EMERGENCE OF LIFE

by Bruce H. Weber

Abstract. Discussions of the origin of life usually assume that there is a specific event, however improbable, by which dead matter became a living entity. Naturalistic accounts, although in seeming opposition to theistic explanations of the apparent design of even the simplest cells, often share the assumption that there is a specific line to be crossed. If the problem is recast as one of a process of emergence of biochemistry from protobiochemistry, which in turn emerged from the organic chemistry and geochemistry of primitive earth, the resources of the new sciences of complex systems dynamics can provide a more robust conceptual framework within which to explore the possible pathways of chemical complexification leading to life. In such a view the emergence of life is the result of deep natural laws (the outlines of which we are only beginning to perceive) and reflects a degree of holism in those systems that led to life. Further, there is the possibility of developing a more general theory of biology and of natural organization from such an approach. The emergence of life may thus be seen as an instance of the broader innate creativity of nature and consistent with a possible natural teleology.

Keywords: biogenesis; complexity; emergence; natural organization; natural teleology; origin of life; process

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> *How far can we reduce life and still call it life? Is DNA alive? Where is the line between chemistry and life?*
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> —James Rollins, Black Order (2006, 211)

In the beginning . . .

All cultures tell stories about the origins of the cosmos, of life, and of people. Such narratives give us insight into what people of that culture

Bruce H. Weber is Professor of Biochemistry Emeritus, California State University Fullerton, and Robert H. Woodworth Chair in Science and Natural Philosophy Emeritus, Bennington College. His address is Department of Chemistry & Biochemistry, California State University Fullerton, Fullerton, CA 92835-6866; email bhweber@fullerton.edu.

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believe to be important about themselves and the natural world in which they are embedded. In our culture increasingly the creation narratives of received religious traditions are being replaced by accounts provided by science. In the scientific account, the origin of life is increasingly seen to be the result of a natural process of emergence rather than an event of creation or a line to be crossed (R. F. Fox 1997; Weber 1998; Kauffman 2000; Lurquin 2003).

If the origin of life is a highly improbable event, it can either be the result of chance or seem to be a miracle brought into being by a cause outside of nature. The latter is the claim of creationists and advocates of intelligent design. Specifically, they challenge any attempt to account for the emergence of life by natural causes and processes. In contrast, the methodological naturalism of scientists assumes that scientific explanations must be confined to causes within nature. This provides a framework for exploring the possible avenues by which life might have arisen as an expected result of the action of natural processes. A commitment to methodological naturalism does not logically entail a commitment to metaphysical naturalism (a.k.a. philosophical materialism). Indeed, it is quite possible to be a theist while pursuing methodological accounts of nature (Haught 2000; 2003; 2006; K. R. Miller 1999; Ruse 2001). Although philosophical materialism, to be a viable position, must be able to provide a naturalistic account of the emergence of life, such accounts neither require nor refute theism (Clayton 2006; Haught 2006).

In this essay I review the history of ideas about the origin of life and assess the current status of such research, particularly in light of the new sciences of emergent complexity. Then I consider the possibility that such a naturalistic account of the emergence of life could allow the legitimate use of teleological language in scientific discourse, what we can term a natural teleology. Finally, I explore some implications of this view of nature as innately creative.

EARLY SCIENTIFIC SPECULATION ON THE ORIGIN OF LIFE

Charles Darwin was careful to bracket off the issue of the origin of life from his account of the origin of species through the action of natural selection culling heritable variations in populations of species in particular environments. He stated, “How a nerve becomes sensitive to light hardly concerns us more than how life itself originated” (Darwin [1859] 1964, 187), and envisioned life being “breathed into a few forms or into one” ([1859] 1964, 490). Privately, however, Darwin was willing to speculate in more naturalistic terms. In a letter to Joseph Hooker in 1871 he wrote, “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).

One reason for keeping his speculations private was that there was a ongoing debate in the nineteenth century about the spontaneous generation of life based upon the "active materialism" of French biologists, such as Jean Baptiste Lamarck and Etienne Geoffroy Saint Hilaire. This view, introduced into England in the 1820s by Robert Grant, one of Darwin's teachers, saw matter as capable of spontaneous self-organization. This was a position accepted and avidly advocated by English socialists of the 1830s (Desmond 1989; Fry 2000; Strick 2000). In the end it was shown that spontaneous generation was an illusion and that even if such incipient life should form today it would be quickly devoured by existing life forms. It was Herbert Spencer (1864) who argued that biological evolution was part of a cosmic process of becoming less homogeneous and more complex in which the origin of life was an instance. At the beginning of the last century Josiah Royce (1904) clearly distinguished the broader vision of Spencerism from the more focused claims of Darwinism. Most advocates of the Modern Evolutionary Synthesis, or neo-Darwinism, continue to argue that evolutionary theory and the origin of life are conceptually separate issues (Scott 2004). Opponents of Darwinism continue to conflate the two (Behe 1996; Meyer 2003; Bradley 2004).

