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Short Note

The road ahead for Rosennean Complexity☆,☆☆

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1. Introduction

To end the Special Issue (SI), it is useful to recall that its original purpose was to "call attention to this 'fork in the road' (Frost, 1916) and to suggest that the less travelled road of Rosennean Complexity (RC) deserves more exploration, especially by ecologists. My objectives in this paper are twofold: first, to point out that Rosen's legacy is revolutionary, much larger than complexity theory *per se,* and indicative of his character and scientific integrity. This SI is being published on the 20th anniversary of Rosen's death, which evokes an added historical perspective on his legacy and the remarkable man behind that legacy (See Section 2). He was a good friend and colleague for more than 20 years and I include some personal observations in this section. Second, I summarize some of the key suggestions, examples, criticisms, and applications of Rosennean Complexity (RC) discussed in the Special Issue that together constitute some useful advice for the Road Ahead for ecologists (See Section 3). Contributing authors were invited to provide a range of disciplinary viewpoints of the applicability of RC to ecology.[1] The breadth of approaches of the 23 contributors reinforces Rosen's applicability to many areas of interest to ecologists. The authors suggest how ecologists might build bridges between Rosen's work and these other areas both explicitly and by example. While it is impossible to get 23 people to agree on anything, agreement was not the goal. No two of the papers are similar. Therefore, the SI does not read like a textbook by a single author who systematically expounds a thesis from first principles, but rather as a collection of diverse and even conflicting ideas, which is consistent with the original vision. Every paper, however, gives encouragement to ecologists to venture down the 'less travelled road'.

The journey to the destination of ecological complexity will not end with this SI; in fact, there is much road ahead. If anything, the SI has raised even more questions about how ecologists could best venture down the 'less travelled road' if they chose to pursue RC. Some of the questions are difficult and do not have easy answers, but the 'asking' cannot be avoided. Asking the right questions in science is half the battle – perhaps the more important half, and difficult questions without apparent answers can motivate creativity and progress. Rosen was a master at asking the right question even when he was criticized for asking questions that no one cared about (Rosen, 2006). To be sure, he also did not shy away from asking extremely difficult questions, starting with "what is life?" He termed this the central question of biology (Rosen, 2000) and of his career, so much so that he called it his "Imperative" (Rosen, 2006).[2] He realized that to ask this question was, "to find oneself standing essentially alone" (Rosen, 1991).

'What is life?' is such a difficult question that most introductory biology textbooks avoid answering it entirely; for example, in Campbell Biology (Reece et al., 2014), the eleven authors described the 'living' using over 1500 verbose pages, but they did not attempt to define life. Instead, they provided only a list of non-unique features of living systems. Rosen did not believe such lists are very helpful. He said: "despite the profound differences between those materials systems that are alive and those that are not, these differences have never been expressible in

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[1] When Special Issue (SI) papers are referenced in this paper, the citation appears as follows: (Author, 2018, this issue).

[2] Rosen always capitalized 'Imperative'.

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the form of a list – an explicit set of conditions that formally demarcate those materials systems that are organisms from those that are not. Without such a list, Schrödinger's question, and biology itself, becomes unanswerable at best, meaningless at worse so we must probe more deeply into what the quest for such a list actually connotes. No such list means there is no algorithm, no decision procedure, where we can find organisms in a presumably larger universe of inorganic systems. It has, of course, never been demonstrated that there is no such list. But no one has ever found one. I take seriously the possibility that there is no list, no algorithm, no decision procedure that finds us the organisms in a presumptively larger universe of inorganic systems. This possibility is already a kind of non-computability assertion, one that asserts that the world of lists and algorithms is too small to deal with the problem, too non-generic" (Rosen, 2000).

Curiously, it seems we discourage biology students from asking this central question at their earliest stage of professional development. When Rosen would lecture to my classes, the students became entranced as he outlined the shortcomings of measurement, the richness of complexity theory, the virtue of qualitative relationships, the vice of preoccupation with 'matter', and the meaning of life. His ideas were completely foreign to their whole nascent academic experience of quantification and reductionism. He summed this up in Rosen (2000) as follows: "I am always asked by experimentalists why I do not propose explicit experiments for them to perform, and subject my approaches to verification at their hands. I do not do so because, in my view, the basic questions of biology are not empirical questions at all, but, rather, conceptual ones…" Yet, biology professors teach that experiment, measurement, and statistical testing are the most essential ways to 'do science'.

In summary, it is difficult to pick up a single thread of Rosen's work like RC and to discuss it as if it was an isolated concept because it is fully embedded into a much larger conceptual framework that is beyond the scope of the Special Issue, but of all the threads, complexity is a good one to start with, however, it is not the whole answer to what is life. Rosen said that "for a material system to be alive, there is a necessary condition that it be complex, but this is not a sufficient condition" (Rosen, 2000). The best way to understand his total framework is to study his publications and some suggestions are given in Section 4. I have not found any shortcut to this understanding.

2. Rosen's revolutionary legacy

2.1. Scientific Revolutions

Science has had a long history with revolution when the First Scientific Revolution began with Copernicus' 1543 publication on "The Revolutions of the Heavenly Spheres", which eventually led to the Newtonian Paradigm. The latter has permeated most of human endeavors, even beyond science itself, from the Enlightenment to Modernity and Postmodernity. The Newtonian Paradigm, while successfully applied to physical systems, has failed in biology (Kitto and Kortschak, 2013). Some, like Rosen, have proposed a Second Scientific Revolution that will emanate from biology in the 21st Century. It can be termed the Biological Revolution or the Biological Complexity Revolution (BCR). Rosen advanced the notion that biology would become the central trunk of the generic tree of science, with other sciences like chemistry and physics serving as non-generic branches of the tree. He pointed out: "At present, the fact is that there is still no inferential chain which leads from anything important in physics to anything important in biology" (Rosen, 2012). He spent a great deal of time imagining the future, especially his vision for the future of science.

