

## Article



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# Rethinking Abiogenesis: Part II, Life as a Simplification of the Nonliving Universe

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*In Part I, we argued that it may be useful, even important, to perceive the origin of life as a seamlessly continuous (and arguably incomplete) process, rather than any specific point in time or evolutionary history.<sup>1</sup> Here we challenge another widespread assumption: that abiogenesis involves some sort of increase in complexity. Instead, we argue that in at least some useful ways, natural selection can be viewed as a process that simplifies the nonliving universe, yielding organisms that are increasingly efficient in processing energy and genomes that capture only a fraction of the information available in the broader environmental context. We show how this view of “life as simplification” connects with our previous argument for abiogenesis as a seamlessly continuous process in time: anything we consider alive makes sense only in the context of, and in relationship to, neighboring points in time and space. Overlooking this context tempts unproductive questions, such as how could something nonliving move toward the complexity of life? Seen in context, life’s complexity merely reflects the greater complexity of the surrounding universe. This shift in perspective opens productive scientific and theological reflections that include conceptions of “order out of chaos.”*

Living things, we are often taught to perceive, are more complex than their nonliving environment. This view can be traced back at least as far as Aristotle, who argued explicitly that all living things are something more than inanimate matter precisely because they also possess a soul.<sup>2</sup> Subsequent to Aristotle, the idea that biology is more than matter alone travelled through centuries

of western civilization, gathering considerable nuance along the way, to become the “Great Chain of Being”<sup>3</sup> which describes the exact hierarchy, or ladder of all creation, stretching from God at the top, down through animals, to plants, onwards to minerals and rocks. This system firmly locates inanimate matter as less than anything living.

Universal acceptance of this state of affairs led, for example, to all pre-Darwinian evolutionary theories of Western science seeking an answer to the question, “What causes matter to ascend this ladder, to become more over time?” Thus, the word “evolution” originally entered biology in theories which extended biological development (from fertilized egg to embryo to adult) onwards to include equally deterministic development of simpler, “lower” species into “higher” forms of life.<sup>4</sup> It was in this sense that Darwin’s grandfather used the word “evolution” in a poem to describe the unfolding of a plan for the

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ascent of matter into ever more complex forms of life.<sup>5</sup>

Although concepts of the soul are rarely recognized by contemporary science, and mainstream evolutionary biology tends to reject explicit notions of teleology<sup>6</sup> and progress,<sup>7</sup> Aristotle's idea continues to exert a profound influence on how we think today. The very word *inanimate*, for example, means "without soul" or "without breath": life possesses something which nonlife lacks. More pragmatically,

students of a traditional undergraduate science curriculum in the USA will typically meet organic chemistry before biochemistry, as if the latter builds upon the simpler knowledge of the former. But where, in fact, does chemistry become "complex" enough that it attains the special attention we give to living things? Science offers little objectivity with which to distinguish clear lines of separation (box 1). The terminology of "organic chemistry" and "biochemistry" is better understood through a lens of science history as successive attempts to define an

### BOX 1: "ORGANIC" CHEMISTRY AND "BIO"CHEMISTRY ARE CULTURAL CONSTRUCTS

Does the molecule carbon dioxide belong to organic chemistry or inorganic chemistry? Here is how the American Chemical Society explains the situation:

*Organic chemistry is defined as the study of carbon-containing compounds and inorganic chemistry is the study of the remaining subset of compounds other than organic compounds; there is overlap between the two fields ...<sup>8</sup>*

Taken at face value, much depends upon whether one approaches the molecule as an oxidized state of carbon or a reduced state of oxygen. Move onwards to biochemistry, and the relevance of carbon dioxide is indisputable. It is crucial to understanding carbon fixation (photosynthesis) and its chemical inverse, respiration: the former harnesses energy to convert carbon dioxide and water into sugar; the latter converts sugar into carbon dioxide and water, releasing energy. Phenomena more central to life's chemistry are not easy to think of. We could travel onwards (and "upwards" in the fictional hierarchy of complexity) to scientific disciplines of plant biology, animal physiology, ecology, and evolutionary biology only to find equally valid reasons for considering carbon dioxide part of their legitimate domains of inquiry. Net flux in carbon dioxide is, for example, a major determinant of average, global temperature, experienced by all life. It seems that the domain of chemistry to which carbon dioxide belongs is not inherent to the molecule, but rather a subjective property of the questions being asked about the molecule: it is about the perspective from which this molecule is approached.

Perhaps the simplicity of carbon dioxide, with its single molecule of carbon, causes this overlap of multiple domains, and things become clearer when multiple carbon atoms join together. In a deeply influential book about life's origins, chemist Robert Shapiro describes the situation thus:

*Carbon atoms have a marvelous ability to join with one another and ... such long chains are characteristic of many molecules important to life ... Up to the early nineteenth century it was thought that the division between organic and inorganic chemistry was the basis that separated living and nonliving matter. Now we know better. Certain meteorites, for example, contain a complex mixture of organic compounds, with chains of various length. Yet they do not contain life, nor is there any indication that they were ever in contact with life before they fell to Earth ... The essence of the difference between life and nonlife at the molecular level lies not in the presence of ... long chains of atoms but rather in the organization, as well as the identity, of the molecules ...<sup>9</sup>*

This final phrase refers to sequences of nucleotides that form genetic material and sequences of amino acids that form proteins. In the main text of our article, we discuss how these sequences comprise a subset of the building blocks produced by nonbiological chemistry, and then how the organization of these sequences results from the process of natural selection forming simplified "reflections" of the nonliving environment. Biochemistry is not a subset of the universe; it is a vantage point from which to view that universe.

# Article

## *Rethinking Abiogenesis: Part II, Life as a Simplification of the Nonliving Universe*

assumed difference between the chemistry of life and nonlife. This difference has proven surprisingly elusive, and at least some aspects of life's chemistry that are different seem distilled from greater chemical diversity: a purification or reduction of abiotic chemistry rather than an increase in complexity. We will argue that this is exactly what we should expect from evolution by natural selection, and yet here, as much as anywhere, echoes of Aristotle's teleological thinking persist.

Take, for example, Richard Dawkins, who opened an otherwise excellent exposition of late-twentieth-century evolutionary theory by suggesting that, unlike biology, "*physics is the study of simple things that do not tempt us to invoke design ... even large physical objects like stars consist of a rather limited array of parts, more or less haphazardly arranged.*"<sup>10</sup> The truth of this statement hinges upon what perspective one assumes as a basis for investigation: how one chooses to define "simple," "more or less haphazard," and "parts."<sup>11</sup>

Dawkins's description of evolutionary theory cares and notices little about atoms as parts. A nuclear physicist or astronomer, on the other hand, would perceive and describe the chemical composition and physical structure of a star as anything but haphazard. Atomic reactions at high pressure/temperature convert hydrogen into concentric shells of helium, carbon, oxygen, sulfur, and so on through subtle, sophisticated equations by which science has come to describe matter and energy. It is not clear to us that any of these research areas involve something "simpler" than evolutionary biology: certainly, the processes involved continue to occupy sharp minds in full-time exploration on multiple fronts.<sup>12</sup> Thus, the statement that the structure of a star seems haphazard and simple relies on a subjective choice of definition.

