Towards a General Biology: Emergence of Life and Information from the Perspective of Complex Systems Dynamics[1]

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Abstract

I argue that Darwinism is best described as a research tradition in which specific theories of how natural selection acts to produce common descent and evolutionary change are instantiated by specific dynamical assumptions. The current Darwinian research program is the genetical theory of natural selection, or the Modern Evolutionary Synthesis. Presently, however, there is ferment in the Darwinian Research Tradition as new knowledge from molecular and developmental biology, together with the deployment of complex systems dynamics, suggests that an expanded and extended evolutionary synthesis is possible, one that could be particularly robust in explaining the emergence of evolutionary novelties and even of life itself. Critics of Darwinism need to address such theoretical advances and not just respond to earlier versions of the research tradition.

Key words: complex systems dynamics; Darwinian Research Tradition; emergence; expanded/extended evolutionary synthesis; genetical theory of natural selection; Modern Evolutionary Synthesis; origin of life; self-organization

My thesis is that the Darwinian Research Tradition, defined below, is being enriched, extended and expanded by new information and concepts and that a Darwinian evolutionary synthesis deploying background assumptions of complex systems dynamics can robustly guide further research into biological phenomena and lead to the

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[1] The Wistar Institute held a conference in 1966 to explore the adequacy of the neo-Darwinian interpretation of evolution, the proceedings of which were subsequently published by the Wistar Institute Press as *Mathematical Challenges to the Neo-Darwinian Interpretation of Evolution* [1]. In addition to mathematical critiques of the version of population genetics upon which the neo-Darwinian Synthesis, or more accurately the Modern Evolutionary Synthesis, was based, there were presentations, particularly by Conrad Waddington, that pointed out that the synthesis had not adequately included developmental biological phenomena and was by implication incomplete. Two of the key figures in the development and deployment of the second phase of the neo-Darwinian synthesis, Richard Lewontin and Ernst Mayr, were participants, defending the Modern Evolutionary Synthesis even as they provided some criticism of the limitations of one version of the neo-Darwinian program that reduced all biological phenomena to population genetics.

development of a theory of general biology. Such a general theory could and should address issues of the emergence of life, topics properly previously screened off in the Darwinian discourse. After reviewing the history of neo-Darwinism and the Modern Evolutionary Synthesis in the Darwinian Research Tradition,[2] and making the case for shifting background dynamical assumptions to those of complex systems, I will focus specifically on the current status of "origin of life" research and how such work may contribute to a theory of general biology. Finally, I will argue that intelligent design theory does not provide a suitable scientific alternative in that it does not provide a conceptual framework for empirical and theoretical research on the phenomena of emergent complexity.[3] However, criticisms from intelligent design theorists, among others, of on-going efforts to develop a new Darwinian evolutionary synthesis can help sharpen the deployment of such a research program.

The Modern Evolutionary Synthesis and the Darwinian Research Tradition

In *Darwinism Evolving* and subsequent publications, David Depew and I have argued that there is not a single Darwinism synonymous with evolutionary theory,

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This paper had its origins in a 2007 conference in Boston organized by Bruce Gordon under the auspices of the Center for Science and Culture at Discovery Institute, which funded the event, In the style and spirit of the Wistar Conference, it was meant to explore, some forty years later, the robustness of the earlier neo-Darwinian mathematical population-genetics theory of evolution in light of the progress in molecular and developmental biology, as well as in ecology, in the intervening time. A number of the critics of Darwinism present at the conference articulated an alternative explanation of functional biological complexity known as 'intelligent design' or more succinctly ID. Others present, like myself, while moving beyond the specific program based upon population genetics, defended the more general concept of a Darwinian evolutionary synthesis under a 'self-organizational' rubric.

[2] Since there was a research program known as neo-Darwinism in the late nineteenth century based upon Weismannian inheritance that was taken to preclude any Lamarckian mechanisms of heredity, many historians of biology prefer to use the term 'Modern Evolutionary Synthesis' rather than neo-Darwinism, or neo-Darwinian synthesis, to characterize the genetical theory of evolution based upon population genetics (see discussion in [2]). I will use neo-Darwinism to mean the specific program based upon early Mendelian genetics and Modern Evolutionary Synthesis for a more broadly conceived synthesis that includes the version based upon population genetics. I will use the term 'Darwinian Research Tradition' to refer to an interlinked set of research programs over time that share a commitment to natural selection as a major, though not sole, source of biological adaptation, order, and innovation, even as the concept of natural selection is articulated against different sets of background assumptions about systems dynamics.

[3] This is not to say that there cannot be a productive research program based upon assumptions of intelligent design, particularly in areas studying cultural artifacts and social and cultural phenomena more generally. Also, I can imagine productive programs so based for studying atemporal aspects of biological phenomena.

nor is the Modern Evolutionary Synthesis (often called neo-Darwinism, but see footnote 2) a monolithic research program [2–6]. Rather, we see a Darwinian Research Tradition, which has itself changed over time in light of new empirical data and conceptual advances, and which has assimilated new information and resolved entailing theoretical problems through a process of modifying underlying assumptions about the nature of biological systems and the dynamics of their changes over time. For example, we see "Darwin's Darwinism" as being informed by Newtonian systems dynamics that emphasized differential survival of individual organisms in populations and saw natural selection as analogous to a Newtonian force that acted gradually, instantaneously equilibrating with other forces (such as variation), to produce adaptation. For the two to three decades following the rediscovery of Mendelian genetics in 1900 the discrete nature of mutations seemed to contradict the notion of small, continuous variation that was assumed by Darwin in his Newtonian conceptual framework. Indeed, many critics saw and/or hoped for the demise of Darwinism.