Scientific revolutions begin after tiny cracks appear in the prevailing paradigm, which eventually turn into large fissures (Kuhn, 1970). Rosen consciously accelerated this process and he did this with meticulous integrity. At every opportunity, he took his intellectual sledgehammer to the Newtonian Paradigm that portrayed biological systems as machines and he cracked it in as many places as possible. He was a prime mover in this current scientific paradigm shift and his work will undoubtedly continue to illuminate the way throughout this century. The BCR has the maturing of complexity theory at its center especially for biological systems. This is our present. I cannot identify the exact day the first hairline fracture blemished the Newtonian Paradigm in the past, nor can I predict when its replacement will fully manifest in the future, but I do know that Rosen's vision continues to take hold, increase in momentum, and gain adherents. Paradigm shift is never easy. It is extremely difficult for a scientist who has so much invested in a prevailing paradigm to shift their conceptual foundation, and even identity, to embrace a new one. Kuhn (1970) concluded that most paradigm shifts in science come about as the believers in the old paradigm die out. It appears that scientists, like everyone else, wrap themselves in their paradigms like protective shrouds, smug and threadbare to the end. Nothing is more comforting, until that comfort is no longer required. Thus, paradigm shifts tend to be generational. They can encompass all of science like Rosen's proposal or have a smaller scope.

No one knows what science will be like in 2100, but the cracks in the old scientific paradigm seem too large and irreversible to end the 21st century with biology under physics. The latter could assume a reduced role for simple systems as its proponents expire or cease trying to treat open biological systems as if they are closed. Science, however, has taken many enigmatic turns in the past, and it is a far more subjective and social undertaking than most of us would like to admit. Progress is rarely an upward linear trajectory, and in the limit, there is no absolute truth. Science is always flawed and imperfect, always seeking the next truth, however transitory. The exhilaration of the search, however, can be addicting.

Scientific revolutions in the making can also have adverse consequences for the scientists who promote them. The First Scientific Revolution was certainly dangerous for its participants as the Roman Catholic Church sought to quell it. For example, Galileo stood trial for heresy in 1633 and ordered[3] "to abandon his doctrine, not to teach it to others, not to defend it, and not to treat of it". He was not officially exonerated by the Church until 1992 when Pope John Paul II concluded, "Thanks to his intuition as a brilliant physicist and by relying on different arguments, Galileo, who practically invented the experimental method, understood why only the sun could function as the center of the world, as it was then known, that is to say, as a planetary system. The error of the theologians of the time, when they maintained the centrality of the Earth, was to think that our understanding of the physical world's structure was, in some way, imposed by the literal sense of Sacred Scripture…" (Pope John Paul II, Ibid). Clearly, it takes more than a match to burn down a nascent paradigm or a belated apology to absolve one. Similar to Galileo, Rosen focused upon moving the center of science from physics to biology by demoting the former to be the keeper of the specific and simple, while anointing the latter as the true center of science and the keeper of the general and complex.

To initiate a revolution is neither a blasé endeavor nor a random happenstance; it takes purpose and planning to change the culture of communal wisdom permanently. Some of our best scientists throughout history have been ardent revolutionaries,[4] and Robert Rosen is no exception. Revolution is clearly not for milquetoasts, and most share an incredible passion to change science for the better. They usually exhibit a remarkable focus in pursuing their mission, and clearly, Rosen's mission was to ensure that living systems were no longer to be considered as machines. He wanted to explain what makes one bit of matter alive and another inanimate. While scientists no longer fear incarceration or burning at the stake as occurred in the First Scientific

[3] Pope John Paul II, L'Osservatore Romano N. 44 (1264)–November 4, 1992.

[4] Lynn Margulis and Jane Jacobs are two other revolutionary scientists mentioned previously (Lane 2018b, this issue).

Revolution, current scientific adversity can take many forms: unfair criticism, ostracism, funding and publishing constraints, unethical peer review, administrative interference, research center closure, job loss, etc. Rosen certainly had to work in some very disagreeable academic conditions at least three times in his career often with little appreciation, and even when these adverse conditions defeated some of his colleagues (Nadim, 2012). Despite the hardships, Rosen was unwavering in his right to pursue his revolution.

2.2. Rosen the revolutionary

Obviously, given the downsides, no one chooses the revolutionary path for its convenience. It has been my experience that true revolutionaries are a different sort of person. They are stubborn purists, often extremely so – their dedication demands this. Rosen was such a purist in being an honest interpreter of nature, dedicated to his mission, and unwavering in his commitment. He embarked upon his revolution with great purpose and a well-designed mental roadmap for each leg of his journey. There was no happenstance in his approach. He scrupulously began with first principles to build upon a solid conceptual subsurface. To Rosen, science required a paradigm shift, if he was to achieve his Imperative. To an ardent revolutionary, failure is never an option, in fact, most revolutionaries treat failure counterintuitively as a wellspring of opportunity. This type of person is fearless of personal consequences, hard-working, and will suffer considerable aggravation, if not abject ridicule. Any disagreeable aspects of a revolutionary's condition are eclipsed by the enthusiasm they radiate for their cause with life long exuberance.

Thus, Rosen was a man consumed with passion to set science on its rightful path and in every way as revolutionary as the proponents of the First Scientific Revolution. He acknowledged this passion when he explained, "I have never regarded my attachment to science as constituting in any conventional sense a 'career' or vocation or job… It is more akin to what theologians refer to as a 'calling' something which would be corrupted and defiled by being subordinated to any such personal considerations as constitute professional aggrandizement" (Rosen, 2006). Nadin (2012) described Rosen as an 'activist' and a 'radical' in how he questioned existing scientific premises. Everything he did was directed toward establishing the complete abrogation of the Newtonian Paradigm for complex, living systems. Overthrowing 500 years of scientific tradition and conceptualization is a challenging undertaking. He did not seek to decapitate or bury the Newtonian paradigm, but rather to restrict it to simple nonliving systems, and thus, end its distorted and even absurd grip on biology. To Rosen, the idea that life is only a machine, and a detailed analysis of its parts could reveal the whole, was an anathema.

While Rosen had a singular intellect and extraordinary memory,[5] he also had many academic roots. All scientists have an academic genealogy and mentors who influence their early development. No one's ideas spring *de novo*. By the time one is ready to have scientific ideas, one's mental blackboard is filled with the scribblings and chalk dust of legions of previous thinkers. In that sense, all scientists are people of their times. Rosen (2006) acknowledged several main influences on his work such as Nicolas Rashevsky, Edwin Schrödinger and his student Max Delbruck, Norbert Weiner, Claude Shannon, Ludwick von Bertalanffy, Ross Ashby, James Danieli, Saunders MacLane, and Samuel EiIenberg. I would add Howard Pattee and Robert Hutchins. Rosen, an accomplished painter of seascapes, used an artist's metaphor to explain these influences. He said, "to me, though, and in the light of my own Imperative, all these things were potential colors for my pallet, but not the pallet itself. I regarded them as monochromes, individually perhaps lovely in themselves, but not to be applied when a different hue was required. I could not share the prevailing sentiment that these developments, either individually or collectively, would paint themselves into the picture I was striving after. Rather, I felt it was the picture which would illuminate them" (Rosen, 2006). Whereas Rosen incorporated these influences, the paint was applied with his own brushstrokes and his resulting masterpiece was his alone.

