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The road before us: Have we come to a “fork in the road” in defining complexity?

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1. The fork in the road

Welcome to this Special Issue (SI), which examines Rosennean Complexity as conceived by Robert Rosen (1934–1998), a preeminent theoretical biologist. He established a binary framework for conceptualizing complexity: systems are either simple or complex. In this Introduction, this dichotomy is represented by “the fork in the road” with two possible roads before us: Approach 1, the well-travelled road of traditional complexity, and Approach 2, the less-travelled road of Rosennean Complexity. This SI is not meant to cover Rosen‘s whole set of contributions to science, but rather to explore only one, his concept of complexity in so far as it can be separated from his other work. The SI is also not a commemoration of Rosen or a forum for new results. Diverse authors were encouraged to explore his ideas and to suggest ecological applications as well as alternative approaches to improve understanding of ecological complexity. In the following nine invited papers, 22 complexity seekers, offer their insights about the consequences of choosing one approach or the other. These experts work at different levels of the biological hierarchy from cells up to and including ecology and evolution as well as the nexus of ecology with other sciences, society, economy, engineering and technology, mathematics, and the philosophy of science. Some contributors are long term adherents to Rosen’s ideas, while others have come to Rosen’s work more recently.

One of the founding principles of this journal has been to foster ‘conceptual pluralism’ (Li, 2004). This inclusive strategy has worked well for many years. To tackle a difficult and unknown area requires definitional freedom especially at its beginning. There is still little agreement on a single definition of complexity (Gul and Khan, 2011) and a plethora of meanings have been suggested. Some like Melanie Mitchell have even concluded that a single definition is not what we should pursue as it may prove untenable like many concepts in science: force, gene, dark matter, gravity, consciousness, etc. that have not been well-defined, but nevertheless, science has progressed (Mitchell, 2009). While it is possible to have definitional ambiguity for a long time, it is less feasible to have diametrically–opposed, logically-inconsistent, coexisting definitions, as those contrasted by Rosen’s framework. This is the nagging, uncomfortable pebble in the shoe that constitutes Kuhn’s “accumulation of anomalies”, which over time motivates conceptual re-evaluation and new schools of thought that eventually create paradigm shifts (Kuhn, 1970).

Scientists, including ecologists, who seek to study complexity seem to be at the “fork in the road” in attempting to arrive at a destination of definitional and conceptual clarity. Assuming our definitional space is a two-dimensional surface and these two roads diverge to opposite points on the compass, mutually-exclusive paths cannot lead us to the same place. Furthermore, one road is well-travelled with multiple lanes, good signage, and hard paving with asphalt largely poured from reductionism. In contrast, the other road is less-travelled with a narrow passageway, few signs, and a rutty, soft surface. Thus, this “fork in the road” constitutes a major divergence in thinking, not a minor quibble over word preference, and it requires critical consideration. A complexity seeker cannot take both roads simultaneously as Frost (1916) elegantly concluded in the “Road Not Taken”. Selecting one also takes us farther from the other; and there is always the danger of being lost in a pointless cul-de-sac or in arriving at a conceptual dead end. In short, there are consequences of our choice.

The purpose of this Special Issue is to call attention to this “fork in the road” that looms ahead of all complexity seekers, like the

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readers of Ecological Complexity, and to suggest that the less–travelled road of Rosennean Complexity deserves more exploration. It may prove to be the best route to our desired destination. If this is remotely possible, we ignore it at our peril. There have been many conceptual wrong turns in the history of science; each has involved a cost in effort, resources, time, and sometimes reputation.

2. The well-travelled road (Approach 1)

Approach 1 deals with how to describe, create, and compute complexity. Lloyd (2001), a scientist working with information systems and computer-generated graphs, asked three questions concerning complexity: "How difficult is it to describe?" "How hard is it to create?" "What is its degree of organization?" Whereas Lloyd did not believe that any of these questions would be easy to answer, he did think answers were possible, and could be found in the specific structure and function of the system under study. Lloyd (2001) also collected over thirty definitions of complexity based upon answers to his questions; these definitions have been used by many authors. Much of the literature on complexity has dealt with the concepts and questions posed with Approach 1.

