EVOLVING SELF-REFERENCE: MATTER, SYMBOLS, AND SEMANTIC CLOSURE

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Abstract

A theory of emergent or open-ended evolution that is consistent with the epistemological foundations of physical theory and the logic of self-reference requires complementary descriptions of the material and symbolic aspects of events. The matter-symbol complementarity is explained in terms of the logic of self-replication, and physical distinction of laws and initial conditions. Physical laws and natural selection are complementary models of events. Physical laws describe those invariant events over which organisms have no control. Evolution by natural selection is a theory of how organisms increase their control over events. A necessary semantic closure relation is defined relating the material and symbolic aspects of organisms capable of open-ended evolution.

1. What is self-reference?

Self-reference has many meanings. In symbol systems, like logic and language, self-reference may lead to well-known ambiguities and apparent paradoxes as in, "This sentence is false." In material systems, like molecules and machines, self-reference is not clearly defined but may describe causal loops such as autocatalytic cycles, feedback controls, and oscillators. At the cognitive level, self-reference occurs in introspection and is often considered one aspect of consciousness. I define a specific form of self-reference that applies to a closure relation between both the material and the symbolic aspects of organisms. I argue that this view of self-reference is necessary to understand open-ended evolution, development, and learning at all levels of organization from the origin of life to the cognitive level. This is not an entirely new view, but is an elaboration and integration of ideas from several well-established areas of physics, logic, computation theory, molecular biology, and evolution theory. To state my position as briefly as possible, self-reference that has open-ended evolutionary potential is an autonomous closure between the dynamics (physical laws) of the material aspects and the constraints (syntactic rules) of the symbolic aspects of a physical organization. I have called this self-referent relation *semantic closure* (Pattee, 1982) because only by virtue of the freely selected symbolic aspects of matter do the law-determined physical aspects of matter become functional (i.e., have survival value, goals, significance, meaning, self-awareness, etc.). Semantic closure requires complementary models of the material and symbolic aspects of the organism. This brief statement requires much more elaboration.

I have emphasized in many papers (e.g., Pattee, 1969, 1972, 1982) that the matter-symbol distinction is not only an objective basis for defining life but a necessity condition for open-ended evolution. My reasoning is based not only on biological facts but on the principled epistemic requirements of physical theory. In other words, I require that *models of living systems must be epistemologically consistent with physical and logical principles.* It is well known that replication and evolution depend crucially on how the material behavior of the organism is influenced by symbolic memory. Biologists call this matter-symbol distinction the phenotype and genotype. Computationalists call this the hardware-software distinction. Philosophers elevate this distinction to the brain-mind problem. What is not as well known is that even in the formulation of physical theories a form of matter-symbol distinction is necessary to separate laws and initial conditions. I will explain this further in Sec. 4.

The logical necessity of this matter-symbol complementarity was first recognized by von Neumann (1966) in his discussion of self-replicating automata that are capable of creating more and more complicated automata. This is often called emergent evolution. Von Neumann noted that in normal usages matter and symbol are categorically distinct, i.e., neurons generate pulses, but the pulses are not in the same category as neurons; computers generate bits, but bits are not in the same category as computers, measuring devices produce numbers, but numbers are not in the same category as devices, etc. He pointed out that normally the hardware machine designed to output symbols cannot construct another machine, and that a machine designed to construct hardware cannot output a symbol. This was a simple observation about actual machines and the use of natural language, not an ontological or dualistic assertion. Von Neumann also observed that there is a "completely decisive property of complexity," a threshold below which organizations degenerate and above which open-ended complication or emergent evolution is possible. Using a loose analogy with universal computation, he proposed that to reach this threshold requires a universal construction machine that can output any particular material machine according to a symbolic *description* of the machine. Self-replication would then be logically possible if the universal constructor is provided with its own description as well as means of copying and transmitting this description to the newly constructed machine.

As in the case of the universal computing machine, to avoid the ambiguities of self-reference, logic requires the categorical distinction between a machine and a description of a machine. This logic does not differ if the machine is a material machine or only a formal machine. To avoid self-reference requires two logical types or categories. This is the logical basis of the symbol-matter distinction. It is significant that his so-called kinetic model required primitive parts with both symbolic functions (i.e., logic functions,) and material functions (e.g., cutting, moving, etc.). I will discuss this argument in Sec. 9. Von Neumann made no suggestion as to how these symbolic and material functions could have originated. He felt, "That they should occur in the world at all is a miracle of the first magnitude." This is the origin of life problem.