A small description of the man might help elucidate his revolutionary contributions. He possessed the 'just right' set of skills and abilities for his life's work and for his time. He was both an accomplished mathematician and superb biologist as well as being knowledgeable about modern physics and chemistry. He was a transdisciplinary thinker long before the term came into vogue. He was also a very clear communicator in both speaking and writing, as clear as he could be given the depth of his subject matter. He normally did not heavily edit his manuscripts, and the first draft was often the final draft. I once edited one of his books and in several hundred typed pages found only three or four small grammatical errors. He would simply think about a subject, organize it in his mind, and effortlessly commit his thoughts to paper as if he was having a conversation with the reader. He lectured without notes as effortlessly as one might make small talk about the weather. Of course, he didn't often make small talk.

Rosen was self-confident, but not in an arrogant way, but neither was he overly modest. He acknowledged his capabilities realistically, and he didn't apologize for them. He did not suffer fools in any positive way, and certainly not gladly. He once said his colleagues will only understand about 15% of his work and not the same 15% across all of them (Rosen, 1997). This should motivate all of us to read his work as carefully as we can. He essentially left no academic clones of himself who could make his unique transdisciplinary contributions, but he did leave heirs such as his daughter, Judith Rosen (2012), who has increased the availability and interpretation of his published work as well as his former Ph.D. student, H. Aldoios Louie, who has significantly improved upon the mathematical understanding and application of Rosen's use of relational biology and category theory. Without either of them, Rosen's contributions would be much more opaque than they are now.

By nature, Rosen was a solitary creature. He attended one to two academic meetings a year; but he didn't undertake lecture tours nor popularize science for the masses. He was selective with his encounters with others because he was careful not to waste time; his mission and his Imperative were always the priorities. By the 1990s, certainly a part of his isolation was the urgency to bring his ideas to publication despite his failing health. I also think he enjoyed his own company when he could unleash his mind to range freely. He often said "I let the problems tell me what to do" (Rosen, 2012). Whereas he often preferred to be alone, I don't think he was lonely, at least not in the way many people are. Revolutionaries have a strong independent core. When he wanted company, he could always find it, but only when a break in his work schedule was convenient. His best friends were respectful of his creative space and his priorities. I would be dishonest, however, to not admit that to watch his mind at work, to be able to interact and spar with this unique intellect, to learn about his progress, and to have him explain his vision of the future of the biological sciences was a true delight. I enjoyed peppering him with questions, and while he was never reluctant to say "I don't know" or "I'm not sure", those times were few – most often when I pressed him about ecological systems. Usually he provided detailed answers that required considerable processing on my part between our conversations.

Rosen believed that it was "his duty to report" his scientific findings regardless of the tedium of explaining what to him was obvious. Despite his prolific publication record, he is not that well known in many areas of science. After analyzing Rosen's publication citation statistics until

[5] As an example of his memory, I remember one night we watched an old-World War II movie: "Patton" with U.S. 4-star General George S. Patton, played by George C. Scott. Rosen recited each line in English, German, French, Italian, and Russian before the actors spoke and he had only seen the movie once, years earlier. Thus, I saw the movie once and heard it twice. He was fluent in several languages.

2009, Nadin (2012) concluded that Rosen did not promote himself very well, he was mostly quoted indirectly, and his recognition does not match his accomplishments. We all know scientists who are better at self-promotion than actually doing science; the Internet has facilitated this annoying phenomenon by providing far too many electronic tools for this activity. All too often mediocrity and self-promotion are highly correlated. This was not Rosen's approach. For him, science was a serious and even noble endeavor, and there was no place for game playing or petty rivalries or self-promotion. He was not interested in politics at any level. If his work was his first priority, then how he comported himself was his second. He simply relied upon his published work to make his case. He said, "I am not by nature a proselytizer; but my reports are out there, for others to make of it what they will" (Rosen, 2006). For Rosen, it was the right thing to do; science had to be conducted with pure integrity. In this, he was noble, but perhaps also a little naïve. Unfortunately in science as well as life, the cream and the noble do not always rise to the top. Rosen is a unique case in which a little more self-promotion would have been a good thing for the rest of us, and of course for science generally, but that was not his character. As he said, "…my nature is not that of a preacher or advocate" (Rosen, 2006).

In terms of the SI, it is important to remember that Rosen's central question-his Imperative was 'what is life?' and not 'what is complexity?' (Rosen, 1977,1978,1985,1987,1991,2000,2012). He said, "…complexity, though I suggest it is the habitat of life, it is not itself life. Something else is needed to characterize what is alive from what is complex", (Rosen, 1991). Answering his Imperative led him through a transdisciplinary labyrinth of observation, conceptualization, logic, and modeling that encompassed many different areas. He had a brilliant insight into everything biological. In no particular order, he made many contributions to: relational biology, use of category theory in biology, criticisms of the Newtonian paradigm and the machine metaphor in science, theory of modeling and the modeling relation, metabolism, repair or replacement (M, R) systems, optimality theory, dynamical stability, biomathematics, biophysics, measurement and observation, anticipation-feed forward, general systems theory, senescence, and the philosophy of science. Even this listing cannot be considered complete. He developed the concept of MR (metabolism, repair) systems largely for cells and their associated mathematical formalism, not ecosystems (Rosen, 1991; Cárdenas et al., 2018, this issue). He distrusted measurement in science and the associated disruption in systems caused by observers and their meters (Rosen, 1978). He authored a book on anticipation and feedforward – about how organisms could read off of the future (Rosen, 2012), in which he concluded: "In order for a system to be anticipatory it must be complex" (Rosen, 2012).