After all, Darwinism was not the only research tradition that addressed the phenomena of evolutionary biology. There were many evolutionary biologists in the nineteenth and early twentieth centuries who worked within a Lamarckian, a Geoffroyean, or a Spencerian conceptual framework and research program, in which internal factors, developmental processes, or natural laws of complexification, respectively, were taken as the driving force of evolution rather than natural selection as a Newtonian-type of force. All three of these alternatives seemed to be gaining adherents in the early twentieth century, even when such scientists called themselves Darwinians, which was for some just a label for accepting descent by modification. As Depew and I recount, the great conceptual advance brought about by Sergei Chetverikov, J.B.S. Haldane, Ronald Fisher, and Sewall Wright that produced the basis of the "genetical theory of evolution." This move, which formed the basis of the "Modern Evolutionary Synthesis," involved shifting the underlying concepts of systems and systems dynamics from Newtonian to Boltzmannian. This shift took advantage of statistical insights used by Boltzmann in his development of statistical mechanics in which macroscopic, thermodynamic properties of matter and physical processes were re-described in terms of the aggregate behavior of the microscopic atomic and molecular constituents. The analogy of the action of selection on the frequencies of genes in populations with statistical mechanics was explicitly formulated by Fisher in his seminal *The Genetical Theory of Natural Selection* [7]. What mattered in this view was that the gradual shifting of the frequencies of a number of genes within an interbreeding population of a species due to the action of adaptive natural selection, by which change the fitness of the overall population was increased.

Not only did this first phase of the Modern Evolutionary Synthesis resolve the apparent conflict of discontinuous Mendelian genetical variation and gradualistic Darwinian natural selection by changing the background systems dynamics, it was attractive since it provided biologists with a mathematical theory of population genetics that could be rigorously tested. Further it placed biology within the broader "statistical revolution" that had already occurred in the physical sciences. Finally, during the 1930s and 1940s it provided the basis for a second phase and a broader synthesis of a number of areas of biology within the rubric of population genetics. The creative work of Theodosius Dobzhansky, Julian Huxley, Ernst Mayr, George Gaylord Simpson, and G. Ledyard Stebbins produced a more general synthesis of evolutionary biology, based upon population genetics, that incorporated much of biology including botany, paleontology, systematics and population ecology [8,9]. This version of the Modern Evolutionary Synthesis, as noted above, is sometimes called neo-Darwinism or the Synthetic Theory of Evolution and continues to provide a basis for a robust program of empirical and theoretical biology [10].

Despite any misgivings about the completeness of the Modern Evolutionary Synthesis, its advocates assumed that the action of natural selection on gene frequencies over generational time ("microevolution" see [11]) could account for the phenomena of common descent over geological time ("macroevolution"). But this synthesis was not complete, as Conrad Waddington repeatedly argued, since it bracketed off developmental biological phenomena, which were assumed to be merely the readout of the genes in the conceptual framework of neo-Darwinism [12–14]. Similarly bracketed off were aspects of ecology, such as energy flow and community interactions that went beyond population ecology [15–20]. Despite expectations that knowledge of the molecular sequence structures of biological macromolecules (DNA, RNA, proteins) would fit neatly into the neo-Darwinian framework, such knowledge has raised interesting puzzles and identified new evolutionary phenomena that need to be either incorporated into an expanded version of the Modern Evolutionary Synthesis or serve as the basis for a new, yet Darwinian, Expanded and Extended Modern Evolutionary Synthesis [2, 21–23]. Paleontologists Stephen Gould and Niles Eldredge have argued that the Synthesis is unfinished and needs a hierarchical expansion with selection acting in different ways at different levels of the biological hierarchy [24–26]. Scott Gilbert has continued Waddington's efforts to call for taking developmental phenomena seriously in an expanded and extended evolutionary synthesis, especially in light of the advances in "evo-devo" [27–32]. Gilbert sees development as a complementary process working with natural selection, producing variation and novelty, rather than replacing population genetics [28]. Mary Jane West-Eberhard has shown how developmental plasticity can provide variation even when there are no changes in the genome and how such phenomena impact evolutionary theory in ways that are not anticipated in the Modern Evolutionary Synthesis even though they are consistent with a more broadly conceived Darwinism [33,34].

