

A Network Dynamical Approach to Artificial Life: Morowitz's Challenge*

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Abstract

The recent work of Harold Morowitz on biogenesis represents a strong challenge to many existing research communities. Morowitz's work is firmly rooted in classical biochemistry, and is independent not only of what can now be recognized as "traditional" Artificial Life (AL), but also of the more esoteric approaches to biogenesis (for example, systems theoretical biology, biosemiotics, and autopoiesis). Morowitz more than hints at, he virtually promises, the quick movement towards a "common sense" realization of AL: the formation of pre-biotic protocells in the test-tube, closer to Frankenstein than Turing. In this paper we consider some of the consequences of Morowitz's network dynamical theory of biogenesis, and also the challenge of generalizing his results to other modalities and computer implementations in the context of current AL research.

Keywords: Artificial Life, biogenesis, dynamical systems, network thermodynamics, network dynamics, symbols.

For many years, Harold Morowitz has been a leading researcher in biogenesis and theoretical biology [7, 8, 9] as well as popular science [10]. A recent book, *Beginning of Cellular Life: Metabolism Recapitulates Biogenesis* [11], represents the culmination of many years of his effort in theoretical biology and biogenesis. He advances many challenging, even radical, ideas, but always remains rooted in solid biochemistry and careful attention to empirical methodology.

While Morowitz rarely refers explicitly to the recent "sciences of complexity" and Artificial Life (AL) movements, it is clear that he is quite familiar with them, and indeed he frequently engages their arguments, directly but implicitly. Here again, his views represent a strong challenge to these fields, and deserve careful attention. Indeed, this book is an important contribution not just to the literature on the origins of life, but also to the systems sciences in general.

In this paper I will first argue for the significance of biogenesis to AL, and then briefly explain some of the highlights of Morowitz's model of a non-genetic origins to life. Acceptance of this challenge should lead AL to consider anew the emphasis it has placed on computation and informatics over dynamics and energetics. Rather, it seems that AL is *exactly* the field where these disparate views must be synthesized and reconciled. This leaves a special challenge for any attempt to approach these issues through computer implementation.

1 The Significance of Biogenesis for AL

AL, as the attempt to model biological systems, obviously must stand in a close and peculiar relation to biology proper. Every model is, of course, simultaneously somewhat similar and dissimilar to what is being modeled. To the extent that AL strives to be accurate, it must emulate real biological

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organization. But to the extent that AL wants to explore new techniques and technologies, it should not be too closely constrained by biology.

This problem is familiar from other recent endeavors in the systems sciences. Throughout the history of Artificial Intelligence (AI), for example, there has been a dispute over the extent to which AI should emulate real human (or animal) intelligence, or should embark on a mission of its own to create useful systems and technologies *inspired by* human cognition. Similarly, artificial neural networks have such a relation with neural psychology, and, closer to AL proper, genetic algorithms with genetic biochemistry.

My initial purpose here is not to review this familiar ground, or to recapitulate “religious wars” of the past or present. Rather, I simply want to first argue for a (modest) position which I feel is quite obvious: AL should be informed (whatever that means) by real biology. Empirical exploration of the basic processes of real living systems promises to have a profound effect on these seeking to emulate and implement such processes in other media. One would hope that such an influence would be reciprocated, with real biologists paying attention to recent work in AL. But that is, perhaps, an issue for another conference.

Beyond the significance of biology for AL, which does not strike me as a controversial view, is the particular significance of biogenesis, as the study of the origins of life, for AL. The *prima facie* argument is simple: current AL systems are not alive, we wish for biological or pseudo-biological processes to emerge from them, therefore the process of real biological emergence is relevant.

The problem of the origins of life has stood throughout the history of the systems sciences as perhaps their greatest challenge. On considering general evolutionary change and the emergence of new biological forms, mind, language, and society, we are constantly drawn back to the first, the primary emergence of extreme complexity and organization *de novo* with the appearance of life on this planet. This is true not only of theoretical biogenesis, but also, to the extent that it exists, of *experimental* biogenesis. It is towards this final goal which Morowitz most forcefully directs himself.

