Why should engineers be interested in bizarre systems?

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Abstract

This paper examines the shortcomings of conventional analysis when it is applied to complex processes. In particular it considers the consequences of ignoring behaviors of processes simply because they do not conveniently project onto lists of numbers.

Complex behavior is bizarre, but not absurd. Absurd behavior is unpredictable, unconstrained by any laws of natural systems, and not amenable to logical analysis or synthesis. In contrast, bizarre systems are merely counterintuitive. Bizarre behavior is logically tractable. The inferential linkages within a bizarre system's epistemological model are congruent with the causal linkages that govern its ontological behavior.

The author argues that from the perspective of neurophysiology, the behaviors that we normally consider to be intelligent are irreducible to a list of numbers. This being the case, no list of numbers, no matter how big, can emulate intelligent behavior. To discuss intelligence other than by empirical observation, some logical description of it must be found that is not limited to predicative inferential structures. It is little appreciated by engineers that mathematics abounds with such alternatives. Lists of numbers and the predicative inferential entailments governing the behavior of lists of numbers are only a small part of mathematics. Impredicative mathematical entities provide far more powerful ways of describing complex behavior. They do so at a cost, being non-algorithmic.

Engineering decisions based on predictions made by attempting to reduce complex behaviors to algorithms cannot be trusted. The projection ignores key aspects of the behavior. Present day computers only work for algorithmic processes. An engineered artifact that exhibits intelligent behavior requires at least one, and possibly both, of the following developments: a more powerful model of computation than the Turing Machine, or a computing element that has entailments similar to those observed in complex processes.

Index Terms: mind, cognition, model, complex, impredicative, decision-making, behavior, knowledge, reality.

1 Introduction

Can an instrument tell whether or not a process "feels right?" No such instrument has ever been constructed, nor can one be constructed with present-day technology. Nevertheless, there is no fundamental reason (including appeals to causality) to suppose that it cannot be done. Indeed, it is expected that cognitive instrumentation systems will be one of the major engineering breakthroughs in sensing and control within in the next 10 to 20 years.

Consider the impact of the application of cognitive systems to manufacturing processes. They will enable the implementation of anticipatory maintenance, allowing defective components in production systems to be replaced before they fail, based on a complex metric. They will anticipate catastrophic occurrences, such as pump failures, and provide sufficient warning to enable operators (whether robotic or human) to prevent the catastrophe. They will be able to make on-line real-time observations of phenomena not currently accessible, such as the time-evolution of phases in solidifying molten metal.

Cognitive instrumentation is not currently available and it is reasonable to ask why. The short answer is that present-day mathematical techniques used in artificial intelligence and data fusion are simply not up to the task of abstracting meaning from real-world processes. For example the connectionist paradigm does not emulate cognitive behavior; it simply performs a non-linear curve fit for transformations that warp long lists of numbers into small sets. In so doing it fails to describe key behaviors in real-world processes.

However, there are two facts that seldom come to the attention of engineers. One is that in natural systems there exist causal linkages, or entailments, that cannot be reduced to numbers. The other fact is that there are formal systems (mathematical descriptions) that have inferential entailments that are likewise irreducible to lists of numbers. These inferential entailments can be made congruent with causal entailments and are amenable to logical manipulation. Because these things exist, it should be possible, by projecting natural systems onto categories and manipulating the categories, to make predictions about complex processes in natural systems without recourse to guessing, hopeful intuition, or mysticism.

The promise of cognitive instruments and their current unavailability lead to several questions. Notwithstanding the popular claim that computer algorithms can perform cognitive functions like the abstraction of meaning, why do we say that they cannot? How does wetware perform abstractions? If we wish to emulate the processes occurring in wetware, what should we do next?

2 The Tedious Conversation

For the answers of these questions to make sense, the reader must appreciate that we cannot escape the resort to popular buzzwords. We must appreciate that before they achieved the meaningless status of buzzwords, but they stood for particular technical concepts. Recovering the meaning of buzzwords is an unfortunate but necessary instance of "the tedious conversation."