Toward an Expanded Darwinian Synthesis and a General Biology

More innovative approaches to catch evolutionary phenomena in a expanded synthesis have relied upon a variety of tools from the still developing sciences of complexity. One example is that of Daniel Brooks and E.O. Wiley who, along with John Collier and Jonathan Smith, have sought to expand the evolutionary synthesis by introducing concepts from information theory and non-equilibrium thermodynamics to robustly account for the appearance of new biological information and pattern as well as natural selection itself via a process of ‘infodynamics’ [35–42; see also 43]. Using non-equilibrium thermodynamics in a more conventional usage Jeffrey Wicken sought to “expand the Darwinian program” not only to account for the emergence of new information in biological systems but to extend a kind of Darwinian approach to the problem of the origin, or more properly the emergence, of life [44]. Stuart Kauffman applied concepts of non-linear dynamics and self-organization to both developmental genetic systems and to the problem of the origin of life, to the latter of which he also brought in non-equilibrium thermodynamic considerations as well as consideration of the emergence of ‘agency’ [45–47]. I will return to the issue of the origin of life below. With regard to the inclusion of developmental biology into evolutionary theory, Depew and I have argued that the shift to such systems dynamics employing insights from the behavior of complex systems can provide the conceptual context within which a synthesis both can be effected while staying within in the Darwinian Research Tradition, if not narrowly formulated versions of neo-Darwinism as espoused by Richard Dawkins, for example [48–50]. One attempt to forge such a synthesis is known as Developmental Systems Theory (see contributions in [51] as well as in [52]). It shows a range of commitment from some form of Darwinism (see [53]) all the way to embracing instead an alternative research tradition, such as the Lamarckian [54–57] or the Geoffroyean [58–60]. Jablonka and Lamb argue that since in later editions of *On the Origin of* Species Darwin’s hypothetical mechanism of inheritance had a Lamarckian character their inclusion of epigenetic factors could be considered as a recovery of Darwin’s original vision [56–57]. A recent review of developmental genetics and epigenetics by Robert Reid argues for an evolutionary theory that is in his own terms outside the Darwinian tradition but more at home in a Lamarckian or Geoffroyean one [61].

A current research program, which we might denote as 'emergentist' as a convenient label, has the goal of developing a theory of general biology, that is, a theory of structural and functional complexity and the emergence of novel structure/function as well as new information and phenomena [45–47,62–77]. This is a program very much in its early stages, but one that holds the promise of eventually developing a theory of biological organization that would hold not only for terrene biology but also for possible biological phenomena elsewhere in the universe. Such a general biology would be part of a more general theory of emergence (see contributions to [66]).

Cautionary Considerations and a Perspective on Emergence

When we are evaluating the sufficiency or inadequacy of the Modern Evolutionary Synthesis, or of Darwinism more generally as a research tradition in some new synthesis, or of rival naturalistic research traditions, or of theories such as intelligent design that posit sources of order and information outside of natural processes, it is important that we take care in being explicit about what we are discussing. Some evolutionary thinkers, such as Gould or Corning, see their approaches, for all the new empirical and theoretical content, as closer in conceptual stance to Darwin's original Darwinism than to a narrowly construed Modern Evolutionary Synthesis. Others, such as Deacon, Depew, Kauffman, Wicken and myself, see the deployment of the new complex systems dynamics leading to a totally new version of Darwinism, but still a research program within the Darwinian Research Tradition. Critics of Darwinism, such as Stanley Salthe, Eva Jablonka, and Robert Reid, are not rejecting evolutionary phenomena nor are they calling for sources of order outside nature. Rather, they are arguing for a different set of naturalist assumptions and dynamics that they regard to be better suited to guide future research. As a commitment to methodological naturalism does not logically entail a commitment to philosophical materialism, so we should not take any version of Darwinism as being a synonym or a placeholder for philosophical materialism, unless such a move is self avowed or can be demonstrated, as is the case in writers such as Dawkins and Dennett.

In what follows, I am going to examine current research on emergence theory as well as current work on emergence of life. Even though this issue of the origin of life historically lies outside the orbit of the Darwinian Research Tradition, I will take the cue from Wicken, as well as Kauffman, and Terrence Deacon that the processes and phenomena are rightfully the topic of a general biology and can and should be incorporated in any expanded version or new synthesis of Darwinism. I will assess the value of any theoretical approach in terms of its potential fecundity and robustness in the development of such a new synthesis and theory of general biology and of emergence. This means I am viewing science not as a body of established facts only, but rather as a process of exploring nature and deepening our understanding of natural phenomena.

Emergence of Emergence as Paradigm

The latter part of the twentieth century saw the rise of a new way of understanding nature, employing complex systems dynamics to explore and explain phenomena of self-organization and emergence (for an overview see for example [2,3,45,46, 65–68,71–73,78–88]). Self-organization, or more properly systems-organization, in which the interaction of the system and its environment under particular initial and boundary conditions leads to the emergence of novel order and structure, occurs widely in nature as well as under laboratory conditions and can be considered as a natural phenomenon [89,90]. Developing a theory of such emergent organization has as its goal providing natural explanations for such phenomena. This is very much a work still in progress but the insights gained so far provide a conceptual framework for thinking about and guiding research on the problem of the origin of life.

I define emergence as the appearance of novel properties, structures, and/or patterns in a system that are not present in the constituent components or easily predicted (weak form) or explained (strong form) from the laws and processes affecting the constituents of the system. The new level of phenomena and the lower level of constituents have mutual constraints and the arrows of causal explanation point in both directions. If we are tracking the process of the appearance of the new phenomena we are speaking of diachronic emergence in which the lower-level causality exceeds that of the upper level, but when the system has settled to a steady state we than have an instance of synchronic emergence in which the constraints fully mutual. In any event, the emergentist view is that the new, upper-level structure/properties/processes/phenomena represent real natural phenomena and not epiphenomena. In reductionism the lower level is the locus of causality and the upper-level properties are regarded as merely epiphenomenal, that is, without causality; in holism the upper level has the causality and the lower levels are epiphenomenal.