2 The Morowitz Program

Morowitz’s program is a bold effort to approach the origins of life problem the “orthodox” way: through chemistry. Thus his view of AL would be as an attempt to produce *real* artificial life by forming objects resembling organisms (protocells) in the laboratory setting: “Biogenesis must be pursued as an experimental science” [p. 97]. A brief appendix suggests that he and his colleagues have made some progress towards this goal, in particular, by producing non-enzymatic catalysis in a non-biotic flask-type experiment. Indeed, he has recently said that they have been hesitant to publish their recent experimental results in order to avoid a “cold fusion effect”.¹

Morowitz’s approach rests on the adoption of some fundamental principles of systems theory. These are general principles, and are thus not specially relevant to biochemical systems, but can (and perhaps should) be broadly applied to problems in complex systems science and AL in general. These principles can be briefly stated:

Historicity: Complex systems are historical. That is, chance is present at the time of their formation, and random event appear as “frozen accidents” within their structure as they evolve. Observing extant systems reveals what *did* happen, not what *must necessarily have* happened.

Continuity: By parsimony or Ockham’s razor, theories which hypothesize a continuous path from extant forms of systems to a world without such systems (from extant organisms to a prebiotic

¹Personal communication, November 1994.

earth, in particular) are favored over those that do not. Thus, since “no vestiges of clay structures exist in contemporary cells and since nothing in the logic of clay chemistry is unique” [p. 27], “clay” theories of biogenesis are not favored.

Universality Implies Primitiveness: Again, by parsimony or Ockham’s razor, theories which favor a common origin of historical, yet also universal, aspects of systems should be favored over those which hypothesize some other mechanism (for example, horizontal transmission or multiple identical origins).

Signature Principle: It follows that knowledge of origins can be gained by analyzing existing systems. That is, the historical accidents which are frozen into organisms, in a continuous way from the pre-biotic earth, leave a “signature” which can provide evidence as to what that historical path was.

The conclusion Morowitz draws from these fundamental principles is that “metabolism recapitulates biogenesis”: evidence about the origins of life can be gained by closely examining the universal, historical properties of extant organisms. There are many of these (cellular membranes, aqueous environments, a universal set of atomic and molecular constituents, energy flow through ATP, genetic coding, etc.), and therefore a “universal ancestor” is hypothesized which included all of them. By continuity, these properties did not all occur at once. So by the signature principle, we should be able to reason about the path of proto-evolution from the prebiotic earth to the first appearance of this universal ancestor over a period of 200 m. years, between approximately 3.8 and 3.6 billion years ago.

From the historical perspective, the most cogent universal property of organisms is the particular chemical network of metabolic pathways which can be drawn on a universal chart or graph. Morowitz emphasizes that the science of networks in general, and chemical networks in particular, is still significantly underdeveloped. For example, current metabolic charts are highly non-planar, with multiple redundant representations of common nodes (for example, ATP). Not only are multidimensional methods required, but significant progress remains to be made in discovering many of the basic properties of networks in general, and chemical reaction networks in particular.

Morowitz’s basic premise is to turn the traditional (Miller-Urrey [6]) approach to biogenesis on its head. Rather than a “primordial soup” of prebiotic organic monomers and macromolecules, within which is established a complex set of reactions eventually leading to vesicle formation, Morowitz proposes the formation of closed amphiphilic (lipid) bilayer membrane vesicles very early. Echoing the autopoietic theory of Maturana and Varela [14], these protocellular vesicles provide the key property of systems formation: a thermodynamic boundary dividing system from environment, and establishing a three-way phase separation across which energy and molecules are asymmetrically transported. Just by itself, this could result in protocellular growth, division, and replication.

It should be emphasized that there are many key hypotheses which must be satisfied for Morowitz’s theory to hold. They include:

Non-Enzymatic Catalysis: Catalysis and autocatalysis play an important role in Morowitz’s theory, but the late introduction of nitrogen (see below) requires non-enzymatic catalysis (albeit less efficient than enzymatic). This is, indeed, the empirical program being pursued by him and his colleagues.

Early Proto-Photosynthesis: Rather than photosynthesis being considered as a late feature, it is postulated as an early source of energy input to the protocells. The only other alternative is geothermal energy input, which is argued against due to the dependence of deep-ocean

organisms on oxidizers falling from the surface. This early form of proto-photosynthesis is not seen as equivalent to full-fledged photosynthesis, but rather photonic energy transport mediated by a variety of non-chlorophyll pigments (chromophores and retinals).