The possibility of an abiotic generation of living entities under the conditions of the primitive earth was taken up anew in the 1920s and 1930s by scientists, many of whom, as it happened, had Marxist philosophical commitments. At this time the understanding of biochemistry and geochemistry had advanced sufficiently that scientifically based speculations about a natural origin of life seemed possible. J. B. S. Haldane and Alexander Oparin suggested that abiotic chemical processes could produce and accumulate organic compounds of increasing complexity from which a possible protometabolism of chemical transformations similar to the metabolism in modern cells could emerge (Haldane [1929] 1967; Oparin 1924; 1938). Another Marxist scientist, J. D. Bernal (1951; 1967), suggested that various clays could provide the catalytic and template characteristics needed to facilitate the emergence of such a protometabolism. Such speculations set the stage for experimental and theoretical exploration of the possible routes of the emergence of life over the next sixty-some years.

1953 AND AFTER BUT BEFORE THE RISE OF COMPLEXITY THEORIES

The year 1953 is remarkable in the history of science not only for the discovery of the double helical structure of DNA (Watson and Crick 1953) but also for the demonstration, by then graduate student Stanley Miller working in the laboratory of Harold Urey at the University of Chicago, that chemical processes possible on the early Earth could produce molecules needed for life (S. L. Miller 1953). His experiment showed that an electrical discharge passed through a mixture of gases of methane, ammonia, water, and hydrogen (then believed to reproduce Earth's primitive atmosphere) produced a mixture of some of the amino acids needed as building blocks for proteins. This set off a flurry of activity to see how many different amino acids could be made as well as other key molecules needed for life, such as sugars and the purine and pyrimidine bases needed for nucleic acids (see Lahav 1999; Wills and Bada 2000; Bada and Lazcano 2003 for a description of the Miller experiment and its subsequent impact).

After 1953 it became commonplace to think of a prebiotic "soup" or "broth" of increasingly complex molecules from which macromolecular polymers, proteins and nucleic acids, could be formed (R. F. Fox 1997; Lurquin 2003). This soup scenario contrasted with the earlier metabolism-first proposals of Oparin, Haldane, and Bernal that saw directed synthesis of protein catalysts from nucleic acid templates as arising later in the emergence of life after the a metabolic web of chemical transformations had arisen. The soup model proposed instead the following sequence: small molecules → macromolecules → directed synthetic systems → protocell → cell, where the appearance of macromolecules capable of self-replication (nucleic acids) arose by accident. Afterward the macromolecular catalysts (proteins acting as enzymes) would have made metabolism possible.

This latter approach has dominated recent research on the emergence of life. In one version it is assumed that proteins came first and later became templated by nucleic acids (S. W. Fox and Dose 1972; S. W. Fox 1988). In another, known as the "RNA world," it is assumed that nucleic acids, specifically RNA, came first and had both catalytic and template function (Woese 1967; Orgel 1968; Cech 1986). Alternatively, it is possible that both types of polymers (proteins and RNA) emerged together through mutual chemical interactions (R. F. Fox 1982; 1988; 1997; Wicken 1987). More recently, there have been various attempts to revive versions of metabolism-first (Morowitz 1992; Wächterhäuser 1988; 1992; 1997). Finally, there are proposals to place some sort of encapsulating barrier, which would allow protocell formation, as the first crucial step in the process of the emergence of life (Morowitz, Deamer and Smith 1991; Morowitz 1992). In effect, each approach assumes priority to some aspect characteristic of living systems today. There also is the possibility that the emergence involved parallel processes of several or all of these features (Weber 1998; 2000).