2. What is matter?

For my argument here, I will mean by matter and energy those aspects of our experience that are normally associated with physical laws. These laws describe those events that are as independent of the observer as possible, i.e., independent of initial conditions. The laws themselves are moot until we provide the initial conditions by a process of measurement. Laws and measurements are necessarily distinct categories. Laws do not make measurements, individuals make measurements. Measurement is an intentional act that has local significance and hence involves symbolic aspects usually in the form of a numerical record. This is the physical basis of the matter-symbol distinction. I elaborate on this in Sec. 5. This well-established distinction between the physical and symbolic aspects matter we have no trouble recognizing in practice. Whether one is a material reductionist or a formalist, in practice we rarely have difficulty distinguishing our descriptions of matter using physical laws and our descriptions of symbols using syntactical rules and programs. Also, we all know the difference between formulating theories, constructing instruments, making measurements, and computing.

The difficulty begins when we try to describe how these complementary material and symbolic aspects are related. Traditional philosophy sees this relation as the problem of reference, or how symbols come to stand for material structures (e.g., Whitehead, 1927; Cassirer, 1957; Harnad, 1990). I have always found the complementary question of how material structures ever came to be symbolic much more fundamental. From the origin of life and evolutionary perspective the most difficult problem is how material structures following physical laws with no function or significance were gradually harnessed by syntactical rules to provide function and significance as symbols (e.g., Pattee, 1969; 1992). I will not say much more about the origin problem here. For several reasons, one of which is its difficulty, the origin of symbols is not considered one of the central problems in any area of philosophy or science. Another reason is that for most scientific models it is not necessary to know the nature or origin of symbols. Natural language, logic, mathematical symbol systems, and computers are most commonly treated simply as well-developed tools, and for most models there is no need to ask how they originated.

3. Material and symbol complementarity - neither reductionism nor dualism

The biologist, largely for historical reasons, often considers dualism as the only alternative to reductionism. This is not my view. I am a physical reductionist in the sense that I believe all symbolic behavior must have a material embodiment, following physical laws, that correlates with this behavior. For example, the chemical structure and reactions of DNA must correlate with its function as the record of genetic instructions, the chemical structure and reactions of a photosensitive emulsion must correlate with its function as a record of a measurement process, and the biochemistry of neurons must correlate with all perception and thought. Material reductions are certainly one necessary type of model for understanding symbol systems.

However, I am not a reductionist in the sense of those who claim that symbols are "nothing but" matter. "Nothing but" implies that the only model that is required to understand symbols is a complete materialist or physical law model. Reductionists are generally happy when they have discovered the material correlates of higher level behavior. My position is that no complete physical description of these material structures, although correct in all details, will tell us all we need to know about their symbolic function. Briefly, this is because symbol function, like all biological function, is not an intrinsic or law-based property of the material symbol vehicles but a selective survival property of the populations of individuals that use the symbols for material construction and control in a particular environment. In other words, one exclusive material reductionist model is not adequate to describe function or significance. An alternative, complementary model is necessary. I will elaborate on this in Sec. 4.

I want to emphasize that my position did not originate from this metaphysical view, but from the way physicists and biologists actually formulate their models of the world. Therefore, rather than trying to clarify the thorny issues of reductionisms vs. dualisms that historically have been scientifically sterile, I will only elaborates on the well-established value of using complementary models without entering into the undecidable metaphysical issue of which model represents reality. Complementary models are well-known in physics. Particle and wave, microscopic and macroscopic, deterministic and stochastic, coarse and fine grained, reversible and irreversible models are necessary for fully understanding any complex system. Rosen (1977) has usefully defined a measure of system complexity by the number of models that we require to adequately understand its behavior.