It is the strong form of emergence that will be of concern here, especially with regard to the emergence of life. In strong emergence, the emergent phenomena are novel in that they have properties not contained in the components, and are irreducible in sense that the emergent phenomena are not identical to their composition. Emergent systems exhibit a kind of holism in that the emergent phenomena cannot be analyzed into their parts without losing sight of their essential character. Further, in strong emergence the emergent phenomena obey laws that rely, in at least part, on their novel properties, that is, some of the processes and laws themselves are emergent, even as the process of their emergence itself operates under general natural laws (including for example a putative ‘fourth of thermodynamics’ in addition to other natural laws [45,46]). Finally, in strong emergence the emergent phenomena can impose conditions on their constituents that depend on the nature of the identity of the emergent phenomena, that is, such systems can exhibit downward causation.

Following Deacon’s analysis I will further distinguish three types of emergence: first-order or supervenience, second-order or self-organization, and third order or evolution [67]. In supervenience, the higher-order properties of an *aggregate* are determined by the statistical or stochastic properties of the ensemble. For example, the liquid properties of water are said to *supervene* on the properties of individual water molecules. Second-order emergence, or self-organization, occurs on a higher hierarchical level than first-order emergence but as in all hierarchical systems the lower level continues to operate. In self-organization the configurations of individual components and the unique interactions in the system exert an organizing effect on the entire ensemble. Initial conditions and outliers can strongly affect the ensemble properties. Self-organization occurs in systems *open* to matter/energy flows that keep the systems *away from equilibrium*, resulting in *macroscopic structures* such as convection cells. Second order emergence also includes phenomena associated with nonlinearity and chaos. It is characteristic of all second-order emergent systems that they have a spatially distributed re-entrant causality that allows microstate variation to amplify and influence macrostate development, even as the macro-relationships undermine, constrain and bias micro-relationships. Snowflakes, Benard convection cells, tornados, chemical waves in the Belousov-Zhabotinskii reaction are examples of such second-order emergence. Self-organizing systems that generate and store information that is useful for system stability and survival *evolve*. Such informational memory produces *recursive*, *self-referential* self-organization that exerts a causal, cumulative (over time) influence over the future of the system. Fitness, function, and natural selection itself can be seen as examples of third-order emergence. Third-order emergence biases across iterations or generations, as in biological development or biological evolution, and can be viewed as an autopoiesis of autopoieses. “So life, even in its simplest forms, is third-order emergent. That is why its products cannot be fully understood apart from either historical or functional concerns” [67, p 300]. Both second and third order emergence exhibit a diachronic symmetry breaking not seen in first order emergence. Although higher levels in the hierarch are based upon the lower ones they can exhibit properties not seen at the lower levels because of this symmetry breaking.

The formation of Benard convection cells is an example of a self-organizing process in which the macroscopic structure of the convection flow allows for more efficient dissipation of the energy gradient, giving a thermodynamic "reward" for the production of structure. The process of formation of such convection cells involves a type of selection process working with self-organization. Rod Swenson has shown that the initial formation of convection cells produces macroscopic structures of various sizes and shapes, but that the system quickly settles down into a pattern of hexagonal cells of uniform size [91,92]. Thus there is a sorting or selection process working with self-organization. Brian Goodwin saw the shape and size selection as an instance of physical selection for the most stable [80,85]. To this Swenson added selection of the most dissipatively efficient. For complex chemical systems exhibiting self-organization there is additionally selection for the catalytically efficient, in addition to that for thermodynamic efficiency and physical stability. Thus, even before there is biological selection for the reproductively fit, emerging with the emergence of life, there exists in nature interplay of self-organization and selection at the level of physical and chemical phenomena [2–4,45,46,68,69,71,92].

Is the Origin of Life a Darwinian Problem?

Darwin himself carefully avoided the issue of the origin of life since he was concerned with explaining how living beings and their lineages changed over time and how novelties could arise through the action of natural selection upon heritable variation. For example, "How a nerve becomes sensitive to light hardly concerns us more than how life itself originated" [93, p187] was consistent with his accepting that life was "breathed into a few forms or into one" [93, p490] (Darwin [1859] 1964, 490). This position served to distinguish Darwin's theory of evolution from Lamarck's in which "active matter" spontaneously and continuously generated life [see 94–96]. Privately, Darwin was willing to speculate about the origin of life, as he did in a letter to Joseph Hooker in 1871, "But if (and oh what a big if) we could conceive in some warm little pond with all sorts of ammonia and phosphoric salts, light, heat, electricity and etc., present, that a protein compound was chemically formed, ready to undergo still more complex changes" (Cambridge University Library Manuscript Collection: DAR 94: 188–89).