For example, "algorithmic" has a precise meaning in computer science. It does not merely mean methodical. It is a process with five attributes [1]. It terminates after a finite number of steps. Each step is unambiguously defined. It has zero or more input data. It has one or more output data. An algorithm must be effective; for example, there is no algorithm that solves the Busy Beaver problem. (Note: The Busy Beaver problem is the problem of finding B(n), the maximum number of ones that a Turing machine with n states and an alphabet of {1, B} will write to an initially blank tape.)

Turing showed that any process that possesses the five attributes of an algorithm could be converted to an operational procedure that has come to be called the Universal Turing Machine [2]. There is a class of problems such as the Busy Beaver problem that cannot be expressed in terms of a Turing machine. These are known as incomputable processes. Any process that can be made to correspond to a list of numbers can be described by an algorithm, or is Turing-computable, or more simply, computable. Any process that cannot be described by a list of numbers cannot be described by an algorithm, and is non-Turing-computable, or incomputable.

A process that can be described by a list of numbers is also said to be reducible. However, the notion of reductionism is broader than this, encompassing numbers and other systems that can be put in correspondence with numbers [3]. Suppose that x is a natural system or referent, and P(x) is a proposition that asserts that some property of x is true. Rosen argues that an *essential attribute* of reductionism is that any such proposition can be algorithmically constructed by "ANDing" $P_i(x)$ where $i \in \{1,...., N\}$, N is a natural number, and there are N true subproperties of x that are described by N independent propositions. Since infinity is not a number this description limits a reducible system to a finite list of properties. This algorithm constitutes a list of conditions, each necessary, and all sufficient to establish the truth of P(x). In Rosen's words, "…every property P(x) of x is of this character."

Another *essential attribute* of reductionism is the context independence of the parts of a system [4]. Suppose that referent, x, can be fractioned into parts, x_j. The listable subproperties of x_j, described by $P_k(x_j)$, are independent of the fractioning process or any other context. $P(x) = \wedge_{j,k} P_k(x_j)$ $j,k \in N$. This algorithm says that the largest property of the system can be found by ANDing all the subproperties of all the parts, and that doing so produces no information whatsoever about the context. In Rosen's words, "It is precisely this context independence that renders reductionism an entirely syntactic exercise, that gives it its algorithmic character, and embodies it in the kinds of lists and programs I described earlier."

These presumed attributes have some consequences [5]. Every proposition describing a property P(x) has an algorithm for assessing its truth. Any natural system, x, can be constructed, given enough parts x_j, and an algorithm for constructing x from x_j. The process of analyzing a system x into its parts x_j is exactly reversible to a process of synthesizing x from its parts x_j. Correspondingly, the process of analyzing P(x) into its subproperties and synthesizing it from its subproperties are reversible and algorithmic. If reductionism is a complete description of reality, then as Rosen says, "everything is computable."

In Rosen's explanation of reductionism, computable, algorithmic, and reducible are three different terms describing the same kind of process. Incomputable, non-algorithmic and irreducible are three equivalent terms describing a different kind of process, in Rosen's parlance, "complex [6]." Unfortunately, "complex" is so widely used for so many different concepts that it seldom conveys any useful meaning. A more descriptive term for Rosenesque complexity is "Bizarre Systems," the bizarreness stemming from the fact that while they are incomputable, they are nevertheless logically tractable.

The fact that they are *impredicative* is the major feature that imparts bizarreness and incomputability to bizarre systems and distinguishes them from reducible self-referential systems (often mistakenly called complex systems)[7]. A property, P(x), of an object $x \in X$, where X is the set of objects possessing property P(x) is impredicative. In other words, a predicative object participates in its own definition. Impredicativity is not an appeal to circular logic. Circular logic is an attempt in formal logic to use a proposition to prove itself. In contrast, impredicative definitions (such as the definition of the least upper bound of a bounded set of real numbers), using closed loops of inferential entailment to create an implicit definition, are indispensable in mathematics. Similarly, there exist impredicative natural systems (such as an anticipatory system whose behavior is influenced by the model of itself within itself) with closed loops of causal entailment.