Many types of complexity measures and methodologies have been suggested for describing, creating, and computing complexity (Brooks, 2007), including information theory (Shannon and Weaver, 1971; Weaver 1948), organizational complexity (Weinberg, 2001), structural and functional complexity (Cadenasso et al., 2006), statistical complexity (Ladyman et al., 2011; Crutchfield and Young, 1989), biocomplexity (Colwell, 1998), logical depth (Bennett, 1988), thermodynamic depth (Lloyd and Pagels, 1988), algorithmic complexity (Kolmogorov, 1965; Solomonoff, 1960), model weight (Du, 2016), hierarchical complexity (Parrott, 2002), complex adaptive systems (Antoniou and Pitsillides, 2007), network complexity (Standish, 2011), among others. Mason (2001) separated complexity research into three components: algorithmic, deterministic, and aggregate complexity. Gell-Mann and Lloyd (1996) stated that systems are random and non-random or regular; they proposed the term 'effective complexity' as the amount of information contained in their descriptions. Lloyd (1999) later attempted to measure effective complexity, "as the amount of information required to describe a system's regularities or rule-governed behavior". Andrey Kolmogorov proposed that the complexity of an object is the size of the shortest computer program that could generate a complete description of the object-algorithmic information content" (Mitchell, 2009). Cohen and Stewart (1994) similarly concluded that the "complexity of a system is the quantity of information needed to describe it."

In the context of complexity, many authors also discuss phenomena such as self-organization, impredicativity, emergence, feedback, feedforward, persistence, robustness, anticipation, hierarchy, adaptation, memory, resilience, criticality, thermodynamic openness, order-disorder, chaos, pattern, control, among others, usually assuming that they can be certainly described, probably measured, and perhaps created. Ladyman et al. (2011) defined a complex system by categorizing about a dozen of these phenomena and related attributes as to whether they were necessary and/or sufficient in identifying complexity. In the end, these latter authors preferred a statistical definition of complexity. There have also been many efforts to subdivide and elaborate upon Approach 1 (Page, 2011; Cohen and Stewart, 1994).

Less anyone think I am overly critical of this well-travelled road; I should confess that I have been a fellow traveller for a considerable period of time. In my own research, I use a qualitative signed-digraph methodology, loop analysis, to study ecological networks in aquatic ecosystems. The methodology has helped identify micro-universes or sets of biologically-reasonable networks, which can be summarized into ecological skeletons, with concurrent enumeration of their variables and links, connectance, connectivity, pathways of effect, feedback relationships, and a number of other structural and functional features (Lane, 2016; In Press). The micro-universes of many trillions of biologically-reasonable networks appear complex, but, in fact with the aid of a computer, it is possible to describe them, create them, enumerate them, graph them, check for stability, and in short, measure their organization with systematic precision. These virtual networks are based upon field ecosystems that I believe occur as complex systems in nature. I sometimes wistfully imagine some inkling of emergence or self-organization in my model results, but ecosystem complexity is not definitively revealed by these endless enumerations. I have come to accept that I am probably trekking more toward a destination called 'ecological complication' than complexity per se.[1]

In summary, what characterizes Approach 1 is the underlying premise that complexity is a property of the system under study; and that it can be described, created, and measured. What if this premise is false?