Importantly, the Miller-Urey experiment, as it is known, moved thinking about the origin of life from primarily philosophical assumptions and theoretical speculations about how biochemical systems came into being to an empirical research program. Sidney Fox (1965) demonstrated that at high temperatures (around 200° Celsius) amino acids could polymerize to form proteins. This suggested that proteins were the first macromolecules to emerge from the soup and, because today proteins function mainly to catalyze metabolic chemical reactions, the proteinoid spheres could have been the cradle in which life emerged. Such proteinoids might have formed at lower temperatures (Kumar and Oliver 2002; Leman, Orgel, and Ghadiri 2004). It also has been suggested that hydrogen cyanide polymers, which also form in the Miller-Urey experiment, could yield polypeptides (and possibly even polynucleotides) directly when reacted with water (Matthews and Moser 1967; Liebman, Pesce-Rodriguez, and Matthews 1995; Minard, Hatcher, Gourley, and Matthews 1998).

Nearly concurrently it was shown that the important purine adenine could be produced abiotically from hydrogen cyanide (Oró 1961). Because other components of nucleic acids appeared to be easily produced abiotically it was suggested that ribonucleic acid (RNA) might have been the original macromolecule since it could not only serve as a template for its own replication but had the potential for some limited catalytic activity (Woese 1967; Orgel 1968). Various ideas have been explored by which polymers of nucleotides could have formed. When catalytic activity of present-day RNA was demonstrated (Cech 1986; 1987; Wilson and Szostak 1995), such proposals of RNA “ribozymes” became more credible and led to the proposal of an RNA world in which RNA was the first template, replicator, and catalyst (Orgel 1992; Joyce and Orgel 1993; Gesteland and Atkins 1993). This fit well with Richard Dawkins’s notion that life arose as a highly improbable event with the first replicating nucleic acids that subsequently decorated themselves with proteins, lipids, carbohydrates, and cellular structure to protect and better perpetuate themselves by templating such “gene machines” (Dawkins 1976; 1989).

There are problems with such RNA-first scenarios. No convincing chemical route has been proposed by which the purine and pyrimidine bases might be attached to ribose abiotically; however, some recent speculative proposals need further exploration (Joyce and Orgel 1993; Schwartz 1997). Also, although RNA can do some limited catalysis, it lacks the range of catalytic activity possible with a set of polypeptides. Stuart Kauffman has explored the potential of ensembles of randomly generated catalytic peptides to foster a wide range of chemical reactions, what he terms “catalytic task space” (Kauffman 1993, 146–54). Kauffman’s computer simulations show that the great richness of possible sequences of the polypeptide chains of proteins (protein sequence space) easily cover the tens of millions of possible chemical reactions of catalytic task space. Such autocatalytic sets of polypeptides not only catalyze reactions generally but also specifically reactions that lead to the formation of more of the compounds of the reaction set, including catalysts (hence, “autocatalytic”). When an ensemble of autocatalytic sets of polymers catalyzes all of the reactions necessary to sustain itself, the condition of *catalytic closure* obtains, and the ensemble behaves to sustain itself, even reproduce itself after a fashion. In such autocatalytic sets the catalysis of purine and pyrimidine attachment to ribose would be easily feasible, and thus RNA could be synthesized by several plausible routes (Weber 1998; 2000). Both proteins and nucleic acids could interact to mutually stabilize each other, and such interactions could have led to specific templating and ultimately gave rise to the genetic code (Carter and Kraut 1974; Wicken 1987; Weber 1998). Further, Kauffman's protein catalyzed protometabolism suggests the possibility that the templating information of nucleic acids arose to stabilize information about those protein sequences that were more chemically and thermodynamically efficient in supporting the autocatalytic sets.

Not only is catalytic closure important; so is physical closure. All cells have a membrane barrier of lipids that encapsulates them, providing an osmotic barrier for molecules and ions. This prevents their diffusion across the barrier because the lipids have amphiphilic character. An amphiphilic molecule has a hydrophobic (water-hating) end and a hydrophilic (water-loving) end. These molecules spontaneously arrange in water to create vesicles of bilayers with a hydrophobic barrier to the movement of charged molecules and atoms while separating an inside from the rest of the outside aqueous environment. If such vesicles could have arisen early in the process of the emergence of life, they could have countered the problems of dilution and diffusion that would otherwise plague the development of autocatalytic sets. So a protocell-first model has been proposed (Morowitz, Deamer, and Smith 1991; Morowitz 1992; Deamer et al. 2002). Amphiphilic molecules, though not lipids, have been discovered in carbonaceous chondrites (meteors containing carbon compounds) and shown capable of producing bilayered vesicles (Deamer and Pashley 1989; Deamer et al. 2002). Amphiphiles of terrestrial origin, likely to have been available early in the history of the earth, also have been shown to form vesicles (Ourisson and Nakatani 1994). Such amphiphiles show autocatalytic self-replication (Bachmann, Luisi, and Lang 1992; Luisi 2006).