4. What is measurement?

In my opinion, the measurement process in physics is the most convincing and fundamental example of the necessity of complementary models with semantic closure. On the one hand, it is possible to describe a measuring device in its material detail, and this may be necessary in its design and construction. On the other hand, if the measuring device is to perform its function (i.e., produce a symbolic record) these details must be selectively ignored. This is not a metaphysical position but arises from the pragmatic fact that to obtain a meaningful result *we must be able to measure something without having to measuring everything.* This means that to function, the number of material degrees of freedom in the measuring device must be reduced to the few *semantically relevant* symbolic degrees of freedom of the result. Without such a classification process we have a divergent infinite regress of measurements, as von Neumann (1955) pointed out.

This concept of measurement generalizes to all interaction of organisms with their environment that require classification for survival. The distinction between the material and symbolic behavior is very sharp in physical theory for the principled reasons I will explain further in the Sec. 5. However, in primitive organisms matter and symbol are not as easy to disentangle. This is the case with all structure-function relations in organisms. As external modelers we need to know the detailed chemical structure of DNA to understand, and perhaps to design, the chemical correlates of its function, but to perform its semantic function in the cell only the cell's classification of the base sequence is relevant to the synthesis of proteins. Just as in the case of a measuring device, there is a great reduction from the many degrees of freedom of the material codon to the few bits of semantic information it actually conveys as a result. Similarly, at the protein level any external structural model of the material folding requires enormous detail and computational power, but folding in the cell is a physical process that requires no description or instruction beyond synthesizing the linear sequence of amino acids. In all cases, from our modeling point of view we cannot ignore multiple-level descriptions when we need to relate structure to function. Similarly, but more objectively, some of the cell's behavior, like reading base sequences, is symbolic, but most of its behavior, like protein folding, is not. That is, DNA symbolically describes only the linear sequence of amino acids, while physical laws take care of folding, self-assembly, and catalysis.

As in the case of measurement, in order to have any useful function, *genes must be able to symbolize something without symbolizing everything.* Otherwise genetic instructions would never end. Without simplification, heritable symbols would suffer the same infinite regress as measurement symbols. Therefore to allow open-ended increase of material complexity while maintaining heritability requires simplification of description. In conventional language, symbolizing something without symbolizing everything is called classification. Consequently organizations with the potential for emergent evolution, above von Neumann's threshold of complication, must perform *autonomous* classifications.

5. What is a symbol?

Symbols are difficult to define in any simple way because symbols are functional, and function cannot be ascribed to local structures in isolation. The concept of symbol, like the more general concept of function, has no intrinsic meaning outside the context of an entire symbol system as well as the material organization that constructs (writes) and interprets (reads) the symbol for a specific function such as classification, control, construction, communication, decision-making, and model-building (e.g., Pattee, 1969). All these activities can be identified as functions only in specific contexts from local goals of individuals to the global survival of species. The symbol vehicle is only a small material structure in a large self-referent organization, but the symbol function is the essential part of the organization's survival and evolution. This autonomous structure-function self-referent organization is what is entailed by my term *semantic closure*.

For this discussion I could alternatively describe a symbol as a relatively simple material structure that, while correctly describable by all normal physical laws, has *significance or semantic function* that is not describable by these laws. The reason that laws cannot describe symbol function, or any function, is because we specifically restrict physical laws to describe only those properties of matter that are, by principles of invariance and symmetry, as independent of observers and individual measurements as possible, as I stated in Sec. 2. This is necessary to achieve the characteristic universality of laws. Symbols, by contrast, are generated with few physical restrictions but are eventually selected for their contribution to the survival of individual units in a local environment. In other words, it is only those universal and intrinsic aspects of matter that have *no* significance for individuals that are described by laws, while it is those context-dependent, selective aspects of matter that have significance for individuals in a local environment that we describe as symbols (Pattee, 1982). Of course, all symbols require material vehicles that obey all the laws, but symbolic function requires another model. These are complementary models, not dualism.