Herbert Spencer argued that biological evolution is a part of a general, cosmic process of the universe becoming less homogeneous and more complex in which the origin of life was a specific instance [97]. Josiah Royce reasserted the more narrow claims of Darwinism as distinguished from those of the Spencerians [98]. With the rise of the Modern Evolutionary Synthesis, the demarcation of the problem of the origin of life from matters Darwinian was reasserted and continues today in mainstream evolutionary discourse [99,100].

However, one of the founders of the Modern Evolutionary Synthesis, J.B.S. Haldane, along with Alexander Oparin and J.D. Bernal (Marxists all), argued that advances in biochemistry and geochemistry meant that serious scientific study of the origin of life is possible, even if not required by the theories of the Darwinian Research Tradition [101–105]. They recognized that from their commitment to philosophical materialism it was necessary that the origin of life be the result of natural processes only. Opponents of Darwinism and also of philosophical materialism similarly argue that the origin of life is conflated with Darwinian theories [106–110]. Indeed, some neo-Darwinian advocates, such as Richard Dawkins, accept this conflation. In order to reduce biological phenomena to "selfish genes" Dawkins assumes that, however improbable, all that was needed for the appearance of life was to get a nucleic acid molecule that could replicate itself, although later this "naked replicator" decorated itself over time with proteins, lipids, etc. to produce better "survival machines" [49,50]. Alex Rosenberg attempts to achieve reduction of all biology to molecular genetics by a slightly different move at the origin of life [111]. He argues that natural selection has to be grounded in chemical and physical selection during the process of life's origin. During the process of life's origins, I agree; but this attempt at reduction points instead toward an emergentist account [112,113,118]. In what follows, I will consider experimental and theoretical approaches to the *emergence* of life as well as the implications of the dynamics of emergent complexity for our understanding of biological organization and how it arises.

Current Perspectives on the Emergence of Life

Whether a reductionist or emergentist approach is taken to the origin of life, the possible reactions and routes to the organized complexity of living entities is constrained by the properties of matter and the laws of chemistry and physics [43,113–118]. Not all types of bonding arrangements and compounds are possible [119]. In aqueous environments, for example, phosphate has unique properties that make it essential for life and even for proto-life. Only phosphoanhydrides had the needed mix of thermodynamic instability and kinetic stability to serve as an intermediate for capturing and providing energy. One consequence is that polypeptides can be synthesized abiotically from amino acids, polyphosphate (a phosphoanhydride) and magnesium cation [120]. Of course, life may be possible using non-aqueous chemistry, and such possibilities should be explored in a theory of general biology. Steven Benner has suggested that what is essential for the emergence of life is some sort of solvent system, the chemical elements carbon, hydrogen, nitrogen, sulfur, phosphorous, and oxygen, along with thermodynamic disequilibrium and temperatures consistent of chemical bonding [121].

However, for the present it is a sufficient challenge to address what might have happened during the emergence of life on earth. Given that, we can proceed with the understanding that the possibility space of chemical reactions in living systems is not unconstrained, nor random, but rather reflects in part structural, thermodynamic, kinetic, and combinatorial constraints. Overall, the transition to life and the subsequent evolution of living systems involves retention of reduced compounds in the presence of the resulting ever more oxidizing environment [114]. With an on-going influx of energy and matter the complexity of chemical reactions would be expected to increase as well as non-sequence specific macromolecules under pre-biotic conditions [44].

The minimal elements that need to be considered in any account of the emergence of life are:

- An energy source (gradient) and a mechanism to capture energy such that the entropy of the 'system' decreases even as the entropy of the system + environment increases
- Abiotically produced component molecules (subsequently produced by autocatalytic networks in proto-cells, and later in cellular metabolism
- Autocatalytic sets of catalysts (polypeptides, polynucleotides)
- Closure in both the sense of physical closure (an osmotic barrier) that separates the system from everything else, and chemical or catalytic closure
- Some means of reproduction and variation at the level of autocatalytic sets and thermodynamic cycles
- Templates for replication and for coding for catalysts.

It is an open question as to which of these steps must be prior to others or if some ensemble of factors is needed before the transition to life could occur. In an emergentist approach it would be expected that several steps could arise concurrently and act synergistically to give rise to more complex structures and phenomena, among which would be included natural selection [43,113,122].

Stanley Miller, working in the laboratory of Harold Urey, demonstrated that a number of amino acids could be produced via chemical processes that might have occurred on the primitive earth [123]. Although the atmosphere globally might not have been as reducing as Miller assumed, mainly due to escape of hydrogen gas, there would be local regions that were, such as near volcanoes or deep-ocean hydrothermal vents [124]. Alternative pathways to amino acids are plausible from carbon dioxide and from hydrogen cyanide [124]. Further, the presence of amino acids in the interior of meteorites indicates that they can be produced elsewhere in the universe by natural processes; indeed, extraterrestrial sources of organic compounds might have been up to three orders of magnitude greater than terrestrial ones for the primitive earth [117 p49,125]. Further, similar such putative processes involving electrical discharge and/or solar-driven photochemical reactions involving hydrogen cyanide, formic acid, hydrogen sulfide, and methane have been shown to produce sugars and purine and pyrimidine bases [for reviews see 113,124,126–129]. Chirality in such momoners could arise in a geologically short period of time due to asymmetry in cosmic radiation that was bombarding the earth [130]. Such monomers could polymerize to form polypeptides and proteins under plausible ambient temperatures [129,131]. Alternatively, hydrogen cyanide polymers form spontaneously when hydrogen cyanide is exposed to an electrical discharge; when such polymers react with water they yield polypeptides, and even polynucleotides [132–134]. Yet another alternative for generating such polymers is considered below involving chemiosmotic-type mechanisms.