Further, the existence of some type of membrane would have allowed for energy-capture mechanisms that could have powered the chemistry of self-organization. Only when systems are driven away from chemical and thermodynamic equilibrium can internal structures in the system arise (Prigogine 1962; 1980; 1997; Prigogine and Stengers 1984; Wicken 1987; Depew and Weber 1995; Weber and Depew 1996; Kauffman 2000; Kleidon and Lorenz 2005). All types of cells use energy (chemical, osmotic, photochemical) to pump protons across membranes to produce a difference in proton concentration and charge across the membranes. This difference can then be used to do chemical or osmotic work; the mechanisms of such systems are called chemiosmotic (Mitchell 1961). The aqueous environment places chemical constraints on, as well as provides opportunities for, the types of compounds and their reactions that are essential for living systems found on Earth (Williams and Fraústo da Silva 1996; 1999; 2003; 2006; forthcoming). Phosphoanhydrides, such as polyphosphates initially and subsequently in life today ATP, are especially suited for serving as the "energy currency" of cells at neutral pH because of their unique combination of properties of kinetic stability and thermodynamic instability in water (Westheimer 1987; Baltscheffsky and Baltscheffsky 1992; Arrhenius, Sales, Mojzsis, and Lee 1997; Yamagata and Inomata 1997). Indeed, the interplay of hydrophobic and hydrophilic domains of membranes provides the basis for the synthesis of ATP and more generally for biological energetics (Mitchell 1961; Williams 1961; Prebble and Weber 2003; Weber and Prebble 2006). Thus, it can be expected that very early in the emergence of life chemiosmotic mechanisms arose. This is substantiated by the observation that the two characteristics that are virtually universal, hence present in the last common ancestor of all life, are the genetic code and chemiosmotic energy coupling (Lane 2006).

The observation that amphiphilic vesicles derived from meteorites, when supplemented with polycyclic hydrocarbons also from meteorites, pump protons when exposed to light, suggests that a protocell-first scenario could provide energy as well as a container for the chemistry of emergence (Deamer 1992; Weber 1998; 2000). But, this is not the only way that compartmentalization and chemiosmotic processes could have arisen. Iron-sulfur membranes have been produced under conditions thought to have existed in the primitive oceans of early Earth (Martin and Russell 2003). Hot, reduced-alkaline waters produced by thermal vents in the crust could have swept up from the ocean depths to mix with cooler, more oxidized, and acidic waters containing iron-sulfur salts and carbon dioxide from above. Where these waters mixed microscopic bubbles with membranous structures would have formed (these form in the laboratory, and there is evidence that such structures have formed in the past in nature). The outside of these iron-sulfur membrane vesicles were naturally acidic and the interior basic, creating a chemiosmotic proton gradient, which in turn could drive polyphosphate synthesis. Further, the iron-sulfur membrane would have all the catalytic and chemical potential for oxidation-reduction reactions that has been proposed (Wächterhäuser 1988a, b; 1992; 1997). Such an iron-sulfur membrane would have allowed simultaneously for a catalytic surface, chemiosmotic mechanisms, and containment of molecules against diffusion. Such might have been the cradle of life.

There are plausible routes by which amino acids and purines and pyrimidines, and their polymers, could have been synthesized from the hydrogen, ammonia, hydrogen cyanide, hydrogen sulfide, methane, and formic acid believed to be produced by the geochemistry of the thermal vents (Imai et al. 1999; Leman, Orgel, and Ghadiri 2004). From the geochemistry the beginnings of a protometabolism could have emerged, ultimately producing catalytic closure and a metabolism capable of generating the lipid molecules that came to replace the iron-sulfur membrane. While such iron-sulfur membranes could have provided a stable chemical environment over hundreds of millions of years, the ability to generate lipids and form cellular membranes meant that cells could break free from this interface zone and occupy a wide range of niches. This would have been so advantageous that there would be no looking back; however, proteins containing iron-sulfur reaction centers remain in the lipid-membrane-embedded respiratory chains of all cells as a relic of this past history. Probably by about 3.8 to 3.5 billion years ago the eubacteria and the archaea (or archaebacteria), two of the three main branches of life, were free to "roam" and to explore new niches in which to flourish. Much later, around 2.0 to 2.5 billion years ago, a symbiotic association of a bacterium and an archaebacterium led to the emergence of complex cells known as eukaryotes by a process that seems much more highly contingent than the paths that led to unicellular bacterial and archaebacterial life (Martin and Russell 2003; Lane 2006). The eukaryotes were much more efficient in their ability to capture metabolic energy from nutrients and thus were able not only to sustain greater internal complexity but also to form stable multicellular organisms over the past 800 million years or so (Lane 2006).