To understand why physical theory cannot treat symbols as nothing but matter described by laws one must first understand that the present concept of physical law makes sense only if we divide experience into things that don't change and things that do change. This distinction is one of the defining characteristics of laws and initial conditions (Wigner, 1964). Furthermore, it is only because of this independence of material and symbolic aspects that physical laws can be modeled with the minimum ambiguity between the boundary of the lawful world and the formal model. In other words, it is the independence of symbolic aspects from material aspects that allows a clear, fundamental separation of laws and initial conditions. There is no way to give much meaning to symmetry, invariance and conservation principles without a sharp separation of laws and initial conditions (e.g., Houtappel, Van Dam, and Wigner, 1965). In physics, the act of measurement of initial conditions is the only contact of the symbolic model with the material world. Laws are moot until provided with specific initial conditions by measurements. Therefore symbols must be viewed as belonging to the general category of initial conditions, which also includes boundary conditions and constraints. Ordinary initial conditions are without regularity, but symbols are special collections of constraints that allow us to describe symbolic behavior by rules.

Another explanation of why symbolic behavior cannot be described by laws is that laws are invented to be complete and inexorable. Therefore, one cannot amend or adjust lawful behavior itself. Laws leave no alternatives. The only meaning we can attach to a choice of alternatives in a system described by deterministic laws is through measurement and control of initial conditions. Writing symbols is a time-dependent dynamic activity that leaves a time-independent structure or record. The mathematician Emil Post (1965) described the writing of symbols as, "Activity in time [that] is frozen into spatial properties." Symbols are read when these structures re-enter the dynamics of laws as constraints (Pattee, 1972). Any highly evolved formal symbol system may be viewed as a particularly versatile collection of initial conditions or constraints, often stored in a memory, producing significant or functional behavior that is usefully described by locally selected rules rather than by physical laws. This means that rules for manipulations of the material symbol vehicles are as independent of mass, energy, -dynamical time, and rates as possible. The genetic code, natural language, logics, formal mathematics, and computer programming languages are the best known examples of such symbol systems. As I have emphasized, all symbol systems must have material embodiments that obey physical laws. But for the reasons just stated, the lawful material description of symbols, even though correct in all details, can reveal no significance.

6. What is a symbolic model?

Any model must in some sense have similar behavior to what it models. In the symbol-based formal models that are the established format for physical theories, similar behavior is a metaphor established by a parallelism between a few selected aspects of behavior of the object, ascribed to inexorable laws, and a few selected aspects of behavior of the symbols, determined by our local mathematical or computational rules. Because the material vehicles of symbols are physically arbitrary (i.e., energy degenerate) structures and their rules based on boundary conditions and not derived from laws, it is a characteristic of symbolic models that outside of these few selected parallel aspects there is generally no other similarity between the material system and the symbolic model. All we can expect from symbolic models is that a few specific aspects of our models and a few specific aspects of the object have similar or predictable behavior.

Hertz (1894) was the first modern scientist to clearly state the relation between matter and symbols in a model: "We form images or symbols of the external objects; the manner in which we form them is such that the logically necessary consequences of the images are invariably the images of the materially necessary consequences of the corresponding objects." Then, to emphasize the limited domain of reference of formal symbolic models, he added, "For our purpose, it is not necessary that they [the symbols] be in conformity with the things [the matter] in any other respect whatever. As a matter of fact, we do not know, nor have we any means of knowing, whether our conception of things are in conformity with them in any other than this one fundamental respect" It is significant that by substituting "instructions" for Hertz's first two usages of "images," and "constructions" for the last usage, we have a concise description of the function of the genetic code.

7. How to evade the matter-symbol problem

Each scientific culture has its own reasons for ignoring the matter-symbol problem. Physics, with its sharp categorical distinction between matter and symbol, does not normally require a theory of symbols even though theories expressed in mathematical symbol systems play the primary role in physics. Also, physicists study material systems that in most cases do not themselves contain intrinsic symbolic activities and functions. In the case of measurement of initial conditions, that is, the mapping of matter to symbols, the measurement is treated as a primitive process for which, fortunately, a theory of symbols is not necessary for useful symbolic results. However, in well-known thought experiments where it is necessary to specify objectively when a measurement is completed, such as Maxwell's demon and Gibb's paradox, the matter-symbol problem is unavoidable (e.g., Leff and Rex, 1990); and in quantum theory, where the measurement process enters the formalism of the laws, the interpretation of measurement remains largely inscrutable (e.g., Wheeler and Zurek, 1983). In any case, neither the evolutionary origin of symbols nor of measurement processes is considered a dominant issue in physics.