If living things are more prone than nonliving things to invoke design in the mind of an intelligent non-expert, then perhaps this thinking occurs because the patterns of cause and effect that explain the physical manifestation of organisms—morphology to behavior—resonate with our own personal experience. Many insects resemble leaves or sticks because the resemblance influences their chances of being eaten by predators. This is something we understand readily in the food webs around us. In contrast, ordered patterns in the anatomy and behavior of a late stage, main sequence star involve "the equations of stellar structure including those for energy conservation,

momentum transfer, mass conservation, and energy transport."<sup>13</sup> In other words, the perspective by which an evolutionary biologist perceives the "purpose" (cause) of living things is one with which we empathize more intuitively.

How could we probe further the objective validity of the idea that life is somehow more than nonlife? One approach is to ask whether we can construct a logical argument for the opposite view: What are useful ways in which life can be defined as simpler than abiotic chemistry?

### A Case Study: The Chemical Simplicity of Life

Consider the small, organic molecules used as building blocks by all life on Earth for the past 3.5 billion years. Students of biology learn early the "Central Dogma" of molecular biology: life encodes genetic messages in sequences of nucleobases; these genes are translated into a different chemical language of protein enzymes so as to form metabolism. Genetic information is "written" using an "alphabet" of just four types of nucleobase, which specify a corresponding protein sequence "written" in an "alphabet" of just twenty different types of amino acid.

It has become clear in recent years that nonbiological processes (and therefore prebiological processes) produce a far greater diversity of both amino acids<sup>14</sup> and nucleobases<sup>15</sup> than are used by life. This insight derives from the unlooked-for convergence of results of laboratory chemistry experiments to simulate prebiological conditions, and analysis of meteorites, which represent the natural counterpart of such simulations. Even within life's reduced "alphabets," nonliving chemistry tends to produce two mirror-image versions (enantiomers) of amino acids and ribose in equal amounts, whereas biochemical polymers (proteins and nucleic acids) use only one. From the perspective of life's origins (and astrobiology), the logical inference is that early evolution sifted the molecular diversity of abiotic chemistry into streamlined components of life's Central Dogma with which it has been working ever since. Our emphasis on simplicity may be unusual, but many prior authors have suggested that the whole system of carbon-based, polymer-based life emerged, via evolution, from a far more heterogeneous and messy prior state.<sup>16</sup>

Zooming in from molecular building blocks to consider the types of atom from which they are

constructed reveals something similar. The periodic table comprises more than 100 different chemical elements. Of these, just six are responsible for fundamental biochemistry, such as amino acids and nucleotides: carbon (C), hydrogen (H), nitrogen (N), oxygen (O), phosphorus (P), and sulphur (S).<sup>17</sup> Certainly these six are used to coordinate a network of chemical reactions that involve a handful of other chemical elements in trace amounts (copper, magnesium, iron, and so forth), but the framework of protein enzymes, nucleic acid genes, cell membranes, and energy storage responsible for this coordination comprises only “CHNOPS.” Six is, objectively, smaller than one hundred! Six is smaller even than the tens of elements that might be present within, say, the sun<sup>18</sup> or those meteorites in which amino acids are found.<sup>19</sup> In this sense of atomic composition, then, the “design” of living organisms is again “simpler” than the analogous design of the nonliving universe.

Of course, counting the molecular building blocks (or types of atom) used by life versus those produced by abiotic chemistry is just one, very limited definition of “simplicity.”<sup>20</sup> Can we extend this thinking usefully by asking why life’s chemical basis is simpler than that of the nonliving universe?

A clue comes from observing that a standardization of components has repeatedly proved advantageous during human history by providing increased efficiency. For example, the metric system emerged to provide advantage over prior, heterogeneous units of measurement, and the standardization of nuts and bolts provided a noticeable contribution to the industrial revolution.<sup>21</sup> A constant drive for efficiency is a well-described theme for biological evolution in times more recent than life’s origins.<sup>22</sup> For example, Eric Chaisson suggests the metric of energy rate flux to express the greater efficiency of living organisms in utilizing energy.<sup>23</sup> Certainly, this perspective aligns well with scattered evidence that life’s “choices” of amino acids,<sup>24</sup> nucleotides,<sup>25</sup> and even the sugar ribose<sup>26</sup> look a lot like the optimized products of natural selection.<sup>27</sup> The biochemical substance of life is simpler than its abiotic context because the general process of natural selection by which life emerges is one of filtering and reduction.

But the clearest potential counterargument to our notion of “life as simplification” is that, within living systems, atoms and the molecular building blocks of the Central Dogma made with them become linked

together into improbably<sup>28</sup> nonrandom sequences (genes and proteins) that do not find any counterparts in the nonliving world. How could we possibly think of these sequences as simpler than the nonliving universe?

The answer is that natural selection continually filters environments into genetic encodings that “summarize” and reflect back just a few key aspects. Since the Central Dogma became established, we encounter these summaries in the language of gene sequences and the protein enzyme sequences that they encode. This idea of natural selection sifting, summarizing, and reflecting back a few key aspects of the environment is the crux of our argument, and carries important implications for the way we think about life’s emergence through both scientific and theological lenses. To get there, let us first explain exactly what we mean by the assertion that evolution by natural selection sifts, summarizes, and reflects back the environment.

## Evolution by Natural Selection Reflects Environments into Genetic Language

Within biology, form tends to fit function. This orthodox, textbook knowledge arises directly from Darwinian theories of adaptation. An introduction to evolution might begin, for example, by comparing dramatically different life forms: cacti and water lilies. Cactus leaves have evolved into spikes, which reduce the plant’s loss of water through transpiration while defending against predators. These are appropriate traits for life in a desert, where water retention (including the defense of hard-won resources) is key to reproductive success. Meanwhile, the lily is buoyant and flat, with a large surface area that transpires water quickly—traits that reflect the abundance of freshwater in lakes and ponds, where staying afloat brings reproductive success through exposure to sunlight and atmospheric carbon dioxide.

The “form fits function” principle guides many of the questions that evolutionary biologists ask about life’s diversity, and helpfully so. We might wonder at the difference in teeth between carnivores and herbivores, the curved beaks of hummingbirds that match specific flowers, or the streamlined shape of fish. A classic “adaptationist” approach—asking, “How is this trait (form) beneficial to the organism’s survival or reproduction (function)?”—usually provides a useful way in which to understand whatever we are looking at, from the number of seconds that

# Article

## *Rethinking Abiogenesis: Part II, Life as a Simplification of the Nonliving Universe*

a male dung fly<sup>29</sup> spends mating to the size of mussel shells preferred by shore crabs.<sup>30</sup> In some famous words from Dobzhansky, “Nothing in biology makes sense except in the light of evolution.”<sup>31</sup> As a thought experiment, consider the challenge faced by visiting aliens trying to make sense of lilies and cacti (or stick insects, or any other plant or animal) if they were to transport the organism into their spaceship before starting their examination. At best, they might infer key features of the environment in which the organism functions. At worst, morphology and behavior would be bewildering, misleading. As pointed out to us during peer review, “This explains why astrobiologists who develop life detection approaches spend time in the field. We know that context is everything.”

The causal mechanism that accounts for these tight links between environments and traits is, of course, natural selection: the process by which genetic variants that confer greater fitness within a population, increase in frequency over time through differential reproductive success. Through this mechanism, the genome becomes programmed by the differential survival of traits (phenotypes) that are beneficial in a given environment. The definition of “beneficial” in this context means traits which lead most effectively to reproduction, often through enhanced survival. The genes (usually complex interacting suites of them) that persist and proliferate through natural selection are those that encode phenotypes through which energy flows more efficiently into reproduction.