ASSESSING THE STATUS OF ORIGIN-OF-LIFE RESEARCH

Ronald Fox, writing in this journal in 1997, provided the background of basic chemistry that underpins research on the origin of life, particularly that generating the "building blocks" of proteins and nucleic acids. In the same year a special issue of the *Journal of Theoretical Biology* was devoted to the origin of life. One fundamental conclusion was that if we can understand the chemistry underlying the emergence of life, we can know how likely life is to exist elsewhere in the universe. This conclusion still holds. In 2004 Jeffrey Bada evaluated the status of research on how life began on Earth and concluded that anywhere water and organic polymers, such as proteins and nucleic acids, can arise there likely will also be living entities. Steven Benner has suggested that what is essential is a solvent system, availability of elements such as carbon, hydrogen, nitrogen, sulfur, and oxygen, and a thermodynamic disequilibrium at temperatures consistent with chemical bonding (Benner, Ricardo, and Carrigan 2004). Although this general notion seems likely, there are many details still to be worked out.

One aspect of the problem of understanding how life emerged on Earth, or might emerge elsewhere, is that it seems likely to have been a process of emergence rather than an event or even a sequence of discrete events. As we have seen, there are plausible scenarios in which metabolism is first, or proteins, or nucleic acids, or amphiphilic membranes. Or, possibly, aspects of all of these needed to be present in crude and inchoate form before the interaction of self-organization and selection acted to effect the transition from chemical complexity to biological chemistry (Depew and Weber 1995; Weber and Depew 1996; Weber 1998; 2000; Luisi 2006).

Ideas about what conditions obtained on the primitive Earth change as more is learned about geochemistry, such that the conditions assumed by Miller and Urey seem unlikely to have been the general case, although there may well have been local environments (near volcanoes or deep-ocean hydrothermal vents) where the chemical environment was as reducing as they assumed (see Schopf 1983 and particularly Bada 2004 for a discussion of the chemistry of the early Earth and its implications for the Miller-Urey experiment). Alternative routes involving carbon monoxide could also produce amino acids, and, further, the formation and polymerization of hydrogen cyanide provide major chemical pathways to amino acids and the purine and pyrimidine constituents of nucleic acids (Bada 2004).

It must be remembered that any earlier entities that existed during the process of emergence of life would have been either outcompeted and gone extinct or used as a nutrient source by cells that we would recognize as being alive. In the five decades since the Miller-Urey experiment we have come to understand much more about geochemistry as well as biochemistry, but we are still very early in the research program to understand how life emerged on Earth and how it might emerge elsewhere, a point made recently by Michael Ruse (2006). We can well expect that in the decades to come significant advances in our understanding of the process of life's emergence will be made. However, we should expect not *the* scenario by which life originated but rather a collection of scientifically feasible routes that can be fitted together into an ensemble of plausible scenarios. This parallels the understanding of paleontologists for whom the phenomenon to be explained is the overall pattern of transitional forms rather than the specific path of descent of some lineage (K. B. Miller 2003). This also is consistent with our developing understanding of how complex systems behave and what we can expect to be able to learn about them.

As pointed out by Ronald Fox (1997), the hard problem for understanding the emergence of life is not so much how the necessary chemical components came into being but how it came to be that a digital type code in nucleic acids came to specify the analogical information of the protein catalysts that make the tens of thousands of reactions and signals of metabolism possible. The emergence and increase of novel, specified, functional information remains the crucial issue (Krüppers 1990; Kauffman 1993; 2000; 2004; Depew and Weber 1995; Weber 1998; Meyer 2003; 2004; Bradley 2004; Yockey 2005; Deacon 2006). Another way to state this problem is, How did the “informed” organization of living systems come about? A promising new conceptual approach comes from the new sciences of emergent complexity.