Because all organisms depend on intrinsic symbolic controls and the origin of life requires a symbolic genetic code as a crucial step, biologists should be much more interested of the matter-symbol problem. However this is not the case. Most biologists are material reductionists, and the discovery of the material structures that correlate with the symbolic activity and function is the only level of explanation they are looking for. Consequently, experimental or material discoveries, not theory, play the primary role in biology. For example, the biologist finds the chemical structure of DNA and the molecular basis of coding a satisfactory description and feels that this fully explains the gene's symbolic behavior. This material reductionism is even extended to cognitive activity where discovering the material neural correlates of thought would be considered by many as a satisfactory reduction of conscious behavior (e.g., Crick, 1993).

Philosophers have traditionally focused on the higher level mind-body problem, but they have also found metaphysical stances that effectively minimize the matter-symbol problem, such as idealism, dualism, material reductionism, functionalism, and the newest and most effective of all, computationalism. Besides the traditional cultures of philosophy, physics and biology, a fourth computer-based culture comprising the classical field of artificial intelligence (e.g., Newell, 1980; Pylyshyn, 1984)) and the more recent field of artificial life (e.g., Langton, 1988) has adopted the programmable computer as a universal symbolic model. This culture explicitly disregards material embodiments of either the computer or what it is modeling. Both artificial intelligence and artificial life evade the matter-symbol problem by accepting a functionalist or the stronger computationalist view of models. Like classical physicalism, functionalism and computationalism also make a sharp categorical distinction between matter and symbol, but they focus only on the symbolic category. Functionalists argue from the half-truth that because there are innumerable possible material embodiments of any given symbol function, the relation of symbols to matter is gratuitous or arbitrary. They believe that the particular facts of biochemistry, neuroanatomy, and neurophysiology represent only one possible material embodiment of biological and mental behavior, and that the computer can, in principle, equally well represent another embodiment. In other words, functionalists consider the particular material embodiment of the symbolic activity as unimportant.

The requirements for functionalist models may sound like they are based on the same classical principles as are the models of physical systems, namely, that selected aspects of the computer model's behavior must parallel selected aspects of the organism's behavior. The computationalist requirements are similar, only the word function now takes a formal symbolic meaning. The main requirement for the computationalist's model is that it computes at least one of the same functions as the object being modeled. In spite of this apparent similarity of physical and computer models there is a fundamentally different view of the role of measurement and consequently of the matter-symbol relation. Physicists view measurement as the only empirical contact with the world. Therefore their observables are precisely defined, relatively simple, and accurately measurable. In physics, enormous effort and by far the largest amount of time and resources is spent on designing and constructing measuring devices and actually performing measurements.

Functionalist and computationalist modeling organism and brains have a much more difficult problem defining observables. Most of their time and resources is spent programming and running computers, and insofar as they use observables, they can seldom define them precisely enough to measure objectively. Artificial intelligence typically models complex cognitive activities such as problem-solving, pattern recognition, or types of thinking. Artificial life typically models activities such as self-replication, adaptation, and emergence. These are not simple enough observables to be precisely defined or measured. Their symbol manipulation is precise enough, but their symbol grounding is vague. Naturally this leads to undecidable arguments, such as where symbols and meaning begin in computers (e.g., Searle's Chinese room), and whether computers are alive. I will suggest other inadequacies of functionalism in Sec. 10. Computationalists must also make the gratuitous assumption that all matter is computing, that is, they assume every material thing is computing something if we choose to interpret it as computing. Such a subjective view evades the matter-symbol problem completely (Pattee, 1990).

8. Self-organization approaches

Many scientists have taken the reasonable strategy of treating the matter-symbol distinction as originating at some late stage of a general process of spontaneously increasing complexity of material systems. This type of model has often been called self-organization. The older literature includes discussions of physical systems that are described simply, but spontaneously grow in complexity (e.g., Yovits and Cameron, (1960; Yovits, Jacobi, and Goldstein, 1962). The few general theories of self-organization were not thoroughly developed at the time (Simon, 1962; Burgers, 1963; Pattee, 1969; Kauffman, 1969). In the 1970's new types of order production were discovered in nonequilibrium thermodynamical and non-linear dynamical models (e.g., Glansdorff and Prigogine, 1971; Haken, 1977; Nicolis and Prigogine, 1977). More recent work on self-organization is collected in Yates (1987). Some of these developments in thermodynamics have lead to speculations about possible organizing principles that modify the traditional neo-Darwinian model (e.g., Weber, Depew, and Smith, 1988). These models and theories of organization are generally applied only to prebiotic or at least pre-symbolic matter, and therefore do not address the matter-symbol relation.