3. A detour

Before proceeding to Approach 2, let us take a detour to consider some background to Robert Rosen's thinking and contributions. Rosen applied relational biology and category theory to study living systems, especially M-R or Metabolism-Repair systems (Rosen, 2000; Thomas, 2007). He also ventured deeply into the essence of modelling. He obtained his Ph.D. under Nicolas Rashevkey (1899–1972) who was a theoretical physicist and bio-mathematician at the University of Chicago in the mid-20th Century (Rashevsky, 1969). After approximately a decade at Chicago, Rosen worked at the Centre for Theoretical Biology at SUNY Buffalo with James Danielli and Howard Pattee, and then became a Killam Professor in the Dalhousie University medical school until illness prompted his early retirement. He was interested in complex systems in biology mostly from the cellular to organism levels with attention to evolution; he did not explore ecological systems in detail, although he had many ecological colleagues like me who tried to entice him into thinking about ecological questions. Occasionally, he would attend ecological meetings and classes to offer ideas and to lecture. He was a prolific author of numerous papers and several books (Rosen, 1971, 1978, 1985, 1991, 2000). Rosennean Complexity was one of his key contributions. He defined complexity differently from how the term is used in Approach 1. He was the first to acknowledge this, "my usage of the term 'complex' differs essentially from the way other authors define it" (Rosen, 2000). The term, 'Rosennean Complexity', was proposed after his death to clarify this difference (Gwinn, 2015). His autobiographical paper contains many more details about his intellectual development and thinking (Rosen, 2006).

In his lifetime, Robert Rosen pursued answers to many challenging biological questions such as what is a model, how does anticipation work in living systems, and what is life? He once told me that he had answered this latter question, but that he did not feel humanity was ready for the answer, and consequently, he would not explicitly publish his results. Instead, he would leave only some hard-to-decipher sign posts (Rosen, 2000; pers. comm.). In a Belgian interview in 1997, he stated, "I may leave them [my

[1] Marinakis (2008, pers. comm.) has suggested digraphs used in loop analysis can be related to categories in his "topos of complexification". Category Theory is a basis of Rosen's thinking so this suggestion could be highly relevant and requires more study.

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ideas on what life is] somewhere . . . like Leonardo da Vinci wrote in a code backward in the mirror . . . in some kind of cipher." He died believing he had sacrificed his legacy to be the first biologist to give a complete description of life. Perhaps, he did. Fortunately, for this Special Issue, he was more forthcoming when publishing his views on complexity.

Fundamental to Rosen's thinking on complexity, was his distrust of reductionism as well as the associated Newtonian paradigm and its role in science. Science has essentially been an application of reductionist methods with a focus upon parts, not wholes, buttressed by the problematic assumption that parts can simply reconstitute the whole whenever necessary like manufacturing a machine. There is also the sticky detail of the 'final reduction', which has neither been proven nor expected to be proven. When a system is reduced, this obliterates many system-level properties, interconnections, and feedback relationships that determine overall system organization, behavior, and integrity. Rosen (2000) concluded, "The essence of reductionism is, in a sense, to keep the matter of which an organism is made and throw away the organization". Emergent properties such as consciousness and life can only be found at the whole system level; they arise from the organization itself and are not reducible to a list of chemicals or a tally of cell types.

For much of the 19th and 20th centuries, biology was viewed as an inferior and a less rigorous science as compared to physics and chemistry, which demonstrated rapid and repeated successes (Speyer, 1994). In these 'hard sciences', several 'laws of nature' were formulated. When physicists construct laws of nature, they focus upon the narrow confines of extreme regularity by identifying invariant relationships with minute error terms. This is not 'nature' in the biological world, which is rich in variation and exception. It is not surprising that biologists to date have not identified a single law of nature. Biology, which came late to the Newtonian paradigm, approximately in the 1930s (Rosen, 2000), for decades was reluctant to discard its adopted paradigm believing that organisms are machines and reductionism is the best way to understand them (Ulanowicz, 1999). Biologists also adhered uncritically to the 'unity of science' principle in which biology is subsumed under chemistry and physics, which eventually will explain all biological phenomena. This is proving to be a proverbial dead end because biological systems are open. Poli (2013) concluded that "science is for the most part a set of techniques for closing open systems in order to scrutinize them." Relying upon physics, which deals with closed systems, does not seem to be a feasible way forward for open biological systems. In contrast, Rosen was convinced that the methods of physics would never be adequate for biology. His criticism of reductionism was not that it is wrong and should be abandoned; on the contrary, it has been central to science for hundreds of years, and it is the methodology of choice for simple systems involving mechanisms. Its successes are unparalleled. In contrast, the problem is that living systems and "life itself" are complex and not generally amenable to reductionist approaches except for their most simple and mechanistic components.

