Rethinking Abiogenesis: Part 1, Continuity of Life through Time

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Evolution teaches that any particular organism, population, or species is a point on a continuous lineage that extends back to life's origins. Apparent discontinuities (for example, species) often reflect subjective, human decisions as much or more than objective measurements. In the same way, no intrinsic, objective reason identifies any particular moment in the development of biochemical complexity as the origin of life other than the origin of the universe itself. There is no natural breakpoint presented by the physical universe. Focusing excessively on any other points robs science of important context and is detrimental to future progress—for example, by failing to extend our view one notch further back in order to understand how and why this particular point emerged. We advocate, instead, a view of abiogenesis that stresses continuity over particular "starting points." This way invites rich resonances with strands of historical and contemporary theology.

One of the standard objections to biological evolution is that there is no scientific explanation for how life could emerge from nonlife. A standard response to this objection is that the theory of evolution deals with only the diversification of life, not the origin of life.[1] Indeed, one form of this argument is that the emergence of "life" and "evolution" can usefully be distinguished from one another.[2] More broadly, a widespread assertion is that "abiogenesis," as the origin of life is sometimes called, is a different field of scientific inquiry, and one for which there is far less scientific consensus at present than there is for evolution.[3] But while this distinction may be made between evolution and abiogenesis, we believe that one of the chief impediments to closing this gap emerges from treating abiogenesis as a discrete event, a point in time, in stark contrast to the recognized continuity of evolution.

Instead, we would benefit from returning to an older and often maligned meaning of the word "evolution," one which encompasses the one continuous (and as-yet-incomplete) transition from the origin of time.[4] A different way to express this idea is that this perspective of continuity in abiogenesis opens up interesting questions on a number of different practical fronts for interdisciplinary research, both within science and beyond, including rich new pairings of theology with evolutionary science.

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Evolutionary Continuity in Biology

For most of Western intellectual history, objective lines of demarcation were perceived to separate individual organisms into natural groupings. Influential philosophical schools reasoned that these lines resulted from particular essences or forms that defined the species and placed them into hierarchical relationship.[5] The theory of biological evolution challenged this view by proposing continuity between species over time. But there is no nonarbitrary way to identify the first member of a species, and the arbitrary identification of such a point implies, for example, an organism that had parents of a different species (see Box 1).[6]

Box 1: A Brief Primer on the Ambiguities of Evolutionary Origins

Evolutionary biology indicates that around 400 million years ago, from within one subgroup of fish, successive generations of descendants evolved into amphibians, reptiles, birds, and mammals—including us.[7] This eventual outcome explains why we find a point of origin interesting (an important idea to which we will return below). But which generation or individual creature marks the origin of terrestrial animal life? Why not their parents or offspring? Or one generation further out from that?

We might hope to find the answer in the molecular basis of life. Genetic material, after all, comes in discrete ("digital") states: sequences. Perhaps we might identify one such sequence as an unambiguous point of origin. But molecular genetics tells us that many slightly different gene sequences encode bodies and behaviors that are identical, and countless more that may or may not be functionally indistinguishable based on circumstance.[8]

Meanwhile, narrowing consideration to any specific characteristic paradoxically increases ambiguity in other ways. For example, fleshy fins that are starting to function as legs appear much later than swim bladders that are starting to function as lungs.[9] And refocusing on the point at which a suite of traits first coincides, merely relocates the ambiguity to the choice of which traits to include or exclude. Indeed, the more characteristics that are considered, the more recent a perceived point of origin becomes. The traits that define you, or any other specific human being, have probably never come together within a single, living organism until your lifetime (this is, after all, the basis of "DNA fingerprinting").[10] In that sense, was the origin of you ... birth? Fertilization? Or some point in the development of the embryonic you?

That final option reminds us that anyone reading this does so with a physical body that is not done changing yet. We should probably consider an entire lifespan before deciding on which side of an origin it belongs. For an extreme example, tadpoles do not look much like land animals—the category in which we place amphibians, therefore, depends on the stage of life we observe. But this gives further pause for thought. The genetic instructions which encode you may well be travelling forward into the future, separated into different bodies alongside different travelling companions.[11] Considered like this, every population of living organisms comprises individuals whose descendants could be identified as significant by future biology in ways not yet known. Are these current individuals better understood as outcomes of a past origin, or as starting points of something new? Origins exist relative to outcomes only, and outcomes reflect the perspective of a particular moment in time.

All such reasoning applies to any scale at which we seek evolutionary origins (from "*homo sapiens*" to "animal"). We can choose to define breakpoints useful for various practical purposes, but biological evolution is fundamentally continuous. Every organism and every gene connect backward, in a direct and unbroken thread, to the origin of life. They likewise connect forward to futures that none of us have witnessed.