Currently, with the discovery of unexpected richness in nonlinear dynamics, self-organization is now usually included in the new field called the science of complexity (e.g., Stein, 1988; Nicolis and Prigogine, 1989; Jen, 1989; Zurek, 1990; Stein and Nadel, 1990; Waldrop, 1992; Kauffman, 1993). Its potential arises from many sources that include mathematicians, physicists, and computer and cognitive scientists, each with characteristic but overlapping approaches, e.g., nonlinear dynamics, chaos, cellular automata, non-equilibrium thermo- dynamics, statistical mechanics, solid-state physics, connectionist machines, artificial neural nets, etc. Even in this new field of complexity theory the origin of symbols is seldom seen as an issue, and most of the computational models in this area do not make any clear distinction between law-based material behavior and rule-based symbol behavior. At least there is no consensus. The field includes some physicists who believe that all our models of physics are limited by the symbolic output of measurements (e.g., Wheeler, 1990), and some computationalist who believe that all lawful material processes are computations (e.g., Toffoli, 1982). The so-called strong artificial intelligence and strong artificial life modelers believe that particular material embodiments are irrelevant, and consequently that a close enough computer simulation becomes a form of realization of what is modeled (e.g., Langton, 1988). Of course if one believes that everything is a computation, or that by improving simulations they will eventually become realizations then one sees no matter-symbol problem (Pattee, 1988). At the other extreme there are physical reductionists who see symbols only as an illusion, like phlogiston and the ether, that will be unnecessary when an adequate material description of symbolic behavior is found (e.g., Churchland, 1981; Crick, 1993).

9. The function of symbols in evolution and cognition

Knowing how protein synthesis works we might conclude that construction was the first function of symbols. However, construction requires the classification and control of parts. Also, construction would be of no evolutionary value unless there was hereditary transmission. This certainly requires communication. In other words, at the primitive levels none of these functions can be isolated as primary nor even objectively distinguished from each other. This is one reason that the origin of symbols and life is such a difficult problem.

At the cognitive level, symbols allow our own subjective sense impressions to be compared with another's and thereby endowed with some degree of objectivity. By objectivity, here, I mean only the ability of different observers to reach a principled agreement by communicating what they observe. For example, if I see a green light there is no way I can tell another viewer what I see without symbols. Even telling you in natural language that I see "green" is no assurance that your experience of "green" is the same as mine. It is only by a measurement process that abstracts complex perceptions to simpler, more universal, symbolic classifications that agreement, and hence communicable objectivity, is possible among populations of individuals. This is Born's (1965) fundamental explanation of why mathematical models are essential for representing physical theory. It essentially defines one necessary condition for objectivity in physics. However, the principle is more general than that. The same universal communicable classification is also an essential function of all heritable symbols in populations of organisms capable of evolution by natural selection. The hereditary transmission requirement in evolution is fundamentally a communication problem.

Why does a material structure need symbols to communicate or transfer its structure to other matter? The first reason, mentioned by von Neumann, is that any universal constructor that could assemble its material parts would function more efficiently if it replicated from a symbolic *description* of its material parts rather than replication by material self-inspection of its parts. I have not found a strong physical or logical support for this efficiency argument, although it sounds plausible. In any case, as any evolutionist would point out, replication by symbolic description must be superior to material self-inspection because it survives. The second reason, indirectly suggested by von Neumann, is that new descriptions, being simpler, are more likely to arise than corresponding new material constructions. This is also not a general physical or logical argument, but again, it is plausible from our knowledge of molecular genetics and the evolution.