Despite all of the success in physics and chemistry, reductionism is increasingly inadequate for answering many biological questions especially ecological ones relating to the urgent environmental crisis that threatens our survival. Weinberg (2001) concluded that science appears so successful because it poses questions that it can answer, yet meanwhile; the very difficult ones pile up dangerously high and threaten to suffocate our potential. Existential risk grows daily for *Homo sapiens sapiens* and the rest of biodiversity, because in part, "science has failed us" (Levins, 1996). In biology and ecology, reductionism is more like a bottomless sinkhole swallowing up our capacity for understanding holistic living systems, then a route to enlightenment.

Rosen predicted the 21st Century will be the 'Age of Biology'. He believed that complex systems are more general and numerous than simple ones, and that biology will become the main trunk of the tree of science in the 21st Century by subsuming physics and chemistry as simple fruits hanging upon its lower branches (Rosen, pers. comm.). The goal of Rosen's life's work was essentially to understand life, and in so doing, to free biology from the shadow of physics and chemistry, and their mechanistic foundations. In his book entitled 'Life Itself' (1991), Rosen asked the question: "How can all the novel features of life be understood by reducing living systems to inanimate ones". He worked continuously to expunge the restrictive Newtonian paradigm in biology because a complex system, such as an organism, has more "causality than can be accommodated by a mechanism" (Rosen, 2000). To Rosen, "the machine metaphor is not just a little bit wrong; it is extremely wrong, and must be discarded", (Rosen, 1991). Thus, Rosen's work constitutes a direct challenge to those who advocate the relevancy of the Newtonian paradigm in biology. In essence, he was a key creator of the new road map for radical conceptual change or paradigm shift in the biological sciences.

Some have considered Robert Rosen to be the 'Newton of Biology' (Mikulecky, 2001), but because he worked so tirelessly against the Newtonian influence in biology, he might not have liked that title. He is similar to Newton, however, in that his scientific contributions may be regarded as monumental by future generations. I prefer to think of Rosen as a 'Biologist's Biologist' and one who always ventured into the unknown with his high beams on.

Today, biology itself is rapidly changing and many believe there is a large paradigm shift underway termed the 'Biological Revolution', with complexity at its center (Baluška and Witzany, 2013; Strohman, 1997; Weatherall, 2008), although authors differ in their opinions as to how radical the changes are or will be or even should be (Woese, 2004; Wake, 2008). Biology is finally asserting more independence from physics, in large part because of the progress made in focusing upon the central role of complexity in living systems, and the failure of the Newtonian paradigm to explain it – a large pebble in the shoe that Rosen sought to remove. This idea is gaining proponents, for example, Henning and Scarfe (2013) assembled a set of authors to "put life back into biology" in their book: Beyond Mechanism. With this detour into Rosen's thinking, let us return to Rosennean Complexity, which is introduced next, but is explained in much more detail in the subsequent contributed papers. It is clear that the 'Age of Biology' will happen faster and easier if we take the right road.

4. The less-travelled road (Approach 2): Rosennean Complexity

Rosen (1977, 1978, 1985, 1987) originally defined complexity not as an "intrinsic property of a system but . . . as a function of the number of ways in which we as observers can interact with the system and the number of separate descriptions required to portray these interactions". Over time, he refined his definition as follows: "a system is simple if all its models are simulable (computable). A system that is not simple, and accordingly must have at least one non-simulable (non-computable) model, is complex" (Rosen, 2000). Simulable models are essentially Turing-computable (Turing, 1948, 1950). Rosen (2000) believed that "simulability mandates an extreme degree of causal impoverishment." In contrast, a complex system contains loops of entailment, that is, has complex models (Baianu, 2006). "Whereas Rosennean Complexity is relational and not a property of the system per se, it is also open-ended in that there is no upper-limit to how complex a system can be constructed, and therefore, no apparent limit to what characteristics such systems might have," (Gwinn, 2015). Rosen (2000) concluded, "A system is complex if it has non-computable models-this characterization has nothing to do with mere complication or with counting of parts or interactions, such notions, being themselves predicative, are beside the point." Thus, models of complex systems are non-simulable and non-computable, and these systems are impredicative, self-referential, and have a purpose, which is similar to Aristotle's final cause. Traditional science has had difficulties with the notions of teleology and purpose. Rosen did not; he concluded: "Complex systems are also unlike simple ones [in that they] admit a category of final causation or anticipation, in a perfectly rigorous and non-mystical way" (Rosen, 1985).