This SI focuses upon only a subset of Rosen's contributions for Rosennean Complexity, but to be fully understood it should be studied in this broader context of his total work.[6] Among scientists, he is also unique in his long term focus on his single central question. Most of his academic effort went into answering that question, and thus, his overall effort was very systematic and comprehensive. It appears he also tried to anticipate all criticisms of his work, which resulted in a solid bulwark of ideas. As Rosen (2006) explained, "if it is I believe, my scientific work constitutes a single unity, then that unity reflects the mandates of the underlying unified problem with which I have been concerned" . As a visionary, Rosen understood what science could be, and how truncated and overreaching it had become. He was, and continues in death, to be a leader of the BCR. His role and contributions will become clearer with time. Many authors and reviewers contributing to this SI also have important roles to play in the BCR, some building directly on Rosen's work. Certainly, Rosen also had critics and those proposing alternative views. For example, Howard Pattee (2007) and Cottam et al. (2007,2016,2018, this issue) have been critical of some of Rosen's ideas, have offered alternatives, and have sought to build on others. Whenever these authors have made criticisms, however, they been constructive, and they help illuminate the journey. See Section 3 for discussions of some of these criticisms.

In summary, there are many reasons why ecologists have not made as much use of Rosennean Complexity as they could have, which the authors of the Special Issue hope are at least partially addressed with its publication. First, Rosen's focus was on 'what is life', which is seldom an ecologist's focus, and for Rosen, complexity became necessary to answer his question, but it was not his primary interest. Second, Rosen worked largely at the cell/organism level and wrote sparingly about ecological systems. Thus, he did not provide many ecological examples or applications. Part of his preference for the non-ecological areas was his training, but he also attempted to answer his Imperative in the simplest way possible, which meant using the smallest units in biology with the most direct genetic relationships, e.g. 1 gene: 1 protein. Third, he did not have a penchant for self-promotion and found it demeaning. The Internet was relatively new when he died. Fourth, he worked largely alone with very few co-authors or references to other papers. Fifth, both his biology and mathematics are deep, and require effort to understand. Gaining an overview of even the main points of Rosen's work is difficult to achieve in a leisurely afternoon. Sixth, paradigm shift is incredibly difficult. Many scientists never change their guiding paradigms during their lifetimes. Rosen proposed a major refocusing on what science is and how it should be conducted. Most scientists, including biologists and ecologists, currently working, have been trained within the Newtonian paradigm and all that entails. Seventh, as an anonymous reviewer pointed out "there are many institutional barriers to how we teach and fund science, and operational ones such as the availability of easily-applied tools for addressing questions of immediate concern using Rosen's ideas". This is probably not a complete listing, but it contains several points made throughout the Special Issue.

3. The road ahead

In this section, each paper in the Special Issue is summarized in order of its appearance, and aspects that inform RC are emphasized. The contributing authors illuminate the Road Ahead in many ways: defining and clarifying Rosen's ideas, providing ecological examples and interpretations, and extending Rosen's work to other areas associated with ecology. In addition, they discuss several topics of relevance to ecologists related to organisms and their environments, population and ecosystem phenomena, hierarchical considerations, and notions of ontology and evolution in terms of RC.

In the first contribution, Poli (2018, this issue) explains Rosen's key comparison of simple (predicative) and complex (impredicative) systems. He proposes that while science has dealt with predicative (closed physical) systems very successfully using analytical and reductionist approaches, it has not been successful with the more generic natural, cognitive, and social systems that are impredicative. To Poli, "reductionism works when a system can be fragmented without a loss of information". Neural nets, social structures, and food webs are not fractionable, and cannot be explained by a single description. Vandermeer and Perfecto (2018, this issue) provide a real-world example of this using their coffee food web. To reduce impredicative systems is to lose their essence. In addition, predicative and impredicative systems are not interchangeable, and one cannot be transformed into the other through simple addition or subtraction of parts. Like Rosen, Poli predicts that as science addresses impredicativity, it itself will be transformed in the 21st century – essentially the Biological Complexity Revolution (BCR) described previously. Poli indicates that impredicativity is the "next paradigmatic frontier of science" in which, "open, non-fractionable, irreversible, non-deterministic, and context-dependent systems" will become the new focus of study that will

[6] In my own library, I have accounted for approximately 270 journal papers, eight books, some unpublished works of fiction., and an unpublished (I believe) book manuscript entitled, "Relational Biology" by Rosen.

necessitate new formalisms and mathematical approaches. He also provides careful definitions of these terms as well as a useful framework of their main characteristics and interrelationships. He stresses that ecology is especially conducive to Rosen's relational biology, which attempts to provide new insights into impredicative systems that contain self-referential loops, are fully or partially closed to efficient cause (CLEF) within hierarchical cycles, and which exhibit anticipatory behavior.[7] He concludes, “apart from biology and sociology, ecology is the ideal discipline to explore relational frameworks because it is already about relations between local organisms and various nonlocal environmental, ecological, and social contexts” (Poli, 2018, this issue). In terms of sustainability, he suggests that Rosen's approach to complex systems can lead to the identifications of patterns of system persistence and resilience that are in essence ‘sustainable’ (see also Wells, 2018, this issue). Thus, Poli's paper provides not only clarity in definition and explanation of Rosennean Complexity (RC), but also a strong rationale and encouragement to ecologists to explore and develop RC for ecological systems and associated transdisciplinary subjects like sustainability. See also Poli's (2017) “Introduction to Anticipatory Systems”.

In the next paper, Cárdenas et al. (2018, this issue) make several suggestions about how Rosen's ideas could be used in ecology. They include many helpful real-world biological examples that illustrate how Rosen's theory works with living systems. After contrasting complex and complicated systems, they give an in-depth analysis of Rosen's category-theoretic models of (M, R) systems or metabolism/repair-replacement systems for the cell and molecular levels. With this modeling methodology, Rosen was able to show how ‘closed to efficient causation (CLEF)’ works as a central feature of all living systems. The authors point out that metabolic closure necessitates that “one catalyst… needs to catalyze more than one reaction… [and that] less than perfect specificity of catalysts may be an absolute necessity for life”. There is no external efficient cause – no carpenter that builds the cell. Thus, cells make everything they require such as the enzymes necessary for life. The authors also explain how downward causation or control by a higher agent does not work in living systems since “everything depends on everything else”. They provide an overview of other theories of life (autopoiesis, chemotron, etc.) contrasted to Rosen's as well as an insightful discussion of Rosen's notion that CLEF systems cannot have computable models, which has been controversial with some authors. Cárdenas et al. (2018, this issue) suggest that (M, R) systems could be useful in ecology in explaining interactions among organisms, and they divide general symbiosis into competition and cooperation phenomena using bacterial examples. The authors provide two models of interacting (M, R) systems to illustrate a rationale for how organisms could form a superorganism by providing additional functions to each other at the biochemical level. Cárdenas et al. (2018, this issue) further suggest that metabolic control analysis (MCA) perhaps could be a bridge between biochemical networks and ecological ones such as food webs. Much of this discussion foreshadows Lane's (2018b, this issue) discussion of ecosystems as chimeras using marine plankton food webs. The authors conclude that “(M, R) systems have relevance to ecology”. At the end of their paper, they extrapolate this relevance to social systems. Like Poli, these authors have had a long and deep relationship with Rosen's ideas that have motivated and informed their research program in cell metabolism and the nature and origin of life at the biochemical, cellular, and unicellular organism levels. Thus, these authors provide more than valuable explanations and examples of how Rosen's ideas are useful across the biological hierarchy in that their careers have informed a larger development of science, which serves to motivate ecologists to participate in the BCR and to apply Rosen's ideas in their ongoing research activities and planning. As Cárdenas et al. (2018, this issue) observe after considering some objections Rosen might have to applications of his (M, R) systems, “nevertheless, the originators of the theory are not its owners, and cannot dictate how it might be extended to domains different from those that they originally had in mind. It is for researchers in the different fields to decide whether theories such as (M, R) systems or autopoiesis shed any useful light on their work”.