Theorizing about the abiotic generation of the organic molecules that are the building blocks of living entities has given rise to a “prebiotic soup” model of increasingly complex molecules, driven by energy flows, from which macromolecules arise allowing the emergence of directed synthesis of catalysts, from which protocells would eventually be possible, followed by metabolism in true cells [44,135]. Alternative approaches follow a “metabolism first” approach, harkening back to Haldane, Oparin, and Bernal, often invoking the catalytic capacities of clays [136–138]. A third group of approaches assumes the early presence of some sort of encapsulating barrier, a “proto-cell first” model in which chemical processes occur in high and sequestered concentrations, within which emerge the catalytic polymers and ultimately directed synthesis [77,139,140]. In this scenario the mutual interaction of catalytic macromolecules and the reactions of a protometabolism within an osmotic barrier provides the “theatre” within which specified information can emerge.

Regardless of the approach, at some point catalytic polymers would be expected to emerge and open new chemical possibilities. Polypeptides and proteins produced abiotically would initially have a random sequence [44]. But such sequences have a high probability (at least 25%) of assuming a compact, globular tertiary structure and can exhibit some weak catalytic activity [117,141]. Given that many different sequences of amino acids fold up into the same or similar three dimensional structure, the number of such possible folds is a relatively rather small number [142]. Further, completely different and unrelated sequences can produce the same active-site geometry and catalytic function, that is they overlap in the map of catalytic task space [143]. Thus a highly specified informational content is not necessary for a polypeptide to serve as a catalyst. However, when such a specification process became available via nucleic acid templates, there would be an enormous advantage to such specified information, selected on the basis of catalytic and thermodynamic efficiency.

The "hard problem" in origin-of-life research is not so much how the monomers and even polymers might have arisen by physical and chemical processes, but rather how it came to be that a digital-type code in nucleic acids came to specify the analogical information in the thousands of proteins that catalyze metabolism and are involved in signally and information processing [43,45–47,69,108,109,113,118,144–148]. It is here that the new sciences of complexity can have their greatest impact.

The Complex Systems View of the Emergence of Life

As Kauffman has analyzed in his simulations, "protein sequence space" can cover what he terms the "catalytic task space" of all possible chemical reactions that can be catalyzed by polypeptides [45]. Thus, even an ensemble of random peptides would be able to provide such coverage. Such an ensemble can be self-sustaining when it can catalyze the formation of more such catalytic polymers in what is called an autocatalytic cycle. When such a set of autocatalytic cycles can produce their components such that they are self-sustaining, a condition termed catalytic closure is said to obtain. Such catalytically closed, autocatalytic cycles can be maintained, grow, and complexify if they also have some mechanism by which they can tap available energy gradients so as to drive the ensemble away from chemical equilibrium [44,46]. In such emergent systems there would be physical selection of clusters of amino acid sequences that are soluble in water and more stable in an aqueous environment since the less stable structures would tend to degrade and less soluble to precipitate. There would also be a chemical selection of those sequences that were more efficient catalysts or which more efficiently contributed to the autocatalytic cycles and/or more efficiently extracted energy from ambient gradients as the ensembles to which they occur would tend to persist longer. Kauffman, who suspects that such an emergence of organization and complexity, an emergence of life, would be an expected consequence of natural law, possibly a fourth law of thermodynamics, writes: "We can think of the origin of life as an *expected emergent collective property* of a modestly complex mixture of catalytic polymers" [45, xvi, emphasis in original]. Such ensembles of catalytic polymers would be expected to show weak inheritance due to the action of physical and chemical selection. Such systems as those modeled by Kauffman currently are being experimentally studied by Reza Ghardiri to document their dynamics as compared to those shown in computer simulations (Kauffman, personal communication). These experiments could be enhanced through incorporating thermodynamic work cycles in their action to make them more realistic. We are moving from theoretical speculation and computer simulations to experimental testing of approaches based upon complex systems dynamics.

In such autocatalytic ensembles, possibly encapsulated in ensembles of proto-cells (see below), would be catalyzing not only their assembly but could catalyze, if weakly, chemical reactions to produce component monomers as well as the processes by which energy is extracted from the environment. These ensembles could grow and reproduce themselves even in the absence of central templates coding for such catalytic sets. Not only does Kauffman see an innate holism during the emergence of life, but he concludes that "the routes to life are broader than imagined" [45, p. 330]. Nevertheless, a crucial event during the emergence of life was the appearance of nucleic acids.

Although an "RNA World" is a popular scenario for the emergence of life, since RNA can both code and serve as a limited catalyst, there are problems with this approach because of the difficulty of abiotically adding purine and pyrimidine bases to ribose phosphate to form nucleosides and nucleotides. However, some speculative proposals still need exploration [109,149,150]. Such a problem could easily be overcome if there were some sort of proto-metabolism catalyzed by an ensemble of polypeptides that covered catalytic task space. This would be particularly so if there were an ensemble of proto-cells in which the Kauffman catalytic sets were sequestered.