THE COMPLEX SYSTEMS VIEW OF THE EMERGENCE OF LIFE

In the past few decades, conceptual and computational developments have given rise to what may be characterized as the sciences of complexity, or complex systems dynamics. In this new field, nonlinear dynamics, nonequilibrium thermodynamics, and information theory, inter alia have been joined to address the behavior of complex systems (Prigogine 1980; 1997; Peacocke 1983; Brooks and Wiley 1986; Wicken 1987; Pagels 1988; Swenson 1989; Waldrup 1992; Casti 1994; Weber and Depew 1996; Ulanowicz 1997; Bar-Yam 1997; Dewar 2003; Taylor 2003; Kleidon and Lorenz 2005; Schneider and Sagan 2005). Exploration of the dynamics of complex systems has reinvigorated notions of and interest in the process of emergence, which seems to be intimately connected with the self-organization observed in complex systems (Ulanowicz 1997; Kauffman 2000; Corning 2002; 2003; Morowitz 2002; Silberstein 2002; Deacon 2003; 2006; Clayton 2004; 2006; Schneider and Sagan 2005; Luisi 2006). Such systems have a type of natural teleology in the sense that there are rewards for competing entities that function to produce more thermodynamic or informational entropy externally while building internal structural and informational organization, or that decrease gradients of matter/energy more effectively (Weber and Depew 1996; Camazine et al. 2001).

Kauffman, who has applied such approaches to the origin of life, views the emergence of life as an expectable phenomenon: "We can think of the origin of life as an *expected emergent collective property* of a modestly complex mixture of catalytic polymers" (1993, xvi). A ensemble of protocells could emerge even in the absence of genetic information; indeed, that role of nucleic acids could have come later, with of course very great consequences for the stability of such systems over time. "If this model is correct," Kauffman writes, "then the routes to life in the universe are broader than imagined" (1993, 330). Kauffman worries, though, if we understand enough about how natural systems self-organize, whether we have a viable theory of organization that allows for the emergence of not only complexity but agency (Kauffman 2000; 2004). Kauffman's project is to work toward an understanding of what he calls the fourth law of thermodynamics that can be used to explain and explore the wide range of phenomena that proceed spontaneously (under the right conditions) to greater complexity.

Ian Stewart agrees that there is a lack of closure such that another principle is needed; he sees the quest for a fourth law having as its goal "to formalize or explain the tendency of living systems to increase their order. Any such law must be formulated in a context-dependent manner and not simply adjoined to the first three laws of thermodynamics on the assumption that such laws are universally valid. Kauffman's proposals about autonomous agents are suitably context dependent" (Stewart 2003, 141–42).

Kauffman assumes that the universe is not closed and fully determined by initial and boundary conditions but that it is open and that the possibility space so enormous such that 14 to 15 billion years has allowed for only a very small exploration of possible organization. Of course, this makes the formulation of the putative fourth law more problematic (Kauffman 2000). Such a putative law is envisioned as favoring the emergence of life, as described by autocatalytic cycles capable of reproduction, performing thermodynamic work cycles (extracting energy from gradients), and exhibiting autonomous agency (Morowitz 1992; Kaufmann 1993; 2000; 2004; Weber 1998; Ulanowicz 1997; 2002; 2004; Deacon 2006).

Terrence Deacon has addressed a broader issue of developing a theory of general biology by proposing that we expand our conception of *organism* to include a wider variety of organized systems (Deacon 2006). He suggests a taxonomy of natural organization that distinguishes entities that are organized, self-maintaining, self-reproducing chemical systems—designated *Autaea* because of their autonomous self-maintenance—from all other configurations of matter. Autaea include living organisms but also chemical systems that he calls autocells, which exhibit coherent integrated organization and self-reproduction by direct morphological means, not via "coded" (for example, genetic) mechanisms. Autocells are members of a taxon he calls *Morphota*, characterized by morphological reproduction, which is distinguished from *Semeota*, reproduction via separate transmission of genetic representation (Deacon 2006). Morphota exhibit properties that are intermediate between simple self-organization on the one hand and life on the other. Morphota have functions and thus exhibit a primitive form of "purpose" derived from the integration of their component self-organizing processes, but they are not alive in any usual sense. To the extent that self-organizational properties of the universe more generally are considered, the proper analog of a coherently integrated self-organizing universe would be to Morphota rather than Semeota. This allows us to identify purpose of a kind in the universe irrespective of the distinctive characteristics of life. It also suggests that life did not arise as an event that transformed dead matter but rather as a process of emergence from rich chemical dynamical systems. Deacon applies his notion of autocell dynamics specifically to the problem of the emergence of life in an attempt to delineate the logical requirements of the dynamics of life's emergence, regardless of the chemical specifics in any specific location or time (Deacon 2006). In his view, as in that of Weber and Depew, natural selection emerges as a phenomenon with the emergence of life, in which it is an instance of a more general selective principle interacting with self-organizational principles (Weber and Depew 1996; Weber 1998; 2000; Weber and Deacon 2000; Deacon 2003; 2006).