In summary, Rosennean Complexity is binary; there are only two types of systems: complex and simple without intergrades or degrees of complexity. Furthermore, complexity cannot be describe, measured, created, computed, or simulated; it is totally incompatible with Approach 1. While in one sense, Rosen's approach evokes both difficulty of description and computation since it posits upon the premise that complete description, measurement, and simulation etc. are impossible, its true focus is upon the interaction between the observer and the system, and the encoding and decoding between the real world of natural systems and the formal or mathematical world of model systems (Rosen, 1991, 2000). The divergent directions of these two approaches constitute the "fork in the road" based upon studying simple versus complex systems. Travelling on one cannot get us to the other; in fact, to Rosen, no amount of studying simple systems can help us understand complex ones.

5. Why should choosing the right road matter to ecologists?

Ecologists have disagreed about ecosystem complexity. For example, the Community Structure Controversy has been debated for a century. Clements (1916) proposed the Superorganism Concept that communities are highly structured like organisms. In contrast, Gleason (1926) promoted the Individualistic Concept, which views ecosystems as random assemblages of species with similar tolerance curves, fortuitously coexisting in space and time. This latter view questions whether ecosystems are systems let alone complex ones. Most ecologists, however, would agree that ecosystems are not a pile of insert 'p', word should be particles like a sand pile. Other ecologists chose not to define ecological complexity and simply declare that ecosystems are inherently complex as a self-evident truth (Levin, 1998; Montoya et al., 2006). Ecosystems appear to be complex even if they have not been well-defined in terms of Rosennean Complexity; ecosystems are also undoubtedly complicated (Lane, 2016).

The "fork in the road" for complexity is significant because it is so intricately tied to the Biological Revolution, which will extend far beyond ecology and even biology, to all of science in the 21st Century. If Rosen and supporters of Rosennean Complexity are correct in their definition of complexity, then this logically leads to the conclusion that much of Approach 1 described above is not about complexity, but probably complication, which can be described, created, and measured, often in exhaustive detail. While there are no degrees of complexity for Rosennean Complexity, there can be degrees of complication. Even Rosen (2000) acknowledged that "it is probably too late to change this terminology now, but I would much prefer to use a word like complication rather than complexity". Researchers, however, have been rather dismissive about complication as a cheaper second-class mode of passage and most state they are studying complexity. Thus, the prevalent and favored use of complexity terminology is problematic, but even more so are the conceptual difficulties.

As the complexity literature accumulates and the Biological Revolution unfolds, confusion will increase without a clearer delineation between these two approaches. How harmful is it if investigators are working on ecological complication, but think it is complexity? How much fog can persist on our journey without major collisions and unintended consequences? How much roadkill can we tolerate? While Rosen was an extremely clear and accomplished writer, his material is mathematical and difficult; and he is no longer here to explain his concepts and conclusions. Many ecologists are also unfamiliar with his work since he seldom published in ecological journals or addressed ecological issues. To 2015, there were only eight papers that referred to Rosen's work published in Ecological Complexity. Five included a more or less cursory reference and only three papers featured his work prominently. This overall coverage is insufficient for most ecologists to understand the "fork in the road", make an informed choice, possibly adjust their research itinerary, and mode of passage.

In conclusion, we have come to the "fork in the road" in considering ecological complexity. The choices and consequences associated with this decision point are discussed in the following papers.

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