Consider the various physical processes that a simple material structure might use to self-replicate. Assume the structure consists of N parts that will self-assemble if brought close enough together. How can the structure bring together the correct parts? Given a reservoir of parts, the simplest way is to have every part of the structure individually heritable, that is, to have each of its parts capable of selecting a similar part from the reservoir. In principle, specially folded macromolecules could do this by template or specific binding, a kind of crystallization with many parts. However, this hereditary process does not have open-ended evolutionary potential, because first, all mutant parts must also have this intrinsic hereditary property. In other words, for this process to achieve open-ended evolution we must assume that the universal heredity property is a rather general intrinsic property of macromolecules. This is not the case. Second, template-identified material structures are limited to the outside parts, just as is crystal growth. The only known way out of the first limitation is to use special adaptors that are universal, that is, a small set of adaptors that can bind any number of correct parts as well as mutant parts. The only known way out of the second limitation is by unfolding to get at the inside parts. We know that molecular adaptors and folding are general strategies of all cells, but the actual implementation is even more complex.

Von Neumann did not discuss the need for adaptors, but it is clear from his solution that he saw the self-referent logical difficulties in postulating universal adaptors that could adapt to themselves. As we outlined in Sec. 1, his solution was based on the logical requirements for universality in a formal Turing machine applied to a universal material constructor machine. Generally, a universal machine is one particular adaptor machine that can be instructed to mimic the behavior of any machine. The logical point is that to mimic another machine there must be two categorically distinct levels of instruction. The machine must know when to mimic and when not to mimic. In other words, it must distinguish the virtual machine from the real machine. It is important to understand that universality applies only to the domain of possible symbolic *descriptions* of machines. In other words, mutations may be acceptable in the descriptions, but mutations are not likely to be acceptable in the universal machine itself. This is the case with the genetic code which is the universal reader for an enormous open-ended variety of *descriptions* of proteins. However, the material parts and code itself are essentially the same for all organisms.

10. The role of matter in evolution and cognition

Why are particular material embodiments or hardware important for open-ended evolution if this logic can be satisfied in a symbol system like a computer? Von Neumann himself switched from his kinetic model that recognized the matter-symbol distinction to a formal cellular automaton model that did not. However, he warned that, "By axiomatizing automata in this manner, one has thrown half the problem out the window, and it may be the more important half." There is no doubt that programmable computers can simulate many important aspects of life, evolution, and cognitive activity. This has been clearly demonstrated by a vast number of programs. The stronger claims of artificial intelligence and artificial life that a computer can *realize* thought and life are not empirically, or even logically, decidable issues because they hinge entirely on the degree of abstraction one is willing to accept as a realization. If we could agree to define life and thought abstractly so as to leave out enough of its material aspects then obviously, by definition, a live, thinking computer is possible. Similarly, if we could agree to define the concept of computer broadly enough to include enough material aspects then, by definition, everything may be called a computation. I do not see much value in pursuing this type of undecidable issue. In any case, it is a fact that exclusive models of either symbolic or material aspects of life have not yet answered the functional and semantic issues to everyone's satisfaction.

One inexorable aspect of physical systems that formalists often ignore, or view completely differently from physicists and biologists, is noise. Noise is not only inevitable in all measurements, but is essential for evolution. Computer hardware and neurons are also noisy, but formal models do not recognize noise. By good design of symbol systems and their hardware noise can usually be ignored for the purposes of symbol manipulation. One of the proposed challenges to the Turing Test for assessing whether a machine can think is to see if the machine makes mistakes. Of course, to pass this test one can introduce random error in the program. A more effective and more difficult test is to continually introduce errors in both the challenger and the machine and compare their learning or evolving behaviors.

Formalists and functionalists argue that since different material hardwares can compute the identical function, the computation is independent of its material implementation. This is true only in the ideal case of noiseless, error-free symbol manipulation. However, it is easy to see that two computations that are formally equivalent, i.e., that compute the same function, will generally respond to error in entirely different ways. This occurs even within formal systems. As a simple example, identical bit strings are generated by the rewrite productions $0 \rightarrow 1$ and $1 \rightarrow 01$ starting with 0, and the recursion $S_{n+1} \rightarrow S_{n-1} \circ S_n$ starting with $S_0 = 0$ and $S_1 = 1$. However, completely different strings will be generated following an error in any bit at any place in the string. This problem only gets worse if the material structures implementing the computation also have noise. Such mutation tests can of course be used to discover if two formally equivalent computations are implemented with different hardware, architectures, or programs. For example, a connectionist machine, cellular automaton, or any number of machines may be formally equivalent, but it is highly unlikely that their response to noise in hardware or software will be similar or even related in any predictable way.