Peter Corning agrees that the crucial problem is understanding how emergent complexity comes about but argues that a new law per se does not need to be discovered; what is needed is a recognition of a principle of synergy that encompasses chance, necessity, selection, and teleonomy (appearance of goal-directed behavior that is actually *because of* the action of natural law) and that also gives a major role to history. For Corning, history matters: “Evolution is not simply an epiphenomenon of a few deep laws” (2003, 293). He sees that the science of history, which he hopes can be developed, is not dissimilar to the theory of organization to which Kauffman aspires, since, particularly in his more recent writings, Kauffman views the universe as having an almost unlimited number of potential states, of which only a minuscule fraction have been explored in the last 14 billion years or so, and hence its history, though contingent, is nonergodic. Rather than being an enemy to the emergence of life and mind, Kauffman’s exploration of possibility space provides the opportunity for these to emerge, in some sense, as an expectation of the action of natural processes. Arguing from different premises based upon observations of evolutionary convergence, Simon Conway Morris (2003) comes to a similar conclusion about the inevitability of life and mind within the limitations of life as we know it on Earth. Contingency is constrained by convergence.

Life may be expected anywhere in the universe where the right type of conditions obtain, and those conditions may well be broader than those of terrestrial life. But, if history is important, the particular trajectories of the emergence and evolution of life may not be so inevitable. The appearance of more complex cells and multicellular organisms may depend upon contingent events as much as the action of deep laws. If we should encounter living entities elsewhere we will likely recognize them as alive, but we might find alien minds, well, alien.

IF LIFE IS NATURALLY EMERGENT, IS A NATURAL TELEOLOGY POSSIBLE?

Shifting the discourse about chance, necessity, design (apparent or real), and teleology in nature from assumptions of a closed universe, in which initial and boundary conditions determine the future, to that of an open universe, in which genuine novelty can emerge, would constitute a paradigm shift in which there might be a “teleology without teleology,” as Paul Davies suggested (1998). Philip Clayton similarly suggests that there can be a proto-purpose or “*purposiveness without purpose*” (2004, 97). These suggestions revive and extend notions about a possible natural teleology put forward earlier by Lawrence Henderson (1917) and Joseph Needham (1936). Recent speculations point to such a possibility, that the universe is radically non-ergodic in principle and that genuine, unexpected novelty has arisen and will continue to by the processes of nature (Kauffman 2000; Conway Morris 2003; Deacon 2003; Polkinghorne 2004; Ulanowicz 2004; Weber and Depew 2004; Clayton 2004). If such notions prove sustain-able, there are important implications for science, for design arguments, and for teleology. As Charles Harper notes, "a scientific appraisal of the nature of reality admitting hierachically emergent ontology requires that theories of everything cannot aspire to completeness" (2005, 47). Davies opines that

> emergent laws of complexity offer reasonable hope for a better understanding not only of biogenesis [ie emergence of life], but of biological evolution too. Such laws might differ from the familiar laws of physics in a fundamental and important respect. Whereas the laws of physics merely shuffle information around, a complexity law might actually *create* information, or at least wrest it from the environment and etch it onto a material structure. (Davies 1999, 259)

A putative "fourth law" would thus be expected to have a role not only for history but also for information generation. Perhaps there is a new science of "infodynamics" coming into being. Robert Laughlin writes, "I think a good case can be made that science has now moved from an Age of Reductionism to an Age of Emergence, a time when the search for ultimate causes of things shifts from the behavior of parts to the behavior of the collective" (2005, 208). He notes, "Nature is regulated not only by a microscopic rule base but by powerful and general principles of organization. Some of these principles are known, but the vast majority are not" (p. xi). He argues that informational organizational principles are prior to the laws of physics, "since principles of organization—or, more precisely, their consequences—can be laws, these can themselves organize into new laws, and these into still newer laws, and so on" (p. 7).