Approaching RC from the physical sciences, engineering, and informatics is the paper by Cottam et al. (2018, this issue). Over many years, like Rosen, these authors have created a unified conceptual framework for understanding living systems, which is inspired by RC, but also seeks to transform it while providing several novel features and concepts. The authors focus upon a new concept of a model hierarchy to include the more traditionally-defined compositional and subsumption hierarchies as well as heterarchy, which lacks hierarchical structure more like a network of cycles in a neural net (their example). They suggest that life's hierarchical structures have adaptive value since they facilitate an efficient response to environmental change. In contrast to some authors who consider hierarchies as mental concepts, these authors believe that they are real and essential for nature to function (See also Cottam et al., 2016 for diagrams of their model hierarchy and additional description.) Whereas Cottam et al. are well-versed in RC and their overall hierarchical model includes it, they also diverge in important ways and criticize some of his ideas (Cottam et al., 2018, this issue, 2016). For example, they have analyzed Rosen's (M,R) systems in detail (Cottam et al., 2007) and found them to be deficient in not representing ‘one to many mappings’ and using a one gene-one protein concept that has been rendered obsolete by current genetics. Rosen's goal was to illustrate the minimum model for an organism and not all its relationships, however, Cottam et al. (2018, this issue) concluded Rosen's representation is incomplete enough to only partially achieve this. They have reconstructed Rosen's (M, R) model as a model hierarchy (Cottam et al., 2007) of two partial hierarchies of extant levels and inter-level regions. They describe the inter-level regions as contextual depositories of RC that has been ‘dumped out’ or ‘squeezed out’ of the extant levels as they undergo simplification. This idea requires more elaboration for ecologists, and perhaps others. Their model hierarchy, however, also avoids downward causation that Cárdenas et al. (2018, this issue) found objectionable. The authors bring both hierarchy and environment into focus in ways Rosen did not. For example, the term ‘hierarchy’ does not appear in the indices of either Rosen's Life Itself (1991) or his Essays on Life Itself (2000), but it is not because he was unfamiliar with the concept as he published two papers on hierarchy in the earlier part of his career (Rosen, 1968,1969). More recently, Louie and Poli (2011) and Louie (2017) have also included hierarchical loops in models of Rosen's (M, R) systems. Common sense dictates that living systems appear to have some type of hierarchical structure, and that complexification cannot proceed *ad infinitum* without simplification. In addition, logic dictates that living systems as open systems are *a priori* always associated with an environment – essentially a context, and that there must be communication and information flowing between each living system and its environment. Thus, Cottam's work has immediate appeal to ecologists because of their emphasis on the relationships of organism and environment, ontology and epistemology, complexity and simplicity, the notion of hyperscale, and the roles of hierarchy and information in ecosystems. Also like Rosen's work, it is difficult for a reader to achieve the total overview via a single paper by these authors. Cottam and Ranson's (2018) forthcoming book entitled “Bridging the Gap Between Life and Physics” will undoubtedly help to consolidate their ideas in one place for the reader's convenience and enhanced understanding.

The next paper by Siekmann (2018, this issue), an applied

[7] Efficient cause comes from Aristotle's four causes: material, formal, efficient, and final, which Rosen referred to several times in his publications (Rosen, 1991,2000). Material cause is ‘what’ something is made of like wooden houses are made of wood. Formal cause refers to the plan or blueprint for the house. Efficient cause is ‘how’ the house comes about, for example, constructed by the carpenter; and final cause is the purpose or the ‘why’ of building a house, that is, to provide shelter. See Aristotle on Causality (2015).

mathematician, is useful for both bio-mathematicians and ecologists. For the former, his systematic discussion illustrates why mathematicians interested in living systems should pay attention to Rosen as well as explaining why many have not. For ecologists, Siekmann places Rosen's notions of modeling and simulation as well as the use of category theory within a larger mathematical context that most ecologists would not be familiar with. Siekmann's approach is helpful to gain an overview Rosen's mathematics and how some of these formalisms have changed with recent developments generally in biomathematics and more specifically in category theory. For example, many mathematicians use category theory to discover mathematical analogies across various areas of mathematics, whereas he concludes Rosen extended graph theory incrementally into category theory. Rosen was not looking for mathematical analogies *per se*, although he sometimes mentioned them in his lectures. The author goes further to question several of Rosen's assumptions and to examine some of the core ideas associated with RC including: (M, R) systems, relational versus mechanistic modeling, closure to efficient causation (CLEF), and even Rosen's definition of complexity in terms of a complex system containing at least one non-simulable model, although Siekmann does not explicitly address impredicative systems. He points out that mechanistic models are influenced by their purpose: why they were constructed, which is usually to provide insight into one aspect of a natural system. Siekmann (2018, this issue) also discusses how Rosen considered model components as black boxes and placed his emphasis on the relationships among them. He explains in detail how Rosen considered a model and the modeling process, and how these topics are approached by applied mathematicians using mechanistic models. He also extends Rosen's preference for relational models into current developments in networks and the Integral Biomathes program (Simeonov et al., 2012) for positioning the organism rather than the cell as the central focus of biology. He criticizes models at the organism level if they do not account for environmental exchange, which Rosen's models did not. This author's criticisms are thought-provoking, and together provide a balanced discussion of Rosen's contributions while motivating both biomathematicians and ecologists to become more familiar with Rosen's work especially as many others now work toward answering the central question of biology: “what is life?”.