Furthermore, no single criterion identifies species objectively.[12] We might use morphology or reproductive behavior or genetics to group individuals, but—and this is the important point—different choices tend to identify different starting points in evolutionary history. Scientists who study speciation in our present-day world are among the best at explaining the limitations of the species concept.[13] It is not that the concept of species is meaningless. Rather, there are many ways to define the idea, and no one choice is inherently superior to the others. Each identifies something useful and is better or worse suited to a particular question and the context in which it is being asked. Conservation biology might identify one set of criteria in order to guide policy and thought about what exactly we are trying to conserve.[14] Paleontology might define another in order to understand when and under what conditions a particular fossil transition occurred.[15] Microbiology might define yet another for the purposes of medical diagnosis or quarantine.[16]

By analogy, think of the movie *Star Wars: Episode IV – A New Hope*. It seems perfectly legitimate to ask, at which point, in the original movie, did we meet the arch villain Darth Vader? And because the film consists of individual frames (over 174,000 of them), we ought to be able identify one specific frame as the point of meeting this character, right? But what exactly constitutes the "first meet" of this character?

During the opening scenes of the movie, the garrison of a small spaceship is quickly overrun by a much larger and better-equipped force of boarders. As the battle smoke clears, we hear an ominous heavy breathing and a figure steps forward wearing a dark cloak and mask. We will soon learn that this is Darth Vader who ordered this hostile boarding party. So when does Vader first appear? Is it the first frame in which any part of his clothing becomes visible through the smoke? Or the first frame in which his entire body is in view (with or without smoke obscuring our view, by the way)? Maybe it is the movie's opening sequence in which we see Vader's gigantic spaceship from afar; technically he was in that scene, right? Or perhaps we might choose a more traditional "face-to-face" option, except that we never get to see his face at any point in the movie! In another sense, were we not beginning to meet Vader through the violent actions of his troops, before his physical presence manifested? These are all visual evidences, but could we not first meet him through other senses? We hear Vader's distinctive breathing before we see any part of him. Should we just ignore that? Or maybe we should wait until the first time he is identified by name.

None of these are particularly bad choices. All of these points capture something of what we are interested in. But identifying any single frame reflects our choice, not an intrinsically meaningful measurement. There are clearly frames of the film that we could identify as before and after we meet Vader, according to any reasonable criterion. The specific point of this transition, however, is open to different interpretations.

So, too, with biological evolution. Given some concept of a species, clear before-and-after points exist within the evolutionary lineages of many species. No one suggests that the morphology we call *Homo sapiens* existed one million years ago; and clearly the morphology we label *Archaeopteryx* does not exist today. But the point of transition to either of these morphologies is a matter of subjective interpretation.

This logic is not limited to species. It also extends to any scale at which we choose to identify biological types. We might choose to perceive breakpoints at animals, tetrapods, hominids, or human beings. And different choices may be useful for a given aim (e.g., directing science funding, guiding conservation policy, or directing specific medical treatments). But any such point will gather useful context by extending the focus one notch backward or one notch forward, thus blurring that chosen line of demarcation. Therefore, one might think that the academic discipline of evolutionary biology can defend only one choice of origins as objective: living is a different category than nonliving, and abiogenesis—when chemistry became biology—is the point at which the continuity begins. Or is it?

Evolutionary Continuity Applied to Abiogenesis

In order to pinpoint a moment of transition from nonlife to life, we need a definition for what counts as life … and here the problems begin.

Cell theory

Elementary courses in biology often teach that cells are the most basic unit of life. This cell theory

definition works reasonably well to lead us to useful inquiry such as, "What does it take for a cell to function?" But today, cell theory is taught as a useful simplification, not an accurate and sophisticated reflection of current science. In particular, a cell theory definition is not particularly helpful for thinking about abiogenesis because it is not intended for this purpose.

By analogy, elementary physics and chemistry teach that electrons orbit atomic nuclei rather like moon(s) orbit a planet. This is a useful foundation for beginning to learn about the ways in which energy and matter interact, such as in chemical reactions. But students who travel deeper into such science will have to overwrite this simple, conceptual model with something very different before they can come to grips with reaction dynamics or quantum mechanics. It would show poor reasoning—detrimental to scientific progress—if researchers had rejected the evidence for quantum physics because of its inconsistencies with the simple, introductory definition of atomic structure.

In the same way, subservience to the cell theory definition of life leads to misleading questions about abiogenesis: for instance, how did the first cell pop into existence from the primordial soup? Such a question reflects a failure to realize that our topic of interest, abiogenesis, has moved beyond the useful scope and purpose of the definition of life with which we are working.