Emphasis on emergence shifts attention from static structures, which might be construed as designed, to a process in which both laws and chance play crucial roles. Earlier, Davies argued that the laws of nature allow for "genuine emergence of complexity in nature, an emergence that requires these laws but goes far beyond a mere unfolding of their consequences" (1998, 151). Thus complexity requires not just the action of laws but also radical chance to produce self-organization and emergence, such that the process is not simply deterministic. Because of the role of chance Davies doubts that the laws of physics can be said to contain life or mind. But the principles of emergence give rise to novelty just because history is important. Thus, the laws of physics are necessary, though not sufficient, for the emergence of life and mind. Emergent structures may give the appearance of well-crafted design (Dembski 1998), but "it is entirely the result of natural process. In effect, it renders a teleology without providing one" (Davies 1998, 151). This teleology without teleology is, I believe, a teleology of emergent organization and complexity. As I argue (Weber forthcoming), this is not the teleology of the classical design arguments of Plato, Cicero, William Paley, or William Prout but rather more like the teleology of Aristotle, Kant, Asa Gray, or Charles Darwin, in which causality and purpose exist *within* organisms or in their relationship to the environment. Nor is it even the teleology of William Whewell, with his emphasis on the properties of deep laws. Rather, in such a natural teleology, chance is not the enemy but a collaborator in creation.

But have we now emptied teleology of any possible theological interest? Ian Barbour recently has explored the implications for process philosophy, and by implication for process theology, focusing on a number of issues, including several we have examined here: teleology and its relationship to contingency, complexity, and design, as well as self-organization and emergence (Barbour 2005). Contingency means that the teleology of nature cannot fulfill a detailed plan, but there could be a broad directionality without a preordained goal. Barbour argues that recent progress on these issues opens new dimensions of consideration of the interplay of science and metaphysics, concluding, “It is to be hoped that the dialogue can be fruitful between philosophers or theologians well informed about current evolutionary theories and biologists open to alternative philosophical assumptions” (2005, 175).

As Gray pointed out about Darwinism, in itself it neither supports nor denies theism. Conway Morris (2003) admits that any directionality or teleology observed in evolution is consistent with theism but that it does not provide any proof of it. A similar point has been made recently by Clayton (2006) with regard to the issue of directionality in natural, particularly biological, processes. Having a natural explanation for something does not logically require denying that God exists or plays a role in bringing forth and sustaining the cosmos (Cobbe 1872); but arguments about design of the origin and evolution of life do not necessarily make for good theology, either (Barth and Brunner 1947). Methodological naturalism requires that science be practiced as if it were without a priori metaphysical commitments, just methodological ones, such that the same science can be done and debated by theists, agnostics, and atheists.

John Haught views emergent complexity as far from problematic for theology but still very consistent with it: “Since God is love and not domineering force, the world must be endowed with an inner spontaneity and self-creativity that allows it to ‘become itself’ and thus to participate in the adventure of its own creation. Any other kind of world, in fact, is theologically inconceivable” (2004, 243).

It is as if the theological principle of grace is exemplified by the process of self-organization and emergence deep in the grain of nature. Such a view seems quite compatible with, though not logically necessitated by, a theory of organization and natural teleology that includes emergence of life. Embracing emergent complexity as a phenomenon caused by laws very deep in the grain of nature opens new avenues for scientific, philosophical, and theological thought. Taking the emergent complexity turn calls for a philosophical and theological response. As Davies notes, “it is clear that any general principle of advancing complexity would reintroduce a teleological element into science" (2004, 207). Haught and Conway Morris have called for the development of a theology of nature, as opposed to a natural theology, in response not only to evolutionary principles but also to the growing appreciation of the genuine complexity of nature and the reality of emergent phenomena (Haught 2000; 2003; Conway Morris 2003). Such a theology requires that "the world must be endowed with an inner spontaneity and self-creativity that allows it to . . . participate in the adventure of its own creation" (Haught 2004, 243). This is not a universe of detailed design (Behe 1996; Dembski 1998). This is not an unfolding but preprogrammed universe. This is not Daniel Dennett's "Darwin's Dangerous Idea" of an algorithm of stark chance and necessity (Dennett 1995). Rather, this is a universe reflecting John Polkinghorne's notion of *kenosis* as love (Polkinghorne 2001; 2004), a dangerous love for settled assumptions about God and nature.

NOTES

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