sites will accumulate more material than others. Such being the case, the nonlinear autocatalytic factor determines that, given two sites with unequal accumulations, the site with more material will grow at a faster rate than the site with less material. In the spatial diffusion of the pheromone molecules, marked inflections will appear in the diffusion space defining "preferred" locations on which the chemotactic trajectories of the termites will converge. The diffusion space is no longer homogeneous; the previous stable state of affairs, characterized by the random depositing behavior of the termites, gives way to instability and, in turn, to a new stability - a stage of activity in which the termites "coordinate" their individual activities at certain sites, producing, by their combined efforts, pillars and walls. Now, if in a certain area two large deposits are in close proximity, then we may suppose that within that area the distribution of pheromone molecules will articulate gradients pointing toward a local region of greatest density between, and approximately at the height of, the two deposits. One can intuit how termite movements on these gradients, according to the simple chemotactic principle, will eventuate in links between the two proximate deposits, that is, to the formation of arches.

In Prigogine's terms (Nicolis & Prigogine 1978; Prigogine 1976; Prigogine & Nicolis 1971) the termite nest is a dissipative structure - a stable organization that is maintained away from maximal entropy through the degrading of a good deal of free energy. The form of the nest arises as an a posteriori fact of the termit ecosystem. It is not owing to a plan or program invested a priori in the individual termite or in the "collective" termite. That self-actional explanation, which would make "plan" a principle sui generis, is replaced by an explanation of greater generality that is consistent with physical theory.

Terms such as "algorithm" and "memory" are commonly used in inquiry to fulfill the role of an a priori ordering principle. Obviously, from the arguments presented here, such terms and the roles assigned to them are suspect and may well owe their existence to an improper analysis of the physical conditions surrounding the phenomenon they are meant to account for.

Concluding remarks. We have argued that the necessary condition for "cognitive penetrability," conceived in its most general form, fails to segregate those phenomena requiring the privileged vocabulary of representation and computation from those accommodated by the nonprivileged vocabulary of physical theory. We have further questioned the propriety of the representational-computational vocabulary being used to reject realism simply because epistemic relations between animal and environment may lack a deterministic character. Consequently, we suspect that the search for fundamentals in cognitive science would fare better in the long term if it chose a model source that embraces the conditions of autonomy and morphogenesis as an a posteriori fact in the spirit, perhaps, of Piaget (1977), Prigogine (1978), or Berrill (1961) – the vocabulary of physical theory – rather than a model source that embraces conditions of neither kind – the vocabulary of formal machine theory. Admittedly, this suspicion, if valid, seriously reduces the promise of any immediate gratification from the very popular representational-computational approach to cognitive phenomena. But perhaps it would not be too harmful to ask computer scientists who address cognitive issues to temper their hubris, since the difficulty of the search for a scientific basis to realism counsels the need for considerable patience.

Editorial Note The author of the target article, Zenon Pylyshyn, has had the opportunity to read this commentary and has elected not to respond.

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On Jeannette McGlone (1980) Sex differences in human brain asymmetry: A critical survey. BBS 3:215–263.

Abstract of the original article: Dual functional brain asymmetry refers to the notion that in most individuals the left cerebral hemisphere is specialized for language functions, whereas the right cerebral hemisphere is more important than the left for the perception, construction, and recall of stimuli that are difficult to verbalize. In the last twenty years there have been scattered reports of sex differences in degree of hemispheric specialization. This review provides a critical framework within which two related topics are discussed: Do meaningful sex differences in verbal or spatial cerebral lateralization exist? and, if so, Is the brain of one sex more symmetrically organized than the other? Data gathered on right-handed adults are examined from clinical studies of patients with unilateral brain lesions; from dichotic listening, tachistoscopic, and sensorimotor studies of functional asymmetries in non-brain-damaged subjects; from anatomical and electrophysiological investigations, as well as from the developmental literature. Retrospective and descriptive findings predominate over prospective and experimental methodologies. Nevertheless, there is an impressive accumulation of evidence suggesting that the male brain may be more asymmetrically organized than the female brain, both for verbal and nonverbal functions. These trends are rarely found in childhood but are often significant in the mature organism.