Electron and Proton Transport: Protocells are hypothesized to have a variety of non-protein molecules adsorbed within them to effect energy and molecular transport, much as proteins act in modern cells. This involves both electron transport, to facilitate redox reactions, and proton transport, to facilitate acid-base reactions.

3 A Dynamic Biogenesis and AL

A key result for our consideration here is that the metabolic chart provides evidence (by the signature principle) that the inner, more primitive parts of the metabolic network involve cycles of CHO compounds. But it is only *much later*, through “gateway” reactions introducing ammonia, that nitrogen is introduced. Thus Morowitz comes to the startling hypothesis that amino acids and peptides, not to mention the far more complex machinery of enzymatic catalysis, RNA transcription, and protein synthesis, are simply *not relevant* for biogenesis.

This has far-reaching consequences for theories of biogenesis. First, as discussed above, a robust theory of non-enzymatic catalysis is required. Morowitz admits that such catalysis will be less efficient than enzymatic, indeed, this fact explains the huge evolutionary benefit gained later by the introduction of enzymes. And by continuity and the signature principle, there must be evidence of the remnants of such pathways in extant organisms.

Obviously, this view also requires an altered perspective on replication and heredity, since this is so dominated in extant organisms by genetic reproduction. Morowitz suggests that this would involve the emergence of non-genetic molecules which provided increased fitness through the reflexive action of autocatalysis, increased energy transduction, or increased transport of its own chemical constituents. But through the differential production and faithful reproduction of various forms of protocells with different species of molecules, and therefore different chemical networks and cycles, all of these cases would result in a form of non-genetic, but nevertheless Darwinian, variation, selection, inheritance and evolution.

But the most important consequence of the “no early nitrogen” result is to eliminate all of the mechanisms of proteins and nucleotide bases from early forms of life: the early stages of cellular development went on for millions of years without any genetic coding. This thereby lessens the importance of *symbolic* activity in biogenesis, and increases the importance of *dynamical* activity. For Morowitz, the development of protocells is almost *entirely* within the realm of dynamics, in particular the dynamics of these complex chemical reaction networks.

If this is indeed the domain in which life evolved, so that genetic coding is a later development, and the basic life processes must be considered in the absence of any kind of coding, then all approaches to biogenesis will have to more forcefully address issues in the dynamics of complex networks. This is true, for example, of the biosemiotics movement [2, 4, 13], which stresses the fundamental role of semantic relations and coding in all life processes. And it is also true of AL, which throughout its history has stressed the rule-following, computational aspects of biological systems.

Thus, in addition to the systems theoretical concepts of order, organization, complexity, and information, which AL does currently include, it will also have to more diligently address the concepts of energy, entropy, flows, sources, sinks, attractors, equilibria, steady states, and stability. These are concepts from physics and dynamical systems theory, and not from computer or information science. While new theories about global organization and complexification under different

circumstances (e.g. communities of independent rule-following actors) are indeed crucial for AL, and are being incorporated within it, other powerful new theories of *dynamical* systems also need to be incorporated.

4 The Cycling Theorem

Peusner's network thermodynamics [12] can be pointed to in particular as a powerful dynamical and systems theoretical modeling theory. Although developed for electrical circuits, Kirchoff's theorem about the balance and distribution of flows in a network applies in general to complex reactive networks in any modality.

Note that Peusner's ideas necessarily hold in far-from-equilibrium conditions, because at equilibrium conditions all flows cease, and Kirchoff's theorem becomes trivial. Morowitz applies this idea in the prebiotic case.

This balance requires that the final flows of material generated by the electronic transitions return to the points in the network where they originated. Thus, the steady state is necessarily characterized by cyclic flows of material around loops in the reaction network. As the material flows around these cycles, the input energy flows out as heat into the isothermal reservoir. Material cycling is seen to be a general feature of chemical networks kept at a far-from-equilibrium steady state by the constant influx of energy in a form capable of electronic excitation. [p. 119]

What results is a form of stability which is nevertheless not an equilibrium, but rather a steady-state, where state variables are constant, but activity is also constant [3].

Morowitz applies this general result as a Cycling Theorem, which has wide ranging consequences for biogenesis, and thus for AL. He describes this in the context of a network kept in a steady state far from equilibrium.