Remarkably, it turns out that even genuinely cybernetic systems are bizarre rather than reducible. Cybernetics does not simply mean "computer stuff," as it is often used in the vernacular. Rather it is the "art of steersmanship," and its principles apply whether the thing being steered is a mechanism or an organism [8]. Ashby's concept of cybernetic complexity includes closed or impredicative loops of causality, just as Rosen's does.

3 Causality

Engineers may object that impredicative loops actually violate causality. The popular view is that a conventional, or reducible, engineering system is influenced by past and present *events* and behaves causally. In this same view, an anticipatory system is influenced by future *events* and is therefore, by contrast, anti-causal.

The objection is not valid because no such contrast exists. Both conventional and anticipatory formalisms are attempts to make a decision based on incomplete *knowledge*. Neither kind of system is directly affected by *events* in reality; both make an estimate of the present condition of reality from a limited description contained in data. Both invoke inductively derived models to make a guess about what to do next. The key distinction is that an anticipatory system modifies its behavior based on its *expectation* of the future, and a conventional system ignores the future, and simply reacts to the past and present [9].

To make a reasonable decision based on uncertain knowledge we must note that knowledge requires a knower [10]. Even more importantly, there is a crucial distinction between ontological events (specific occurrences in reality) and epistemological knowledge (the meaning of the events from the perspective of the knower) [11]. An amusing illustration of this distinction is provided by Sage; he points out that the same meteorological data used by environmental activists as "proof" of global warming are used with equal alarm and enthusiasm by those warning of an impending ice age [12]. Both will probably occur, but it is unclear which will happen sooner.

Dress shows how Rosen's modeling relation can be used to clarify the process of making reasonable decisions based on incomplete knowledge [13]. A natural system is an entity in physical reality. Its past behavior will affect its future behavior due to the inherent material causality of reality. Attributes of its behavior can be perceived by a knower as a stream of encodings (percepts correlated with the actual behavior of the natural system). A formal system is a purely epistemological construct at a higher level of abstraction than the encodings. It is iteratively constructed from the encodings, decodings and other knowledge. The formal system has a logical internal structure, and can be used to draw inferences based on its logical internal structure and the encodings that it is receiving from outside itself. These inferences can produce decodings or predictions about the natural system.

The reductionist strategy ignores the distinction between events and knowledge [14]. The state of a system is completely characterized by a list of numbers, which serves at the initial conditions or *material cause* of a transition to the ensuing state [15]. The system's behavior is constrained by a set of dynamical laws often modeled as a differential equation or an algorithm. The model is regarded as being identical to the underlying constraints on the system in reality, and either can be considered as the *efficient cause* of the next state transition. While a dynamical law is a general constraint on a system's behavior, it must include a parameter set (or genotype) whose specific values characterize the properties of a particular system, and require it to produce a specific response (or phenotypical behavior) to a specific force. This genotype, or parameter set, is the *formal cause* of the state transition [16]. From this perspective, the biography of the universe is nothing more than a constrained sequence of transitions of values in a really big list of numbers [17].

Material, efficient, and formal cause provide three distinct answers to the question, "Why did the state transition, or effect, or phenotypical behavior occur?" It occurred because the system was presented with a set of initial conditions (material cause). It occurred because the system must obey a set of dynamical laws (efficient cause). It occurred because the system has specific properties, or genotype (formal cause). In the absence of any of these causes, this particular effect would not have occurred. Reductionism admits no discussion of final cause; the question of what is the function or purpose of the state transition is disallowed [18]. A world in which models are identical with reality would require that answers to questions about final cause be possible only if future events in reality cause present events.