The next group of authors includes both ecologists and social scientists (Allen et al., 2018, this issue). Their goal is to spare ecologists and other complexity seekers semantic difficulties in future journeys into ecological complexity. These authors explore and contrast Rosen's all or nothing definition for complex systems (Lane, 2018a, this issue) versus Joseph Tainter's concept of societal complexification over time. Many other authors have discussed degrees of complexity, but not Rosen. In their discussion, they also contrast notions of complex and complicated systems as well as the role of emergence. Like Rosen, they focus on epistemology and not ontology, using two intriguing examples of military logistics and genetic dominance. They identify a central problem in complexity definition and discussion, which is whether complexity is a material issue or is only a ramification of observing and analyzing material systems. They point out several pitfalls of assuming it is the former. They use an analogy of a staircase to explain complex (horizontal steps) versus complicated (vertical risers) systems, separated by edges of emergence. This analogy is also used to illustrate how an ecologist or other complexity seeker can reconcile Rosen's definition of complexity and Tainter's notion of a progressive temporal complexification societies, as a problem-solving adaptation analogous to climbing the stairs. When the society reaches the uppermost stair to be considered, its strategy fails as complexification becomes top-heavy and reaches a tipping point of being too costly. Thus, the authors can reconcile both concepts of complexity by distinguishing their respectively narrow and broad contexts, with the latter having a notion of progression in a temporal hierarchy although they do not discuss the latter term. Some of their analogy, however, is reminiscent of Cottam et al.’s hierarchical concept (Cottam et al. 2018, this issue) of interspersed levels of complexity and simplicity, and Allen is both a notable pioneer and master of ecological hierarchy theory (Allen and Starr, 2017). The authors conclude three important points: (1) [complexity] may pertain to material situations, but that does not make complexity itself material”; (2)” complexity is about purpose of the whole as it is captured in the constraints that relate the parts of each other to the wholes…models are always for some purpose or another”; and (3) “…pre-empting a massive waste of time in semantics is an important and practical matter”. These authors certainly provide useful advice on RC.

Vandermeer and Perfecto (2018, this issue), constitute a terrestrial ecological team who have worked broadly from theoretical ecology and modeling studies, to extensive field observations and applied issues like sustainability in the developing world, while tackling problems of equity and poverty. Their paper illuminates some key issues in ecological complexity by using concrete examples to explore the relationship of complex systems to simple and complicated ones, and to relate RC with dialectical complexity advocated by Levins and Lewontin (1985). They focus upon two of Rosen's ideas, first that in simple systems analysis (wholes to parts) and synthesis (parts to wholes) are reversible, whereas in complex systems they are not; and second, complex systems behave counterintuitively. Rosen also believed this. Ecosystems continually surprise us. The authors present two ecological examples: an apparently simple one of population dynamics in a *Tribolium castaneum* laboratory population and an obviously complicated one of pest control in a coffee agroecosystem food web in Latin America. First, *T. Castaneum*, the flour beetle, can be grown easily on flour in small shell vials, and it has been used for decades as a laboratory model for studying population dynamics and intra- and interspecific competition. The authors show how the system, while apparently simple, can exhibit complex behavior. Initially the models seemed to mirror reality, even chaotic reality, but eventually they did not, and the system was clearly not simple. The history of ecology is replete with studies of one and two species interactions under highly-controlled laboratory conditions that proved counterintuitive and surprising such as Gause's high alpha coefficients for simple yeast competitors or Park's discovery of predation and cannibalism in his *Tribolium* spp. competition experiments. Second, the authors attempt to separate out three major pest subsystems in the coffee agro-eosystem and are unable to isolate them successfully consistent with Rosen's idea that complex systems are not fractionable. They conclude that the coffee agroecosystem is RC as are ecosystems generally. They argue from the ecological relationships rather than from the mathematics. They also make a case for dialectical complexity that has some similarity to RC, although the former does not have the mathematical framework of the latter. Dialectical complexity suggests not that the whole is more than the sum of its parts, but that it is different from the sum of its parts (Levins, pers. comm.). Rosen would have agreed with this conclusion. Their book, entitled: Ecological Complexity for Agroecology (Vandermeer and Perfecto, 2017) explores these issues in more detail.

Lane (2018b, this issue) analyses Rosen's notion that ecosystems are chimeras, with components that self-organize into cooperative entities, which exchange functions and extend the overall capabilities of the whole. Ecosystem chimeras also have a purpose to survive and persist. The author employs a ‘Thought Experiment’ to understand how the marine plankton community in Narragansett Bay solves three survival problems: (1) securing matter and energy, (2) maintaining functional and modular integrity as a chimeran individual, and (3) manipulating time to ensure ecological survival and evolutionary persistence. She uses results from loop analysis, a signed digraph technique, to analyze the community's relationships and how they might trade functions. All living organisms are chimeras, some multiply so, which argues that trading functions is highly adaptive. In addition, all levels of the biological hierarchy contain chimeras – they are ubiquitous. If Rosen's notion is correct, then there are several implications for current evolutionary ecology, but especially that chimera construction and function should be studied at the ecosystem level using extant and complex ecosystems, and not at the population level that is more frequently viewed through the lens of niche construction and evolutionary theory. An evolutionary paradigm shift to a Complexity Synthesis is needed to fully encompass the ecosystem level that is qualitatively different from the more traditional population level. In addition, evolutionary theory needs to be focused upon survival adaptations not only genetic changes *per se*. Just as genetic phenomenon such as genetic networks and epigenetics are proving to enrich understanding of evolution with their complexity, ecological networks also imbue evolution and its processes with more complexity. This shifts the focus from gene frequency to survival aspects of evolution at the ecosystem level. RC is not conducive to synthetic analysis, that is, we cannot get to the ecosystem level by summing up population phenomena. Current evolutionary approaches emphasizing only the population level act as a brake on understanding how evolution works. Thus, a Complexity Synthesis approach would integrate multiple levels of complexity throughout the biological hierarchy. This would not negate the Modern or Extended Synthesis, but nor would it assume that complexity considerations can simply be added onto existing evolutionary theory. Complexity at the ecosystem level provides evolutionary insights that are not a simple extension of what exists today. This paper draws as many parallels as possible between RC and a real-world food web.