The cell-first, or proto-cell first, scenarios mentioned above have a potential advantage over the chemistry of dilute solution. David Deamer has shown that amphiphilic molecules, those with a hydrophobic or "water-hating" end and a hydrophilic or "water-loving" end, though not lipids per se, can be extracted from carbonaceous chondrites (meteors containing carbon compounds) and that these molecules spontaneously form bilayered vesicles [151,152]. Other amphiphilic molecules of terrestrial origin similarly show the spontaneous formation of vesicles [153]; also photochemical routes to lipid molecules have been documented [117]. Further, vesicles of generic amphipiles and/or lipids show an autocatalytic self-replication [117,154]. Such a proto-membrane would have provided not only a way of localizing the chemistry in an ensemble of such vesicles or proto-cells, but provide surfaces at which additional chemistry could occur [117]. More importantly, membranes allow for important energy transduction reactions, driven either chemically or photochemically. Such chemiosmotic reactions, as they are called, use proton gradients across, and possibly within, the membrane to energize movement of molecules across the membrane as well as to form phosphoanhydrides — ATP in modern cells — but likely polyphosphate in early proto-cells [115,155–158]. Indeed, such chemiosmotic mechanisms are probably one of the most ancient of the characteristics of life [159]. When vesicles of amphiphiles derived from a meteorite are supplemented with polycyclic hydrocarbons also extracted from meteorites have light shinned upon them they pump protons across the membrane [160]. Thus such vesicles could not only have provided the cradle for life to emerge but also an energy-capture mechanism, which, polyphophates (and later ATP) could power polymerization reactions of amino acids and nucleotides. Alternatively, iron-sulfur membranes could have formed in the ocean of early earth near thermal vents, for which there is geological evidence as well as experimental replication in the laboratory [161]. In either possibility, the chemistry within such membranes would facilitate the actions of autocatalytic polypeptide sets and the reactions needed to generate nucleic acids, as well as the proto-metabolism in which true lipid components for membranes could have been made. What we have here is a scenario in which the elements of a complex system are emerging together and articulating with each other.

In such a case, the role of nucleic acids may have come later rather than sooner. Once both protein and nucleic acid polymers were present, though not yet in a coding relationship, there would be interactions between these types of macromolecules, possibly initially providing mutual stabilization of these polymers against hydrolysis and such interactions have been proposed as having to potential to lead to specific templating and ultimately the genetic code [44,162]. The crucial consequence of such a template coding of nucleic acids for protein sequences would be that the nucleic acids would stabilize the metabolic and autocatalytic cycle information that were more stable and efficient. Pier Luigi Luisi has estimated that such a minimal proto-cell with its osmotic barrier, from which true cells could have emerged, would probably have required around fifty to one hundred nucleic acid templates, or genes, in order to sustain viability rather than the thousands now present in the simplest bacterial cell. From such an emergence of proto-cells would arise true biological or natural selection of the reproductively fit [43]. With this type of perspective made available through the application of complex systems theory, it is possible to develop experimental plans using computer simulations and laboratory experiments to explore how such a process might have occurred. The hard problem is still hard but it is amenable to scientific inquiry.

Drawing upon empirical data and deploying computer models as well as experimental studies, emergentists are seeking to develop a theory that encompasses the problems of the origin of life itself, of biological information and of natural selection that is general in its principles, incorporating life as we know it but also life as it might be. Kauffman assumes that the universe is not a closed system and thus is not fully determined by initial and boundary conditions, but rather is open and has a possibility so enormous that fifteen billion years has been sufficient for exploration of only a small subset of the possible patterns of organization [46]. When a sufficiently complex organization emerges, not only does natural selection arise, but also the autonomous agency exhibited by living entities. He seeks a possible fourth law of thermodynamics that would account for the emergence of life and new organization. Deacon seeks to develop a broader theory of general biology through expanding our conception of organism [69]. His *autaea* are the chemical systems that exhibit autonomous self-maintenance, in contrast to all other configurations of matter, and include autocells. Autocells have coherent and integrated organization as well as self-reproduction in that they can reproduce by direct morphological means. Such *morphota* would include not only autocells, but also bilayer vesicles capable of reproduction or reproduction of autocatalytic sets. The transition to life comes when it is possible to transmit information of representation via genetic coding, so living things as we know them are also examples of *semeota*. The criteria Deacon develops for these categories and the specific example he explores can give us insight as to how to frame questions as to whether some entity encountered elsewhere in the universe is living or to delineate the logical requirements for the emergence of life. In Deacon's view, as in that of Weber and Depew, natural selection emerges as a phenomenon along with the phenomenon of the emergence of life, which in turn is a specific instance of the interaction of self-organizational principles with each other and with general selectional principles [3,43,67,69,71,113,118,163,164].