Our advocacy for a perspective of evolution as a process of simplification is that differential reproduction usually results in the loss of genetic variation over time as natural selection eliminates less favorable sequences from a larger pool of options. The most direct route to reduced genetic diversity is *fixation* in a population of a single variation that confers greatest reproductive success and, by inference, elimination from the gene pool of all alternatives.

The straightforward fact that selection (and, for that matter, genetic drift) acts to reduce genetic variation in a population seems paradoxical when we think of evolution resulting in “*endless forms most beautiful and most wonderful*” (the closing sentence of Darwin’s *Origin of Species*). The resolution to this paradox is that, while natural selection sifts and simplifies from the available genetic variation, mutation<sup>32</sup> is constantly feeding new variation into the

system, providing the raw ingredients on which natural selection continues. From the perspective we advocate, each mutation is a temporary influx of complexity from the universe into evolution’s grinding gears of simplification. Mutation increases the diversity of genomic sequences, while natural selection reduces and simplifies this variation through differential reproduction, according to which variants best reflect the environment. In accord with the second law of thermodynamics, the environment tends to increase chaos while natural selection is a simplification leading to greater order out of chaos.

It is worth pausing here to forestall a potential misunderstanding. The assertion that evolution by natural selection causes genomes to “capture” partial information about an environment does not violate the Central Dogma of molecular biology, which states that information flows from genes to proteins to phenotypes rather than the other way around. No violation is implied, because the environment does not encode information directly into the genome via some mechanism of reverse translation (as Lamarck and many pre-Darwinian theorists, in effect, proposed). Instead, the environment exerts a pressure which, often gradually and through the mechanism of differential reproductive success, changes the distribution of alleles in a population. Natural selection filters random mutations according to how efficiently they convert resources into offspring. That is a statement about life’s relationship to the environment. Variations in traits which exert greater, positive impact on reproductive success will come to dominate and be built upon by future generations. In this way, genomes are shaped by environments in full accord with the foundational ideas of evolutionary theory.<sup>33</sup>

But the portion of the environment that “appears” in the genome is, as we will argue, only a fraction of the total environment at hand.

### What Constitutes an Environment?

If natural selection molds evolving lineages to fit their environment, then what exactly comprises this environment? At first glance, we might notice key physical conditions: the intensity of sunlight, availability of water, ambient temperature, oxygen levels, and so forth. Natural selection, we presume, is tracking such things; that was where our description of lilies and cacti began. But a cactus morphology that

protects hard-won resources from herbivory hints at something important beyond physical features of the environment. To natural selection, biological interactions are equally, if not more important, than abiotic factors in defining an organism's environment. Avoiding predators while successfully finding food, fending off parasites, infections, and competitors while entering into mutually beneficial relationships with individuals from within and beyond the organism's population—these factors all influence reproductive success. What could be more important, after all, than choosing a good mate? Thus, an evolutionary concept of "environment" must extend beyond abiotic factors to consider other species such as predators, prey, and parasites, as well as other members of the same species such as potential mates and competitors.<sup>34</sup> The morphology and behavior of any given lineage will make greater scientific sense if considered in the context of these other interacting biological entities. An interesting logical consequence is that the environment is never the same for two lineages, or even two individuals occupying the same physical locality, because the environment of each is defined in part by the presence of the other. The environment is the whole; the organism is a constituent and fractional part.

### Adaptations Are Simplified Reflections of Their Environments

Our argument for evolution as simplification proceeds by focusing on the difference between those aspects of the environment that become reflected in a genome and those that do not. Setting aside, for a moment, the phenomenon of genetic drift, we can state that adaptive natural selection is driven only by those aspects of an environment that influence the differential replication of genes. Therefore, the record of an environment that makes its way into a genome represents only some features of that environment.

To see why, consider again the cactus. Natural selection might "see" the scarcity of water and the threat of herbivory when it comes to desert cacti, because these exert the most pressure on survival and reproduction. More accurately, we might say that within the lineage which led to a contemporary cactus, somewhere in the recent past, plants with spinier leaves gave rise, on average, to more successful offspring than counterparts with less spiny leaves. Sustain that environment long enough, and we arrive at the cacti we see today. Compared to the price of

water loss in this environment (whether through transpiration or herbivory), minor local variations in soil chemistry, altitude, or a host of other aspects of that same environment are less important beneath the resolving power of natural selection, and thus adaptations related to these conditions will not necessarily be preserved in genes. Put another way, the cactus's genome has evolved to reflect an incomplete picture of the environment in which its predecessors competed to reproduce. An independent observer could never reproduce all aspects of an environment from even the most thorough study of the organism. Natural selection has filtered (simplified) a complicated environment in the process of producing genetically coded "reflections." This is the sense in which we state that all genetic programming may be viewed as a partial "image" of a far more multifaceted environment, much as a photograph captures only some of the information of the object it depicts.

### Simplified Reflections Blur the Line between Organisms and Their Environment

Another way to approach these same ideas is to say that all fundamental properties we associate with life, such as homeostasis, movement, growth, and development, exist only in relation to a richer biotic and abiotic context. The aliens who took a well-adapted organism into space would not only be guessing at the significance of adaptations—they would be studying a dead organism, unless they took an appropriate slice of the right environment along for the trip. That is what we expect from natural selection. Your body has evolved to breathe in a gaseous mixture that is relatively rich in oxygen, and to breathe out a different mixture richer in carbon dioxide. This is the result of natural selection which has shaped your physiology to use the oxygen in breaking down carbohydrates (hydrated carbon) into carbon dioxide and water, releasing energy along the way. Any actual instance of homeostasis, movement, growth, or development dissolves, under scrutiny, into one or more adaptations, each specific to the environment. The oxygen on which your physiology relies originated, of course, in photosynthesis. In the absence of oxygen-producing photosynthesis, our physiology would no longer be an adaptation as our homeostasis, movement, growth, and development would cease. What might pass superficially for properties inherent to life are all genetically encoded, partial reflections of a specific environment, and

# Article

## *Rethinking Abiogenesis: Part II, Life as a Simplification of the Nonliving Universe*

their ongoing manifestation requires the presence of the same (or very similar) environmental conditions which they are programmed to reflect.

Life and its environment are unmistakably intertwined, particularly when we notice that genes are often selected for their influence quite beyond the bodies in which they occur. As Dawkins pointed out, a beaver's dam may be usefully considered as part of its "Extended Phenotype."<sup>35</sup> This extension of adaptations may also encompass the biotic component of any given organism's environment. A fungal secretion which manipulates the behavior of an ant which it parasitizes,<sup>36</sup> or characteristics that provide advantage in securing a mate, illustrate this extended interconnection of organisms. Even the carbon dioxide you breathe out contributes to the atmosphere that other organisms experience—just as the oxygen you breathed in reflects the output of photosynthesis. At this point, it has become difficult to distinguish clear boundaries between interacting organisms and the nonliving environment they inhabit.<sup>37</sup>

### From Continuity with the Environment to Continuity through Time

We have argued thus far that evolution by natural selection causes the genetic material of each lineage to form a simplified reflection of its environment. The resulting adaptations intertwine organisms inextricably with their environment, including one another, through physiology and ecology. Distinctions blur between different organisms and between life and nonlife.