The next author, Peter Taylor, explores the interface between ecology and society (Taylor 2018, this issue). He begins by posing two puzzles for ecologists to consider. First, he integrates the notion of 'unruly complexity', based upon his book of the same title (Taylor, 2005), and May's (1972,1973) notion that ecological stability is inversely related to complexity in a randomly-constructed food web. In addition, diversity operates counter to stability.[8] May (1973) suggested that if such random networks persist, they may contain some non-random features. Of course, real world ecosystems are not random, and the proportion of biologically reasonable – not just mathematically possible networks is small, that is, the former (stable, non-random ecosystems) constitutes a very small subset of the latter (unstable, random ones) (Lane, 2016). In his first puzzle, Taylor asks "why has a constructionist view of ecological complexity been difficult for theorists to take up? He observes that many ecosystems add and subtract species over time. He relates his constructionist idea to recent work in food web assembly, niche construction, and computer simulation modeling of model communities. He notes that simulating natural communities "runs against the Rosennean view that what is interesting about living complexity is not simulable". In the previous paper, (Lane, 2018b, this issue) argued that if ecosystems are chimeras, then adding functional capacities to an ecosystem that facilitates survival and persistence of all community members would be favored, but not always in a straightforward manner. Adding a new species could expand the functional capacity of the whole system, but it could also be a functional substitute for a deleted species, which would not change overall complexity. Thus, it is not the number of species per se but their relationships and roles within their community that matter when all members are acting within a RC framework. That species are added and subtracted from an ecological community over time is not in debate, but how those additions and deletions can be viewed in terms of community stability and complexity is more complicated than merely their numbers. Rosen (2000) was also clear that there is an impassable threshold between simplicity and complexity. Taylor, however, is correct in pointing out that constructionist arguments have not been given enough attention in ecology. Second, he questions "what social implications should be drawn from the resulting view of complexity, especially when it holds that critical events cannot be predicted?" With this question, he is building on Wolf's suggestion that instead of looking at the structure of societies, "…what would follow if those units were to be explained as contingent outcomes of intersections among processes that implicate or span a range of spatial and temporal scales" (Taylor, 2005). He also argues that where the observer is positioned relative to the system matters, a subject key to Rosen and other authors in the Special Issue, e.g. Allen et al. (2018, this issue). Using the example of Holling's Adaptive Environmental Management (AEM) methodology, Taylor argues that there is a fundamental assumption that no model can be constructed that fully describes an ecological system. Rosen would also agree with this conclusion for ecosystems as well as all RC systems. Taylor (2018, this issue) concludes by asking the question "what would RC look like under such an inversion [as suggested by Wolf] – if the units showing RC were conceived as always making their living within intersecting processes, not well-bounded ecological systems?

Jennifer Wells, a transdisciplinary thinker, who works on sustainability issues across the sciences and the social sciences including the philosophy of science, discusses the knowledge gap between science (quantitative) and the social sciences (qualitative) via complexity theory by integrating ideas from both Robert Rosen and Edgar Morin. Rosen also addressed another gap between physics and biology. She cautions that we do not only have to mind the gap, but we also need to mend it. She believes that the prevailing paradigm rising from the First Scientific Revolution needs to be replaced with the Complexity Revolution – essentially a transformation in our knowledge system if social and environmental crises are to be resolved successfully in the Anthropocene – our present. At a minimum, the Anthropocene is a complex phenomenon, and in the limit, a very dangerous one. She points out that the planet is in overshoot, which is driven by "the whole dominant global social organization", which is limited by the current scientific paradigm. In contrast, complex thought… acknowledges characteristics of the world [that are] imbued with webs of feedbacks, network causalities, hierarchically enmeshed scales, enmeshed entailments, and dynamic interactions". She focuses on three concepts: paradox, pluralism and perspectivism, and gives relevant examples of each one. She stresses that since our world is relational and complex, our knowledge system needs to reflect reality and not an oversimplified mechanistic view of the world. She includes many ideas from Rosen's work on relational biology and system complexity, and fully documents how relevant his ideas are to our current social and ecological crises. Rosen also understood the importance of biological knowledge and social knowledge to one another. He recounted as a graduate student how his supervisor Nicolas Rashevsky had told him "that I would not be a true mathematical biologist until I had concerned myself (as he had) with problems of social organization. At the time, I had dismissed these remarks of Rashevsky with a shrug; but I later discovered…that he had been right all along". Later, Rosen would spend a year in 1972 as a Visiting Fellow at the Center for the Study of Democratic Institutions in Santa Barbara, California. The Center was founded by Robert M. Hutchins, also mentioned by Wells. Essentially, Rosen spent a very productive year in both minding and mending the gap. He (Rosen, 2012) discussed his foray into the social sciences and how he discovered homologies between social and biological organization especially relative to predictive models and the anticipatory behaviors of these systems. All of this was possible because he was competent in the use of relational models that stress how systems are organized and not the stuff they are made of. Wells systematically demonstrates by logic and example how in a world with a complex knowledge base, minding and mending the gap are possible using Rosen's ideas and those of other complexity thinkers. She provides a powerful rationale for why complexity matters to human well-being and survival. See also Wells (2013): Complexity and Sustainability.

Marinakis et al. (2018, this issue) discuss an interesting if not cautionary aspect of our technological future. The authors consider how the introduction of a RC cyborged ecosystem could be assessed by both experts and laypersons through posing scenarios for a terrestrial ecosystem. They define a cyborg as "an exogenously extended organizational complex functioning… as an integrated homeostatic system"

[8] Rosen (1971) also wrote extensively on stability theory early in his career.

after Clynes and Kline. In this ecosystem, the plants are sensors and the roots are computers, and the system is designed to operate on optimality principles – another subject Rosen thought deeply about (Rosen, 1967). That our future will be rich in technology is not in doubt. New technologies are being continuously created and adopted often with inadequate consideration of their risks. This is especially pertinent in countries like the United States that are currently undergoing massive environmental deregulation and disregard for science and expert opinion, while an increasing proportion of the economy is technologically-oriented. Rosen thought deeply about the interface between technology and living systems especially such as artificial intelligence and the creation of life. Part V of his *Essays on Life Itself* is entitled: "On Biology and Technology" and it contains five essays on this topic. The authors assume that their cyborged ecosystem is RC. They observe, "Rosen's definition of complexity is relevant here because it implicitly includes impredicative loops. If ecosystems are already RC, then a cyborged ecosystem introduces technology into these endless loops…" I think Rosen would agree with them and would consider it to be a chimera. He said, "chimeras are everywhere around us: ecosystems, social systems, and man-machine interactions; even chemical reactions can be thus regarded…our civilization has become replete with man-machine chimeras and even machine-machine chimeras, which manifest emergent functions their constituents do not possess" (Rosen, 2000). Their discussion extends Lane's (2018b, this issue) focus upon RC natural ecosystem chimeras to cyborged ecosystems with important considerations of purpose and function. Their paper also bridges an additional gap between life and technology, which relates to Wells' (2018, this issue) discussion of how our future planetary sustainability relies upon much minding and mending of gaps among disciplinary silos of knowledge generation and application. Marinakis et al.'s (2018, this issue) study identified similar risks by both experts and laypersons, which offers a degree of reassurance that some gaps can be bridged successfully.