Implications of an Emerging Emergence Paradigm

We are in the very early stages of the development of the emergentist research program. If successful and if widely adopted such theories of emergent organization and general biology may in time become a new paradigm. Even in these early years it is generating new theoretical and experimental approaches that are particularly relevant to the problem of the emergence of life. When a more complete picture of how life might have emerged is available and we see how it fits into a broader theory of general biology, it will be time to assess whether the Darwinian Research Tradition, if not the Modern Evolutionary Synthesis, can encompass such insights, or if some new conceptual synthesis will be required. At this point we can acknowledge that Conrad Waddington's intuitions were fecund but needed the developments in biochemistry, molecular biology, developmental genetics, computer simulations, and complexity theory to be cashed out.

The complexification of abiotic chemical reactions is driven primarily by nonequilibrium thermodynamics, exploring state space in an ergodic fashion. When the transition occurs to living systems, a much larger state space of combinatorial possibilities, provided by catalytic (and templating) polymers, is explored by a combination of self-organizing and selecting processes via what Kauffman terms the "adjacent possible" [45,46]. Though thermodynamics provides the driving force for self-organization, it is the kinetic mechanisms that afford the pathways of emergence. With the emergence of life there is a shift to an extreme expression of kinetic control in which thermodynamic requirements play a supporting rather than directing role. Replication is an instance of this kinetic control. From this emerges the teleonomic and semiotic character of living entities.

In the emergentist perspective, organisms are begotten not made, that is they are the result of developmental processes individually and of evolving lineages. In both cases these phenomena are viewed the result of an on-going interplay of selection and self-organization. What organisms, or their constituent parts, are not, are artifacts. Although emergentist and reductionist approaches to biology share a commitment to methodological naturalism, they view organisms differently in this sense of the importance of epigenetic processes. What the reductionist version of the Modern Evolutionary Synthesis and proponents of intelligent design theory share is a view of biological traits and molecules as artifacts, something made by a designer or by the process of random variation and selection. Emergentists argue that natural and artifactual systems should not be conflated; by anchoring the emergence of life and natural selection in natural laws and processes of thermodynamics and kinetics, a conceptual wedge is driven between natural organization and design.

Elsewhere I address my more general philosophical problems with design arguments [165–167]. Here I am attempting only to argue that whereas the emerging theory of general biology is generating novel theoretical insights, predictions, and experimental approaches by which we can deepen our understanding of the emergence of life, ID theory does not suggest how to proceed theoretically or experimentally as to how life originated, other than to place the causes outside of scientific scrutiny. ID seems to me to provide only a negative capability by criticizing proposed naturalistic and emergentist explanations for the origin of life. Good critics are always helpful in the process of scientific research, but any research program worth its salt also has to guide in the generation of new experiments and theories. The latter is being achieved by those, such as Deacon, Deamer, Ghardiri, Kauffman, Luisi, Morowitz, and Wicken among others, seeking to understand the emergence of life, but not yet substantially by those advocating design arguments.[4]

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[4] ID advocates would, of course, dispute these assessments, arguing that intelligent causes can reliably be distinguished from unintelligent (undirected natural) causes, and that intelligent causation therefore forms a significant part of our understanding of the cause-and-effect structure of the world under uniformitarian assumptions and constraints. As noted above, emergentists would argue against

Through processes of emergence, life itself may be viewed as begotten, not made, from underlying natural laws and a dialectic of self-organization and selection.

What Might We Expect from a Theory of General Biology About the Origin of Life?

We not only have to acknowledge the difficulty of the problem of how life might have emerged here on earth, let alone how it might emerge and instantiate elsewhere in the universe, but we need to accept that we should not expect a single narrative trajectory for life's emergence. Not only would the earliest true living beings destroy the traces of earlier transitional forms, but the action of living systems alters in fundamental ways the chemistry of their environments. Thus, we can only hope to elucidate plausible pathways of emergence, tested by simulations, experiments, and what geological data is available. This is not unlike the point Keith Miller makes about the paleontological record, in which we do not have all the details but do have some general patterns to explain [168]. Thus, we need to explore all possible routes of chemistry and proto-biochemistry to develop a range of plausible scenarios for life's emergence on earth and to eliminate those that are unlikely, through theoretical analysis, computer simulations, and experimentation.

In complex systems not only is the whole defined by closure conditions (physical and catalytic) but there is redundancy and parallelism. Thus even weakly insipient functional patterns of structure and interaction can persist due to greater stability and/or efficiency. With functionality comes pressure for improved structures/stability/efficiency, through an on-going process of selection and self-organization. Thus in the origin of life, we should not expect one function to be perfected, say replication, before others appear, but that there would be an inherent holism in the process by which cellular life arose [43,45,46,113,118,140,147].

If there is not grandeur in this view of the emergence of life at least there is a reasonable hope for progress, through application of the tools of complex systems dynamics, towards developing a theory of emergence and of general biology.

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this conflation of natural and artifactual systems. To be fair to ID advocates, however, a more substantial ID research program seems to be brewing as of late, as evidenced in the research being done through the Evolutionary Informatics Lab (http://www.evoinfo.org) and in the work of Biologic Institute (http://www.biologicinstitute.org) and its journal *BIO-Complexity* (http://bio-complexity.org/ojs/index.php/main/index). Indeed, this present volume is part of that general trend. The only thing that can be said is that we must wait and see whether these efforts will go anywhere. For a broader discussion of these issues from a variety of perspectives, both supportive of ID and critical, see Gordon and Dembski [169].

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