In a previous paper, "Rethinking Abiogenesis: Part I," we argued that abiogenesis, like the rest of biological evolution, is usefully perceived as a seamlessly continuous (and arguably incomplete) process, rather than an event occurring at any specific point in time or evolutionary history.<sup>38</sup> Not every step by which life has emerged is equally relevant to understanding every other step, but no step can be understood without relationship to neighboring points, which can only be understood in relation to others, and so on. We now argue that a similar continuity holds at any one point in time for organisms' relationships to their surroundings (the environment, abiotic and living). Whereas Part I stretched a unique point in time called "abiogenesis" into a continuous line of life's ongoing unfolding,<sup>39</sup> here in Part II, we stretch that timeline into a second continuous dimension: space.

Life at any one point in physical space can be understood only in relationship to neighboring points (points within the "environment"), which can only be understood in relation to others, and so on.

But these two dimensions are not truly distinct. Life's connection to the environment through physiology and ecology is merely the local stage on which evolution plays out its current round of evaluating adaptations and their variations. Environments inevitably change over time, and each organism that contributes to another's environment (potential mates and their preferences, predators, parasites) is, of course, itself an evolving lineage that changes over time in response to its biotic and abiotic environments.

All the while, natural selection is encoding a few salient features of these interactions into the genetic programming of each evolving lineage as genes, and their variations are measured relative to current conditions. Today's adaptations build on those which brought success to prior generations in the environment of yesterday. Ghostly reflections of past environments persist within a genome until natural selection overwrites them (often incompletely) by new, more relevant instructions (or until they "decay" through the accumulating noise of unchecked mutation and genetic drift).

And so the genetic programming of any individual organism can be understood as the accumulated, partial reflections of the chain of environment(s) through which its ancestors passed. That cacti have evolved spine-like leaves reflects the water-scarce environments in which their ancestors lived. That these spines are clearly identifiable as modified leaves reveals an overlay on earlier anatomical features, which helped more distant ancestors thrive on dry land rather than in a watery environment of even more distant (earlier) ancestors ... and so on. An example of this same point from closer to home is to consider the array of medical problems, from diabetes<sup>40</sup> to allergies, which afflict affluent, twenty-first-century humans living in environments that have changed radically and quickly away from those to which their bodies adapted over millennia.

In sum, through a lens of evolution, no sharp lines distinguish life as something distinct from nonlife in either time or space. We arrived at this perspective by questioning the assumption that life, in terms of the chemical evolution of biomolecules, is more

complex than nonlife; and by perceiving this as an outcome typical of natural selection “filtering” information from the surrounding environment into partial genetic reflections.

The ideas we present here are novel in emphasis, not in content. No evolutionary biologist would deny that natural selection “notices” and “reflects” only a few key features of an evolving lineage’s environment, although they might find our language, with its focus on simplification rather than on generation of diversity, unusual. This unusual emphasis emulates the rhetorical device employed by Richard Dawkins in his introduction to *The Extended Phenotype*: the Necker Cube is an optical illusion comprising

a line drawing which the brain interprets as a three-dimensional cube. But there are two possible orientations of the perceived cube, and both are equally compatible with the two-dimensional image on the paper ... if we look for several seconds the cube “flips over” in the mind.<sup>41</sup>

The evidence remains unchanged; the lines of the drawing are constant and, in Dawkins’s words, “neither of the two perceptions of the cube is the correct or ‘true’ one.”<sup>42</sup>

But Dawkins argues, as do we, that a deliberate shift allows us to return to long-accepted, orthodox evidence with fresh perspective, generating new and constructive questions. In our case, we do not deny that the process of natural selection, at the level of organisms or chemical materials, contains elements that may reasonably support a view of “life as greater complexity” or “life as simplification.” But we also believe that given the overwhelming emphasis among present researchers on “life as complexity,” the latter possibility—“life as simplification”—may hold considerable untapped potential for advances in both scientific research and theological thought. In the remaining two sections here, we demonstrate the common roadblocks that our perspective of “life as simplification” may help to alleviate, and we gesture to the new horizons of origin-of-life questions that our perspective shift invites.

## Scientific Reflections

Traditional academic disciplines are responsible for developing most of the ideas we present above.<sup>43</sup> The interconnectedness of organisms with each other and their environment is literally the definition of ecology,<sup>44</sup> and a subcommunity of twenty-first-century

evolutionary biologists has developed significant early concepts of niche construction<sup>45</sup> by which organisms influence their environments rather than the other way around. Another subcommunity of evolutionary biologists has, over a similar period, pioneered a clearer perspective of life’s continuity over time,<sup>46</sup> the subject of our prior Part I. Scientific implications for the future of these ideas therefore lie not in their novelty, but in their further development through integration of separate disciplines and sub-disciplines. While such integration can help research anywhere along the trajectory of life’s history, it becomes increasingly necessary as the subject of our focus becomes increasingly distant in time and space from the world we experience.

The community of researchers who study our planet’s history more than about one billion years ago, for example, find that their questions and insights defy neat, academic boundaries of knowledge. It is not that the process of evolution, including the local stage of evolutionary ecology, was any different: the argument for life’s continuity over time and space argues quite the opposite. Rather, life’s interconnectedness with itself and the nonliving universe is absolutely required to explain major events leading to the planet and biosphere we encounter today. Such events include the evolutionary tightening of interconnectedness between some single-celled organisms that we know today as multicellularity, an innovation from which both plants and animals later emerged.<sup>47</sup> Multicellularity built, in turn, from the prior evolutionary debut of a new type of cell, eukaryotes, which partition the contents of their cell membrane into specialized membrane-bound sub-compartments (organelles): genetic material within the cell nucleus, respiration within mitochondria, and photosynthesis within chloroplasts.<sup>48</sup> The evidence is now overwhelming that eukaryotes represent an evolutionary tightening of an ecological connection between multiple, unrelated cell types: “endosymbiosis,” whereby prokaryotes from different lineages evolved into a single, codependent community.<sup>49</sup> In looking at a eukaryotic cell, we are seeing the distant offspring of independent cells whose survival and reproduction depended on living as a community.

In recent years, evidence has been mounting that both the advent of eukaryotes and the multicellular organisms which emerged among them reflect prior niche construction on a planetary scale. Around 2.5 bya, our planet underwent a one-way transformation,

# Article

## *Rethinking Abiogenesis: Part II, Life as a Simplification of the Nonliving Universe*

from an atmosphere dominated by carbon dioxide to one with a significant presence of free oxygen (O<sub>2</sub>). This planet-changing event was caused by the evolutionary emergence and spread of oxygen-producing photosynthesis by a lineage we know today as cyanobacteria. The new physiology introduced into ancient ecosystems a highly reactive (and therefore toxic) gas to most other lineages, which had, of course, evolved in its prior absence. At least one such lineage, the proteoalphabacteria, “counter-evolved” to harness this oxygen in a controlled burn of sugars— aerobic respiration—which produces far more energy than the previously universal anaerobic respiration (and still found conserved throughout fundamental biochemistry of most living organisms).<sup>50</sup> Somewhere within *this* lineage a further population evolved into the mitochondria of eukaryotes,<sup>51</sup> a sublineage of which later evolved to absorb the photosynthetic cyanobacteria as well, leading to what we know today as plants.<sup>52</sup> Despite these evolutionary success stories, changing an entire planet’s atmosphere so dramatically led to global ecological upheaval and a resulting mass extinction, dwarfing that (much later) of the dinosaurs.<sup>53</sup> Upheaval came not only from the direct challenge of dealing with oxygen, but also from drastic climate change, because climate reflects the gaseous composition of a planet’s atmosphere.<sup>54</sup>

It is difficult to read this account of Earth’s early history without perceiving a continuous chain of cause and effect, reflections back and forth, between biology and the nonliving environment over both space and time. What has been discovered thus far required a fluid exchange of knowledge between geoscience and biology. This merging of different areas of academic expertise, we argue, is our best guide to where future insights await. Indeed, geoscience (and through it biology) is finding an ever-increasing role for comparison with neighboring planets in our solar system, such as Mars and Venus, that are (as far as we know) devoid of life. As the features that distinguish Earth from other planets reveal themselves more and more as consequences of life, not causes (prerequisites) for life, the traditional disciplines of planetary astronomy and geoscience are melding into a new composite known as planetary science:<sup>55</sup> something greater than the sum of its parts as each side informs the other.