This is clearly a very general type of test, because, in fact, when coupled with heritable memory and natural selection, it is the basis of evolution itself. The functionalist's position that the same function can be realized by many material structures should be countered by three additional physical and biological facts. First, the same material structure can perform different functions, since function is not intrinsic to any structure. Second, the domain and quality of potential functions of a given material structure will depend on details of that material structure. That is, two different material structures will not have the identical domains of potentially evolvable functions. Generally, different material structures will evolve differently, even though at one time they may have both had the same function. Third, effective evolutionary search depends on how the space of symbolic description maps to material functions. The 3-dimensional folding of proteins is not related to their 1-dimensional genetic description only by symbolic rules, but depends crucially on material structures and physical laws.

The role of the material structure that implements cognitive activity in brains is not nearly as well understood as its role in the evolution of organisms. The functionalists and computationalists still apply the same argument that symbolic behavior of brains is not dependent on the material implementation. Again, this is true by definition if cognitive behavior is abstracted far enough from its material-dependent precursors, such as sensorimotor controls. However, the three facts just stated above also apply to the evolution of brains and to learning processes, so it is not likely that the successful evolution of rapid and accurate classification processes, such as complex visual pattern recognition, had no dependence on the material sensorimotor structures through which such functions evolved.

11. Conclusions

As I indicated in Sec. 1, I require that theories of life be epistemologically consistent not only with logic but with fundamental physical principles. The most fundamental epistemological classification is between things that do not change and things that change. In physics this principle is used to define laws and initial conditions. This implies a self-referent impotency principle that unchanging events cannot completely describe changing events. That is, laws cannot completely describe measurements. More precisely, the classification function of measurement cannot be derived from laws. Otherwise, the laws could derive their own initial conditions by computation. The corresponding self-referent impotency principle in formal systems is that they cannot prove their own consistency, let alone assign a truth value to their own axioms. This implies that formal symbol systems also cannot make measurements. Symbolic computation can never realize measurement.

Physical laws and natural selection are complementary models of events. Physical laws describes those events over which organisms have no control. Evolution by natural selection is a theory of how organisms increase their control over events. By natural selection I mean the neo-Darwinian process of biasing the relative survival rates of population distributions grown by heritable variations of their symbolic instructions. The biasing is done at many levels of organization (e.g., Sober, 1984). We can define non-selective self-organization as order produced by present or future physical laws in systems unconstrained by symbolic instructions.

Kauffman (1993) in his exploration of non-selective ordering processes points out that no established field of study incorporates the non-selective physical order into evolution theory. To some extent this may be another case of cultural bias in scientific models inherited from the classical physicist's categorical distinction of matter and symbol.

Perhaps it is also because until recently there has been a lack of specific theories of physical self-organization that appeared to be relevant to biological organisms. This is no longer the case. As I mentioned in Sec. 8, there have been many recent discoveries of complex physical systems that exhibit emergent order that to many appear lifelike. However, the matter-symbol distinction is rarely addressed in these studies. Only theories of the origin of the genetic code appear directly relevant to the matter-symbol distinction (e.g., Bedian, 1982). As in the case of artificial intelligence, computational models of emergent evolution while stimulating new interest in the classical matter-symbol problem, have rarely addressed the physical basis for the distinction or how matter and symbol are related by measurement.

For all these reasons, I find that a productive approach to the theories of life, evolution, and cognition must focus on the complementary contributions of non-selective law-based material self-organization and natural selection-based symbolic organization. Hopefully, this is an empirically decidable issue, although it is surely an extremely difficult one. Perhaps it is better stated not in terms of contributions of material and symbolic aspects, but in terms of how the two aspects are related, how this relation itself arose, and, as I have suggested by semantic closure, why this matter-symbol complementarity is necessary for evolving more and more complex organizations and more and more complex thoughts and models.

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