4. Concluding remarks

The SI began by considering a complexity seeker on a two-dimensional flat plane and indeed Rosen himself seemed to give us only two choices: complex-simple, right-left, on-off, black-white, a kind of Boolean algebra for all systems. In the Introduction (Lane 2018a, this issue) a decision was needed at 'the fork in the road' between the well-travelled path (Newtonian Paradigm) and the grassy, less travelled one (Complexity Paradigm). Scientific revolutionaries like Rosen lead us down the less travelled paths. Someone once said that great leaders take us to places we would never go by ourselves.[9] This seems true about Rosen and his Rosennean Complexity. His work has much of value for ecologists. As he formulated a comprehensive approach to explaining life, he refined his explanation of complexity over time. Rosen's (1977)s paper on complexity began with a consideration of measurement and the multiple descriptions a complex system required,[10] and his later publications were more about non-simulability (non-algorithmic), entailment, and anticipation in complex systems. A fuller list of RC properties is given in Appendix 1 of Lane (2018b, this issue).

Although Rosen did not emphasize the ecological level of the biological hierarchy, he certainly understood the role of environment as everywhere present and communicating with open living systems. He was also clear that complex systems cannot be fully described, measured, or created. He did not believe it was possible to journey to complexity by visiting only simple systems or using machine metaphors. Some complexity authors have been too reductionist in their approach, too dismissive of complication, and too indifferent to simplification, to be able to discern how they all relate to each other in the biological hierarchy that is open and continually interacting with the environment, and in 'life itself'. I believe that living systems incorporate a complexity that is non-generalizable to nonliving systems, and we need to distinguish the two. At a minimum, we should not designate complicated and/or simple systems as complex. Identifying living (anticipatory) systems as Rosennean Complex, would be a start and a way to acknowledge Rosen's contributions to complexity theory.

To embark on the grassy path takes a conscious choice and a commitment to expend the effort needed to travel over the rough spots. One does not undertake this journey because Rosen's body of work is easy, but because it is worthwhile and deeply meaningful. Given that Rosen's priorities were first: life and second: complexity, it has always been difficult to approach Rosennean Complexity without understanding what he was saying about living systems and what does it mean to be alive – the very question all young biologists are taught not to ask. It is important to remember that Rosen was a gifted biologist, he scrutinized Mother Nature and probed her secrets relentlessly. He once said, that "the first lesson to learn about biology is that there are lessons to learn about biology" (Rosen, 2000). Although he was an undisputed leader in biomathematics, modeling, the use of category theory in relational biology, etc., his overall biological insight is unparalleled. He was a biologist's biologist above all else. His volume of essays (Rosen, 2000) constitutes a whole biological education – much more useful than any introductory textbook in biology.

If I was advising someone who wanted to begin a study of Rosen's work, I would suggest the following books: Rosen (2000,1991,2012) in this order, and then using a search engine to peruse his overall bibliography[11] and select journal papers that are most appropriate for one's interests, both in terms of subject areas and levels of the biological hierarchy. This reading could be usefully supplemented by selecting a number of other authors who have worked with Rosennean Complexity, like those included in the Special Issue, and in the biographies of their papers. If one is interested in relational biology, mathematical-modeling, and category theory, then Louie's books (Louie, 2009,2013,2017) are important reading, but not easy for non-mathematicians. It would also be beneficial to undertake a personal review of the traditional underpinnings of science and its inordinate focus on analytical approaches and reductionism, the machine metaphor, and other trappings of a paradigm that requires revision – Rosen's revolutionary mission. Rosen's (1996) paper, entitled "The Limits of Science" would be useful for this review. In addition, Henning and Scarfe's (2013) book, "Beyond Mechanism", including Stuart Kauffman's insightful introduction, takes excellent aim at the machine metaphor, and could support such a review.

While we have come to the "fork in the road" in considering ecological complexity and need a lot more clarification in our definitions (complexity, complication, and simplicity), this fork itself may not be such a simple fork situated on a planar surface like Abbott's (1992) Flatland populated by two-dimensional polygons. Perhaps at the fork in the road, there is a clearing with more options. The topography might be multidimensional and hierarchical, and the modes of transportation might be more numerous than mere walking on one of two paths. Slices of time continue to confound us. Furthermore, if computation and simulation are not appropriate tools for modeling complex systems, what should a complexity seeker do? There are presently many developments in biomathematics. For example, a group of more than 80 scientists are working on the new area of Integral Biomathes, with an ambitious agenda to improve the usefulness of mathematical constructs for living

[9] Joel A. Barker, https://www.brainyquote.com/quotes/joel_a_barker_158198 (Accessed February 15, 2018.)

[10] The year before he died (Rosen, 1997), he restated his earlier view of the necessity of multiple modes of description when characterizing the complexity of nonliving systems using an example of mathematical formalisms.

[11] The Panmere site by Gwinn (2015) contains an extensive Rosen bibliography. (Accessed February 1, 2018).

systems (Simeonov et al., 2012). They pursue representations of life over multiple scales, essentially a self-described ‘da Vinci’ approach to science for the 21st Century (Simeonov and Cottam, 2015). They credit Rashevsky and Rosen as two of the founders of biomathematics, and essentially part of the inspiration of their endeavor. As we develop mathematical tools, the goal should be to always let the biology drive the mathematics and not the other way around. This is what Rosen did and why he could get so far down the path.

In closing, we have travelled for 20 years seeking complexity since Rosen's passing, and it is clear that science does not stand still, and the journey is ongoing. It could not be otherwise. Rosen was a complexity seeker who got quite far down “the road not taken”– but, perhaps not to the end, but he certainly journeyed with his high beams on. He cleared a lot of undergrowth away for the rest of us on the grassy path. Understanding Rosen's journey can provide valuable signage for all who follow him down the road less travelled.

Conflicts of interest

None.

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