Not only do biology and geoscience of our planet’s early history advance through input from those who can describe Mars, but Martian exploration learns

from geoscience and biology what to consider in evaluating the past or present existence of life there.<sup>56</sup> It is no coincidence that the Mars Curiosity mission is exploring Gale crater, where rocks date back through (and therefore reveal important information about) the planetary changes that we just described for Earth. Indeed, the rover vehicle is approaching rocks thought to be 4 bya— matching current estimates for the earliest presence for biological activity that we recognize on Earth.<sup>57</sup> Findings at this interface go onwards to inform other astronomers interested in biosignatures that could indicate the presence of life on distant exoplanets<sup>58</sup>— while their observations of younger star systems guide our understanding of the solar system formation<sup>59</sup> which laid the foundations for life’s emergence.

Previously, we described astrobiology as an open network between scientists of different disciplines (rather than a subject mastered by any individual) that widens and improves the study of abiogenesis. But astrobiology is more accurately defined as “the study of the origin, evolution, distribution, and future of life in the universe”<sup>60</sup> because these topics are so interdependent. It would therefore have been more accurate to describe the study of abiogenesis as dissolving into a bigger picture of astrobiology, to the benefit of all concerned. And so our title’s promise about “Rethinking Abiogenesis” speaks here, as in Part 1, of a shift in research patterns toward interdisciplinary networks that connect scientists from different backgrounds into a shared, intellectual community. It expands the sort of fluid exchange of knowledge by which nuclear physicists who study the evolution of stars share their understanding of why hydrogen, carbon, oxygen, and nitrogen are the most abundant chemicals in the universe with biologists who notice that they represent the bulk of life’s chemistry. It is only from a distinctly older and narrower disciplinary perspective that an evolutionary biologist could describe stars as “more or less haphazardly arranged”! For what it is worth, stars tend to become more chemically complex both as they age and as successive generations of stars “die” and “give birth” to one another,<sup>61</sup> although the relationship is not as simple as once believed.<sup>62</sup>

This observation brings us to the one major idea we have presented here but not yet discussed for scientific implications: biological evolution as a process of simplification. Again, we want to emphasize here that it is not the content, but the emphasis, of

our argument that is new. Current understanding of stellar (“abiotic”) evolution implies that in selecting just a handful of lower-mass chemical elements, biological evolution was working in the opposite direction from abiotic processes of increasing chemical complexity—aligning with similar observations we made above for nucleobases and amino acids. But like Dawkins’s Necker Cube, we argue that a subtle shift in perception from life-as-complexity to life-as-simplification helps us approach ongoing questions of origins research in new and productive ways.

For example, one of the biggest remaining challenges in understanding life’s earliest evolutionary steps is the following: how did the molecules which form a foundation for all life find one another within a diverse chemical “soup”? In more formal language, how did life’s chemistry simplify into homopolymers (such as DNA and protein) from a mixture containing nucleobases, amino acids, and thousands of other “organics”? And how did it do so when unguided chemical reactions tend to produce messy, complicated heteropolymers, tar and/or cross-reactions? The answer we offer above is natural selection, in this case applied to chemical entities. But if, by natural selection, we think only of the differential survival of different organisms, then our proposed answer comes dangerously close to begging the question: life comes into being by the process of life. The escape from this apparent circularity, we argue, comes not from erecting a hard line between “chemical evolution” and “biological evolution,” but from noting that if living organisms are inseparable from the nonliving universe, then so is the process of natural selection. As we wrote in Part 1,

The process of natural selection is not limited to acting only on what we take to be alive. [It] applies to anything that leaves behind copies of itself which vary in ways that are inherited from one generation to the next. The necessary outcome is, of course, that those variations, which for any reason leave behind more copies than their counterparts, are likely to form the basis for further variation as time flows forward. This process applies to chemicals ... chemical evolution seems increasingly important to investigate how life-as-we-know-it came into existence.<sup>63</sup>

From the perspective of life as simplification, we can observe that many corners of the universe exist where a throughput of energy leads to material, chemical simplification. Energy from sunlight can distill fresh water from salty oceans, and energy from Brownian motion can cause a crystal comprising one type of

molecule to accrete layers of itself from a complex aqueous solution. In each case, a careful observer could frame the process as one of simplification within an environment of greater complexity. In both cases, it is clear that the components and processes are all part of a seamless whole. Crystallization and evaporation are each processes that reflect the complex, whole environment in which they occur, in the sense that a few key aspects of that complex environment produce the phenomena. From this perspective, life clearly aligns itself with nonlife.

Do not let us underrepresent the enormity of the questions that remain. But for future progress, we might join those who look further into minerals and other examples of naturally occurring “simplifications” of messier chemistry, looking to find replication and selection processes that result in our kind of organics. Interestingly, there probably were not very many different kinds of minerals on the early Earth. According to some accounts, most of mineral diversity seems to be a product or byproduct of life.<sup>64</sup> If these accounts are correct, then you might say that there is *one* area of chemistry where life has increased the complexity of its surrounding environment over time, diversifying the repertoire of minerals occurring on our planet. Or you might say that the regular, repeating arrays of atoms which constitute a mineral are simpler and more ordered than the universe from which they are drawn—that life enlarges and speeds up other ways in which pockets of the universe distill simplicity from complexity.

Rather than speculate further, let us close an advocacy for life’s continuity with the nonliving universe by pointing out that the beauty of this sort of interdisciplinary science is how it ends up speaking to *all* of life (and all of the nonliving universe!). Much of what we think we know about our own atmospheric changes under rapidly increasing levels of carbon dioxide involves the same science that explains, and is fed by, studies of both Earth’s early history and that of Mars and Venus—our neighbor planets. And that, in turn, has provoked some fascinating ideas about the way(s) in which life may, in fact, stabilize geochemical, atmospheric, and even temperature variations that would occur on a nonliving planet.<sup>65</sup>

## Theological Reflection

The scientific narrative we have presented may seem to be devoid of reference to God and therefore equivalent to an atheistic perspective of the origin of life.

# Article

## *Rethinking Abiogenesis: Part II, Life as a Simplification of the Nonliving Universe*

However, it is our perspective that the continuum of evolutionary development in space and time from the abiotic to biotic realms is a trademark of God's handiwork and an invitation to describe and appreciate the nature of such handiwork with greater precision and creativity.<sup>66</sup> God's work is revealed to us through its consistency as well as its awesome grandeur. Observations of how our universe developed are usually influenced by the observer's metaphysical presupposition. Only when consensus is obtained among scientists of different faiths is there confidence in the result.<sup>67</sup> Here, we argue that regardless of a reader's personal religious perspective or beliefs about the content of the Creation narrative, our emphasis on abiogenesis as a continuously unfolding, relational process of simplification helps to circumvent common theological arguments and to generate new linguistic and thematic possibilities with which to speak of God's presence in the created world.