As opposed to violating causality, a complex system makes fuller use of causality than a reducible system [19]. Processes of life and mind cannot be explained in terms of a sequence of causal linkages. They have a closed loop in their causal linkages. Freeman calls this circular causality [20]. Based on his observations of brain behavior, Freeman says that through neural activity, goals emerge in brains, and find expression in goal seeking behavior [21]. This behavior corresponds with Rosen's concept of the role of final cause in organisms.

Since its model is not identical with reality, a closed loop of causality is possible (and necessary) in bizarre systems [22]. The system's internal model's inferential linkages are congruent with *some* of the system's causal linkages, allowing the its present behavior to be influenced by its *estimate* of the future, not by future *events*. Thus, in contrast to a reducible system, which merely unwinds without function or purpose, it is legitimate to attribute function or final cause to a bizarre system.

4 Functional Components

To appreciate the properties of function, suppose we have a perceptibly heterogeneous system [23]. One part has different features than other parts. If we leave the system alone, it will exhibit some sort of behavior. If we remove or change a part, we get a change in behavior of the overall system. Crucially, the change in behavior that we get is unlikely to be the effect that we would predict by merely subtracting the behavior of the part from the overall behavior of the unmodified system. The effect of changing or removing one part is to replace the original system with a new system. The function of a part is the discrepancy in behaviors between the original system with the full complement of parts, and the new system with one part removed.

These parts must not be confused with the directly summable parts of a reducible system. Rosen avoids this confusion by offering a new term for a part that embodies function. He calls it *a functional component*. In this terminology, the difference between the two systems defines the component, and the difference between the two behaviors defines the function. In a complex system, a component with a function is the unit of organization.

A functional component is context dependent. It has inputs, both from the larger system of which it is a component, and the environment of the larger system. It also has outputs, both to the larger system, and the environment. If the environment, A, changes, then the function of the component, B, changes. A can typically be described by a family of mappings that carries a set (the range X, where $x \in X$) to another set (the domain Y, where $y \in Y$), such that, $y = a(x)$, or more formally, $A: X \rightarrow Y$. B can typically be described by another family of mappings that carries a set (the range U, where $u \in U$) to another set (the domain V, where $v \in V$), such that, $v = b(u)$, or more formally, $B: U \rightarrow V$.

The functionality, F, of the functional component can be described as a mapping that maps a domain set of mappings (A, where mapping $a \in A$) to a range set of mappings, (B, where mapping $b \in B$), such that $b = f(a)$, or $F: A \rightarrow B$. The concept of a mapping that maps one set of maps to another set of maps is not unfamiliar to engineers. This is precisely what happens with a symbolic Laplace Transform.

A functional component differs from the idealized particle of Newtonian physics. The particle's identity (defined in terms of parameters such as mass) is unaffected by context. A particle does not acquire new properties by being associated with other particles. A functional component's context dependency requires that its identity be tied to its function in a larger system. Although it is a thing in itself, it acquires new properties as a consequence of association with other functional components.

5 Engineering Cognitive Systems

This perspective should lead to a new kind of science and new tools for engineers. Reducible systems are classified by keeping the constituent matter and ignoring the organization. Organization is interpreted by reductionism as an epiphenemon, a trivial, unimportant and discardable effect. Bizarre systems are classified by regarding the organization as the key distinguishing feature. However, a real and specific instance of complex organization must be manifested in and interact with matter.

Because of the closed-loop causality of functional components, information can cause the material properties to change. From this theoretical consideration, Rosen argues that functional components cannot be fractioned into a distinct software part and a distinct hardware part [24]. Several observers of mental processes embedded in wetware are led to a similar conclusion. Based on his observations of human behaviors and brains, Damasio concludes that the mind is an inseparable entity composed of both matter and organization [25]. Similarly, based on his observations of salamander behaviors and brains, Freeman concludes that the intentionality of lower animals is inseparably composed of both matter and organization [26].