Dynamic [steady] states of the system in which lower-lying molecules are not pumped up to higher states will tend to disappear as the high-energy material drains into the sinks established by the attractors [equilibria]. For steady states to be maintained in the network, the energetically pumped cycles must involve the lower-lying states as inputs. [p. 120]

In other words, network thermodynamical systems kept far from equilibrium involve cycles which move material between high and low energy states. Numerous specific examples of this principle exist in biology and biogenesis as general anabolic/catabolic cycles such as the photosynthetic source and respiratory sink of the oxygen cycle.

In general, anabolic processes create biological complexity by storing free energy in covalent bonds, while catabolic processes then break that complexity down, completing the cycle, and in the process producing thermodynamic entropy. The creation of complex systems has always been of paramount interest in AL. Of less interest has been the existence of complexity-building processes in real dynamical systems, which must necessarily exist as parts of cyclically processing networks. Without the full cycle, the exponential growth of the replicating protocells would quickly exhaust all available raw material.

5 The Challenge for Implementation

So it is clear that, under the assumption that Morowitz's arguments have some validity, AL must be informed by the properties of complex reactive networks and their dynamical attributes. In

the history of proto-evolution such dynamics are fundamental to genetic coding and replication. But of course, that is not to say that symbolic activity is not important, or has no place in AL. Indeed, somewhere along the proto-evolutionary path coding and symbolic activity arose, came to dominate the proto-ecosystem, and became ensconced in the universal ancestor.

But it is also apparent from Morowitz's argument that this level emerged *from* an underlying *dynamical* level. Indeed, the challenge of AL appears to be to extend systems theory enough to include *both* symbolic and dynamical forms in one place. Clearly extant organisms are manifestations of such a synthesis.

But the challenge for AL is more than theoretical. Its task is to *implement* its theories, to *construct* artificial systems which emulate, simulate, embody, or otherwise manifest the properties of organisms. Beyond theory, then, how is *this* effort towards implementation affected by the dynamical approach to biogenesis?

The first, and most obvious, answer is to abandon our workstations for the chemistry lab, to follow Morowitz and Frankenstein rather than Langton and Turing. Clearly this kind of work is in fact Artificial Life in one important sense, and it must be asked what is at stake in the choice of experimental environment. To a certain extent, the rise of the AL movement was fostered exactly by the conditions that where laboratory experimentation was impractical, computer-based simulations became increasingly feasible.

It is useful in this context to consider some of the ideas of Kampis, and in particular his idea of a "component system" [5], whereby simple components are combined or concatenated to produce larger, complex entities. On first consideration, this idea is not extraordinary. But nevertheless, component systems have properties that other systems typically used in AL do not have.

In particular, component systems do not have bounded state spaces, but rather branching state spaces which grow hugely and rapidly with string size. They therefore exhibit properties of complexity, in the sense of irreducible descriptions of Kolmogorov and Chaitin [1]. Furthermore, due (at least) to the intractability of characterizing the state space, component systems also exhibit properties of *emergence* as novel combinations of components result in unpredictable results.

Component systems exist in many modalities (language, genetics), but perhaps the prototypical *real* component system is provided, in fact, by simple chemistry, and in particular the chemistry of light, highly reactive elements (C,H,O). These are, of course, exactly the systems studied in biogenesis. So Morowitz's type of complex chemical reaction networks provide, in one sense, an ideal laboratory environment for studying real component system and their emergent properties. Unlike other historically bound complex systems (for example in astronomy or sociology), their results are reproducible, and the basic chemical processes are well understood.

As stressed by Kampis, opportunities to model or simulate a component system by a formal system (such as a computer) are severely limited. But that does not mean that such attempts should not be made, nor that these environments do not complement each other. Indeed, on first appearances we should presume that both are important components in a robust, complete AL research program. As AL and biology, they should be mutually informative.

But even for those of us who choose to stick with our workstations, lessons can be drawn from Morowitz's work. In particular, we must find ways of incorporating concepts related to *energy* into our simulations. It is energetics which distinguishes real chemical networks from general systems theoretical or mathematical networks. Energetics involves additional constraints, introduces dynamics and kinetics, introduces cycling into network flows, and requires concepts of dissipation and entropy production. This is, of course, easier said than done, and I regret an inability to do more here than make the suggestion.

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