One theological implication of our perspective on abiogenesis lies in the area of apologetics. It is not uncommon for Christians to declare that there must be a God since there is no other explanation for the origin of life. On the other hand, it is also not uncommon for skeptics or atheists to declare that since abiogenesis appears to be plausible, then there is no need for God. To both sides of such arguments, it would appear that a plausible scenario for abiogenesis is a setback for apologists and support for atheists. Let us be clear that such sentiments reflect common fallacies. The claim that "there is no scientific explanation, therefore there is a God" is the fallacy known as "God of the Gaps." It is a fallacy due to the incompleteness of scientific knowledge. Future scientific investigation might discover such an explanation and it is difficult to confidently show that no such explanation is possible.

The claim that "there is a scientific explanation, therefore there is no God," is, in turn, the fallacy of univocity.<sup>68</sup> The thirteenth-century concept of God's single essence of being has been distorted in our modern era as requiring a sole level of explanation. Scientific and theological explanations are thought to be mutually exclusive. This is a fallacy since God might be the creator of all things, whether or not we have attained a scientific understanding.<sup>69</sup> Responses to atheistic claims of this type should therefore not deny the premise (that there is a scientific explanation) but rather the logic (that such explanation

endangers the power of God). Finally, a robust tradition of Christian scholarship illustrates the way in which our description of creation as a continuous, seamless, unfolding process is quite compatible with modern textual interpretation of Genesis and other biblical accounts.<sup>70</sup> On these grounds and more, our interpretation of abiogenesis should conjure little concern for apologetics. Rather, a clearer understanding of how God may have created life from nonlife through evolutionary mechanisms can enhance our awe and wonder at the glory of God's creative power.

Finally, our account of natural selection as a continuous process of simplification is consistent with accounts of creation as "order out of chaos" found in Genesis 1 and 2. See, for example, Welker's compelling argument that the text of Genesis leads to a view of creation not as "an ultimate process of being produced by a transcendent reality and absolute dependence on that reality,"<sup>71</sup> but as "the construction and maintenance of associations of different, interdependent creaturely realms."<sup>72</sup> Multiple times in Genesis, God engages in acts of "evaluative perception" ("And God saw that what had been created was good" — Gen. 1:4a, 10b, 12b, 18b, 21b, 25b, 31a), in which observation of one level of creation influences God's following actions.<sup>73</sup> Additionally, God allows humans to collaborate in the "naming of all cattle, the birds of heaven and all animals of the field" (Gen. 2:19–20),<sup>74</sup> suggesting that God's creative process includes an intention for creatures to "order" their world into cultural categories and meanings.<sup>75</sup> In other words, a close reading of Genesis reveals that elements of reactivity, iteration, and step-wise increase in organization (decrease in chaos) are embedded in the biblical narrative of creation. The simplification of life through natural selection, then, could reasonably be viewed as one mechanism through which God continually brings nature, and the relationships within it, into greater "order." †

### Notes

<sup>1</sup>Emily Boring, J. B. Stump, and Stephen Freeland, "Rethinking Abiogenesis: Part 1, Continuity of Life through Time," *Perspectives on Science and Christian Faith* 72, no. 1 (2020): 25–35, <https://www.asa3.org/ASA/PSCF/2020/PSCF3-20BoringStumpFreeland.pdf>.

<sup>2</sup>Britannica, s.v. "Aristotle: Philosophy of Mind," accessed August 28, 2020, <https://www.britannica.com/biography/Aristotle/Philosophy-of-mind>.

<sup>3</sup>Arthur Lovejoy, *The Great Chain of Being: A Study of the History of an Idea* (Cambridge, MA: Harvard University Press, 1936).

- <sup>4</sup>Charles Bonnet, *La palingénésie philosophique : ou Idées sur l'état passé et sur l'état futur des êtres vivans : ouvrage destiné à servir de supplément aux derniers écrits de l'auteur et qui contient principalement le précis de ses recherches sur le christianisme* (Geneva, Switzerland: Claude Philibert, 1769), <https://archive.org/details/lapalingnsiephil02bonn>; First English translation: —, *Philosophical and Critical Inquiries concerning Christianity*, trans. John L. Boissier (Philadelphia, PA: W. W. Woodward, 1803), <http://archive.org/details/philosophicalan00bonngoog>.
- <sup>5</sup>Stephen J. Gould, "Darwin's Dilemma: the Odyssey of Evolution," in *Ever Since Darwin: Reflection on Natural History* (New York: W.W. Norton and Company, 1979).
- <sup>6</sup>David Hanke, "Teleology: The Explanation That Bedevils Biology," in *Explanations: Styles of Explanation in Science*, ed. John Cornwell (Oxford, UK: Oxford University Press, 2004), 143–55; Richard Dawkins, *The Blind Watchmaker: Why the Evidence of Evolution Reveals a Universe without Design* (New York: W. W. Norton, 1996), 1–2; and Daniel C. Dennett, *Darwin's Dangerous Ideas: Evolution and the Meanings of Life* (New York: Touchstone, 1995).
- <sup>7</sup>Stephen J. Gould, *Wonderful Life: The Burgess Shale and the Nature of History* (New York: W. W. Norton, 1990); and T. Ryan Gregory, "Understanding Natural Selection: Essential Concepts and Common Misconceptions," *Evolution: Education and Outreach* 2, no. 2 (2009): 156–75, <https://doi.org/10.1007/s12052-009-0128-1>.
- <sup>8</sup>American Chemical Society, "What Is Inorganic Chemistry?," accessed August 27, 2020, <https://www.acs.org/content/acs/en/careers/college-to-career/areas-of-chemistry/inorganic-chemistry.html>.
- <sup>9</sup>Robert Shapiro, *Origins: A Skeptic's Guide to the Creation of Life on Earth* (Manitou Springs, CO: Summit Books, 1986), 63.
- <sup>10</sup>Dawkins, *The Blind Watchmaker*, 1–2.
- <sup>11</sup>Dawkins himself would agree that a "subjective choice of definition" influences our perception of whether a process is simple or complex. In *The Extended Phenotype*, he describes how different types of scientists (geneticists, embryologists, ethologists) focus on different levels of phenotypic expression as the "end link in a chain of causation" (Richard Dawkins, *The Extended Phenotype: The Long Reach of the Gene* [Oxford, UK: Oxford University Press, 1989], 230–31). This arbitrary choice in turn guides the hypotheses the scientist makes and the level of complexity which we feel compelled to "explain" in order to account for a phenotypic expression.
- <sup>12</sup>Jakob R. Mosumgaard et al., "Coupling 1D Stellar Evolution with 3D-Hydrodynamical Simulations On-the-Fly II: Stellar Evolution and Asteroseismic Applications," *Monthly Notices of the Royal Astronomical Society* 491, no. 1 (2020): 1160–73, <https://doi.org/10.1093/mnras/stz2979>; Garrett Somers, Lyra Cao, and Marc H. Pinsonneault, "The SPOTS Models: A Grid of Theoretical Stellar Evolution Tracks and Isochrones for Testing the Effects of Starspots on Structure and Colors," *The Astrophysical Journal* 891, no. 1 (2020), <https://iopscience.iop.org/article/10.3847/1538-4357/ab722e>; and V. Silva Aguirre et al., "The Aarhus Red Giants Challenge I: Stellar Structures in the Red Giant Branch Phase," *Astronomy and Astrophysics* 635 (2020), <https://doi.org/10.1051/0004-6361/201935843>.
- <sup>13</sup>Geraldine J. Peters and Raphael Hirschi, "The Evolution of High-Mass Stars," in *Planets, Stars and Stellar Systems*, ed. Terry D. Oswalt and William C. Keel (Dordrecht, The Netherlands: Springer, 2013), 447–84, [https://doi.org/10.1007/978-94-007-5615-1\\_9](https://doi.org/10.1007/978-94-007-5615-1_9).
- <sup>14</sup>Jamie Elsila et al., "Meteoritic Amino Acids: Diversity in Compositions Reflects Parent Body Histories," *ACS Central Science* 2, no. 6 (2016): 370–9, <https://doi.org/10.1021/acscentsci.6b00074>.
- <sup>15</sup>Michael P. Callahan et al., "Carbonaceous Meteorites Contain a Wide Range of Extraterrestrial Nucleobases," *Proceedings of the National Academy of Sciences* 108, no. 34 (2011): 13995–98, <https://doi.org/10.1073/pnas.1106493108>.
- <sup>16</sup>Robert Shapiro, "A Simpler Origin for Life," *Scientific American* 296, no. 6 (2007): 46–53, <https://doi.org/10.1038/scientificamerican0607-46>; and A. G. Cairns-Smith, *Seven Clues to the Origin of Life* (Cambridge, UK: Cambridge University Press, 1985).
- <sup>17</sup>When it comes to amino acids and nucleotides, only the former use sulfur and only the latter use phosphorus: this distinction was the basis of Hershey and Chase's 1969 Nobel Prize for demonstrating that genes (not proteins) carry genetic inheritance.
- <sup>18</sup>Martin Asplund et al., "The Chemical Composition of the Sun," *Annual Review of Astronomy and Astrophysics* 47, no. 1 (2009): 481–522, <https://doi.org/10.1146/annurev.astro.46.060407.145222>.
- <sup>19</sup>Ninja Braukmüller et al., "The Chemical Composition of Carbonaceous Chondrites: Implications for Volatile Element Depletion, Complementarity and Alteration," *Geochimica et Cosmochimica Acta* 239 (2018): 17–48, <https://doi.org/10.1016/j.gca.2018.07.023>.
- <sup>20</sup>The word "simplicity" and its intuitive inverse "complexity" carry meanings that shift as we move from everyday speech into the specialized academic discipline of information theory, where, for example, two strings of characters of equal length may be defined as carrying identical information but different complexity, depending on how easily they compress into shorter representations. A string of 10 "A"s could be compressed into "10xA" whereas a string of random letters might be incapable of compression at all: both carry 10 bits of information but the latter comprises higher complexity. In this disciplinary parlance, genetic sequences produced by natural selection hover around a mid-point between the two extremes: too simple and they could not convey the informational content necessary to build metabolism; too complex and they could not contain the patterns by which molecular machinery decodes these instructions into metabolism. This specialized meaning of complexity bears directly upon the arguments we present and their relationship to faith through deep themes that link life, differential persistence over time, and concepts of "meaning" that science might recognize; however, we leave that for future, careful exploration in order to focus here on the least nuanced (simplest?) meaning of the term "simplicity" that enables us to develop our argument.
- <sup>21</sup>C. Dresser and J. O. Cooke, "Industrial Standardization in the Mechanical Engineering Industry," *Proceedings of the Institution of Mechanical Engineers* 124, no. 1 (1933): 737–42, [https://doi.org/10.1243/PIME\\_PROC\\_1933\\_124\\_022\\_02](https://doi.org/10.1243/PIME_PROC_1933_124_022_02).
- <sup>22</sup>Richard Dawkins, "God's Utility Function," *Scientific American* (1995): 80–85, <https://richarddawkins.net/1995/11/gods-utility-function/>.
- <sup>23</sup>Eric J Chaisson, "The Natural Science underlying Big History," *The Scientific World Journal* (2014): Article ID 384912, <http://dx.doi.org/10.1155/2014/384912>.