Cognition appears to be impredicative. Damasio's work on the neurological basis of human mind shows that self-reference is a key component in subjective experience [27]. Sacks argues that in working around brain damage or malformed brain tissue to (re)construct needed functionality, the self is busily constructing itself [28]. The dysfunctionality of many (but not all) autistics is caused by the inability to identify the boundaries of self [29].

In the principle of analogy, two systems can have the same organization even though their material composition (if any) is different. As already argued, an algorithm (pure abstraction, no hardware) models a reducible process; indeed, reductionist purists consider the algorithm to be indistinguishable from the process. Cognition is predicted by Rosen, and claimed to be observed by Damasio and Freeman, as organization inseparable from substrate. If this notion holds up under scrutiny, then mind is incomputable.

Does this mean that it is forbidden for the Hand of Man to create a conscious system? No! It simply means that it has never been done, and if it is to be done, then it must be done the right way. In fact, the incomputability of mind does not even directly imply that it is impossible to implement a mind on a substrate consisting of semiconductor gates. However, it does require that the organization and material substrate be inseparable.

The Church-Turing Thesis suggests that the engineering task of constructing a man-made impredicative artifact is a fool's errand. But, did Church and Turing have the last word on the matter? To evade their limitations, a new formal model of computing, non-algorithmic, and more universal than the Universal Turing Machine might be found. If such a model could be found (improbable, but evidently not currently proved impossible), then the resulting artifact would be unlike any computer system ever yet constructed. The hardware and organization (now too general to be called a program) would become inseparable, with the actions of each continuously updating the other. Both the organization and the hardware substrate would continuously change configuration, no other entity could duplicate it exactly, and if the power is switched off, the substrate would remain, but the evolved organization would probably vanish irretrievably.

This is a difficult strategy. It seeks to discover a new model of a system in which hardware and software are inseparably entangled. The difficulty stems from the fact that the original system was specifically designed to allow software to be completely separable from its hardware substrate.

A less difficult strategy might assume that mind is entangled with its substrate as suggested above and to synthesize an analog of mind from a substrate that exhibits complex entangled behavior. Entanglement has been reproduced by the Hand of Man, in the form of entangled photons [30]. Thus far, it has only been done on a submicroscopic scale, but like the electric light a few years before Edison, too many people are working on a practical quantum computing element for it to remain undiscovered for very long. Is there a serious possibility that quantum entanglement might provide a physical basis for cognition? The answer is not presently known, but is apparently testable. Snyder offers the basis for an empirical test of whether or not quantum entanglement is the link between human consciousness and the physical world [31].

There is another key task that remains undone, finding the impredicative formal description (otherwise known as a practical engineering model) of the organization of mind. It may be found in mathematical category theory, but that remains to be seen. Remarkably, such a model of mind is completely different from the applications currently envisioned by most researchers in quantum computing. For the most part their goal is merely to construct a platform to run conventional algorithms faster than is possible at present. What actually needs to be done is to rise to the challenge to discover a new mathematics of intelligent behavior.

6 Conclusions

Why should engineers be interested in bizarre systems? In the near future, engineers will be designing systems that either use or are congruent with the processes of life and mind. If approached by algorithmic methods, the effort is likely to fail spectacularly. Practical non-algorithmic engineering methods do not currently exist. Man-made bizarre hardware (functional components based on irreducible effects) is probably a decade away. Similarly, the mathematical methods of impredicative systems are not ready for engineering applications, and need to be developed.

If the challenges are great, the payoffs are far greater. A bizarre organization on a substrate of bizarre hardware could be the enabling technology leading to a revolution in cognitive sensing, control, and computing. In contrast with current attempts at "data fusion," these systems will be able to will be able to recognize from sensor data streams whether or not a process "feels right." In contrast to the current philosophy of control, which presumes that the system is always in error, and continuously reacts to minimize the error, bizarre systems will use anticipation to avoid error to begin with. While a conventional computer flips meaningless symbols syntactically, a bizarre computer would be able to abstract semantic meaning from data with reliability at least as good as that of a trained dog.

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