- <sup>24</sup>Matthias Granold et al., "Modern Diversification of the Amino Acid Repertoire Driven by Oxygen," *Proceedings of the National Academy of Sciences* 115, no. 1 (2018): 41–46; Melissa Ilardo et al., "Extraordinarily Adaptive Properties of the Genetically Encoded Amino Acids," *Scientific Reports* 5, no. 1 (2015): Article number 9414, <https://doi.org/10.1038/srep09414>; Melissa Ilardo and Stephen Freeland, "Testing for Adaptive Signatures of Amino Acid Alphabet Evolution Using Chemistry Space," *Journal of Systems Chemistry* 5, no. 1 (2014): Article number 1, <https://doi.org/10.1186/1759-2208-5-1>; and Gayle K. Philip and Stephen J. Freeland, "Did Evolution Select a Nonrandom 'Alphabet' of Amino Acids?," *Astrobiology* 11, no. 3 (2011): 235–40, <https://doi.org/10.1089/ast.2010.0567>.
- <sup>25</sup>Eors Szathmáry, "What Is the Optimum Size for the Genetic Alphabet?," *Proceedings of the National Academy of Sciences* 89, no. 7 (1992): 2614–18, <https://doi.org/10.1073/pnas.89.7.2614>; and Dónall A. Mac Dónaill, "Why Nature Chose A, C, G and U/T: An Error-Coding Perspective of Nucleotide Alphabet Composition," *Origins of Life and Evolution of the Biosphere* 33, no. 4–5 (2003): 433–55, <https://doi.org/10.1023/a:1025715209867>.
- <sup>26</sup>Albert Eschenmoser, "Chemical Etiology of Nucleic Acid Structure," *Science* 284, no. 5423 (1999): 2118–24, <https://doi.org/10.1126/science.284.5423.2118>.
- <sup>27</sup>Traditionally, the term "natural selection" is used exclusively within the biological realm. Our extension of the term to the abiotic (and therefore prebiotic) realm reflects our suggestion that there exists a continuum of the core principles underlying natural selection into a larger set of related phenomena. In biology, natural selection is based on reproduction with genetic variation, and subsequent differential reproductive success. Beyond biology, we see other, somewhat similar processes of imperfect replication with consequent differential persistence. For example, a mineralogist and planetary scientist peer reviewer for this manuscript noted "the reason why arkose sandstone is found only in dry environments [is] in a sense ... natural selection ... some materials are less robust in wet environments, so they only persist over time in arid conditions."
- <sup>28</sup>For example, a single, small protein enzyme sequence of just 100 amino acids, each drawn from an "alphabet" of size 20 permits  $20^{100}$  (larger than  $10^{130}$ ) possibilities; for an equivalent length gene sequence built from an alphabet of four nucleobases, the number of possible configurations is larger than  $10^{60}$ . By way of comparison, there are estimated to exist approximately  $10^{20}$  stars in the universe. It is virtually impossible that any one specific gene or protein sequence could form by monomers bumping into one another at random.
- <sup>29</sup>Geoff A. Parker and Leigh W. Simmons, "Evolution of Phenotypic Optima and Copula Duration in Dungflies," *Nature* 370, no. 6484 (1994): 53–56, <https://doi.org/10.1038/370053a0>.
- <sup>30</sup>R. W. Elner and Roger N. Hughes, "Energy Maximization in the Diet of the Shore Crab, *Carcinus maenas*," *Journal of Animal Ecology* 47, no. 1 (1978): 103–16, <https://doi.org/10.2307/3925>.
- <sup>31</sup>Theodosius Dobzhansky, "Nothing in Biology Makes Sense except in the Light of Evolution," *American Biology Teacher* 35, no. 3 (1973): 125–29, <https://doi.org/10.2307/4444260>.
- <sup>32</sup>Those who study larger organisms, such as animals, often think more in terms of meiotic recombination, but this evolutionary innovation can only mix and match variations that were, ultimately, generated by mutation: indeed, the mechanism of recombination itself introduces new possibilities for types of mutation. See, for example, Miguel Arenas et al., "Mutation and Recombination in Pathogen Evolution: Relevance, Methods and Controversies," *Infection, Genetics and Evolution* 63 (2018): 295–306, <https://doi.org/10.1016/j.meegid.2017.09.029>.
- <sup>33</sup>For further discussion of how environmental information is injected into the system, see Randy Isaac, "Review of *Introduction to Evolutionary Informatics* by Robert J. Marks II, William A. Dembski, and Winston Ewert," *Perspectives on Science and Christian Faith* 69, no. 2 (2017): 99–104, <https://www.asa3.org/ASA/PSCF/2017/PSCF6-17Isaac.pdf>.
- <sup>34</sup>Dawkins, *The Extended Phenotype*.
- <sup>35</sup>Ibid.
- <sup>36</sup>Charissa de Bekker et al., "Species-Specific Ant Brain Manipulation by a Specialized Fungal Parasite," *BMC Evolutionary Biology* 14, no. 1 (2014): Article number 166, <https://doi.org/10.1186/s12862-014-0166-3>.
- <sup>37</sup>It might seem that the analogy of genomes shaped by natural selection resembling photographs breaks down at this point or, more importantly, that the idea that organisms simplify their nonliving environments breaks down. Far from it. The reader need take only a moment to think about some of the ways in which photographs do, in fact, go on to influence the "real world" – from mass media images that influence a national mood and its manifestations, to personal, idiosyncratic vacation photos that trigger a conversation. The analogy and the point it represents hold up and nothing stops the photograph from being a simplified reflection of the objects it depicts.
- <sup>38</sup>Boring, Stump, and Freeland, "Rethinking Abiogenesis: Part 1."
- <sup>39</sup>For a more detailed discussion of "seamless," including the possibility for important feedback loops, see the exchange between Sy Garte, "A Greater Degree of Discontinuity," *Perspectives on Science and Christian Faith* 72, no. 3 (2020): 188–89, <https://www.asa3.org/ASA/PSCF/2020/PSCF9-20Garte.pdf>; and our authors, "'Rethinking Abiogenesis' Authors Respond," *Perspectives on Science and Christian Faith* 72, no. 3 (2020): 190–91, <https://www.asa3.org/ASA/PSCF/2020/PSCF9-20Boring.pdf>.
- <sup>40</sup>L. Ségurel et al., "Positive Selection of Protective Variants for Type 2 Diabetes from the Neolithic Onward: A Case Study in Central Asia," *European Journal of Human Genetics* 21, no. 10 (2013): 1146–51, <https://doi.org/10.1038/ejhg.2012.295>.
- <sup>41</sup>Dawkins, *The Extended Phenotype*, 1.
- <sup>42</sup>Ibid.
- <sup>43</sup>While the disciplines addressed in this section are necessarily secular in nature, our perspective is that the entire universe is God's creation. By his Word, all things were created through a seamless continuum of processes in space and time. The observation and description of these processes are the same for atheists and theists, though the former discount the underlying source that theists affirm.
- <sup>44</sup>Merriam-Webster Dictionary, s.v. "ecology," accessed August 29, 2020, <https://www.merriam-webster.com/dictionary/ecology>.
- <sup>45</sup>John Odling-Smee, Kevin Laland, and Marcus Feldman, *Niche Construction: The Neglected Process in Evolution* (Princeton, NJ: Princeton University Press, 2003).
- <sup>46</sup>Kevin De Queiroz, "Species Concepts and Species Delimitation," *Systematic Biology* 56, no. 6 (2007): 879–86, <https://doi.org/10.1080/10635150701701083>.

- <sup>47</sup>Philip C. J. Donoghue and Jonathan B. Antcliffe, "Origins of Multicellularity," *Nature* 466, no. 7302 (2010): 41–42, <https://doi.org/10.1038/466041a>.
- <sup>48</sup>Richard K. Grosberg and Richard R. Strathmann, "The Evolution of Multicellularity: A Minor Major Transition?," *Annual Review of Ecology, Evolution, and Systematics* 38 (2007): 621–54, <https://doi.org/10.1146/annurev.ecolsys.36.102403.114735>.
- <sup>49</sup>William F. Martin, Sriram Garg, and Verena Zimorski, "Endosymbiotic Theories for Eukaryote Origin," *Philosophical Transactions of the Royal Society B* 370, no. 1678 (2015), <https://doi.org/10.1098/rstb.2014.0330>.
- <sup>50</sup>Mauro Degli Esposti, "Bioenergetic Evolution in Proteobacteria and Mitochondria," *Genome Biology and Evolution* 6, no. 12 (2014): 3238–51, <https://doi.org/10.1093/gbe/evu257>.
- <sup>51</sup>Matteo P. Ferla et al., "New rRNA Gene-Based Phylogenies of the *Alphaproteobacteria* Provide Perspective on Major Groups, Mitochondrial Ancestry and Phylogenetic Instability," *PLoS ONE* 8, no. 12 (2013): e83383, <https://doi.org/10.1371/journal.pone.0083383>.
- <sup>52</sup>Hwan Su Yoon et al., "A Molecular Timeline for the Origin of Photosynthetic Eukaryotes," *Molecular Biology and Evolution* 21, no. 5 (2004): 809–18, <https://doi.org/10.1093/molbev/msh075>.
- <sup>53</sup>Malcolm S. W. Hodgskiss et al., "A Productivity Collapse to End Earth's Great Oxidation," *Proceedings of the National Academy of Sciences* 116, no. 35 (2019): 17207–12, <https://doi.org/10.1073/pnas.1900325116>.
- <sup>54</sup>Robert E. Kopp et al., "The Paleoproterozoic Snowball Earth: A Climate Disaster Triggered by the Evolution of Oxygenic Photosynthesis," *Proceedings of the National Academy of Sciences* 102, no. 32 (2005): 11131–36, <https://doi.org/10.1073/pnas.0504878102>.
- <sup>55</sup>Wikipedia, s.v. "Planetary Science," [https://en.wikipedia.org/wiki/Planetary\\_science](https://en.wikipedia.org/wiki/Planetary_science).
- <sup>56</sup>NASA, "Mars 2020 Mission Overview," accessed August 28, 2020, <https://mars.nasa.gov/mars2020/mission/overview/>; and Pamela Conrad, "A Tale of Two (Cities) Planets: What Earth and Mars Are Teaching Us about the Evolution of Habitable Worlds," January 21, 2016, accessed August 27, 2020, <https://carnegiescience.edu/events/lectures/drpan-conrad-tale-two-cities-planets-what-earth-and-mars-are-teaching-us-about>.
- <sup>57</sup>Emmanuelle J. Javaux, "Challenges in Evidencing the Earliest Traces of Life," *Nature* 572, no. 7770 (2019): 451–60, <https://doi.org/10.1038/s41586-019-1436-4>.
- <sup>58</sup>Edward W. Schwieterman et al., "Exoplanet Biosignatures: A Review of Remotely Detectable Signs of Life," *Astrobiology* 18, no. 6 (2018): 663–708, <https://www.liebertpub.com/doi/full/10.1089/ast.2017.1729>.
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