There is nothing inappropriate about asking how and when the first recognizable cells were present on Earth (any more than it is inappropriate to ask about how and when the first morphology we call *Homo sapiens* emerged). But progress in answering such questions requires, at a minimum, a somewhat subjective definition of these terms, and, even then, progress can come only from researchers working to understand what came just prior to the first "modern" cell, what came just prior to that, and so on. No serious scientist of the twenty-first century would argue that the state immediately prior to a "modern" cell was chemical chaos. There is, quite simply, too much sophisticated molecular machinery within a cell for it to have emerged simultaneously.[17]

The central dogma and RNA

For students who begin with cell theory, the next step toward deeper understanding of the nature of life is the "Central Dogma of Molecular Biology." The central dogma asserts that within the boundaries of each cell's membrane, genetic information, encoded in DNA, is constantly translated into a suite of proteins. These genetically encoded proteins interact with one another to form the "business end" of life: metabolism, which includes the synthesis and replication of DNA (and, indeed, cell membranes).

The earliest "modern" cell is, in fact, rather similar to what the relevant research community has come to call LUCA—the Last Universal Common (shared) Ancestor of all living organisms.[18] Computer reconstructions of the genetic material of LUCA have led researchers to conclude that this material was "similar [in complexity and size] to … many extant [microbial] organisms." That means LUCA too was clearly the product of considerable biological evolution.[19] So what preceded it?

A compelling body of evidence has accumulated to suggest that somewhere prior to LUCA, the central role of DNA—genetic information and storage—was performed by RNA instead.[20] The atomic structure of RNA differs from DNA by a couple of minor chemical modifications which render DNA less chemically reactive and less prone to mutation. It seems that the evolutionary invention of DNA and its incorporation into life's biochemical foundations reflects an outcome of natural selection for a more stable information storage medium.[21] Where in this implied process of evolutionary upgrading should we locate the origin of life? We may stretch the question further. Exploratory research shows that the precise chemical structure shared in common by both RNA and DNA (types of ribonucleic acid) exhibits several subtle properties which seem slightly better suited to their role in living systems than slightly simpler chemical alternatives.[22] This implies that nucleic acids, as we know them, could be the outcome of natural selection for an optimal molecular representation of genetic information. If so, then would systems which encoded proteins using, say, **t**hreose **n**ucleic **a**cid (TNA) instead of **r**ibo**n**ucleic **a**cid (RNA) have crossed a boundary from the realm of biochemistry into that of nonliving chemistry?

Proteins, amino acids, lipids

So far, this argument has been developed in terms of one component of biology's central dogma: nucleic acids. But a similar situation holds for proteins and

the amino acid building blocks from which they are constructed. The central dogma describes a system of genetically encoded proteins constructed from a molecular "alphabet" of 20 amino acids. Over the past several decades, multiple lines of evidence from diverse academic disciplines have converged on an unexpected finding: the system of genetic encoding probably began with just half of these amino acids.[23] Would a reproducing, evolving system that constructed its proteins using ten amino acids instead of twenty be objectively viewed as not alive? What if it built primitive enzymes from something chemically simpler than amino acids (a point to which we will return below)?

Yet another analogous story seems to be emerging for lipids, which form cell membranes. The precise molecular structure of lipids used in "modern" cell membranes is difficult to justify as a plausible product of prebiotic chemistry. But chemically simpler alternatives which could do the job adequately are plausible. We might infer that lipid membranes as we know them, like nucleic acids and amino acids, are an outcome of natural selection, an upgrade of something earlier.[24] So where in all this evolutionary "upgrading" of the molecular basis for life-as-we-know-it should an objective line be drawn for the origin of living systems?[25]

Simply expanding cell theory to go beyond the precise details of the central dogma that came to define life on our planet does nothing to pinpoint an event we might objectively call "abiogenesis." Perhaps we could regard the evolutionary growth of the amino acid alphabet, or chemical refinements to nucleic acid or to lipids, as changes of degree rather than type—but that distinction is the fundamental ambiguity of evolutionary processes. The thesis of this article has been all along to question whether objective changes of *type*, rather than changes of *degree*, are what we expect from evolution.

The RNA world

For example, we can take one further step backward from a world in which RNA genes may have encoded proteins using a reduced repertoire of amino acids. We can imagine a scenario that removes any act of translation from the central dogma. In 1989, two researchers won a Nobel Prize for demonstrating that RNA sequences can, under the right conditions, fold up spontaneously into three-dimensional shapes capable of catalyzing chemical reactions.[26] So perhaps, prior to the time of genetically encoded proteins, there was a time of reproducing, evolving organisms in which a single biopolymer, RNA, acted as both an information storage medium and the constituent unit of metabolic networks. Is that enough of a typological change to have crossed from nonliving to living?

In its most straightforward interpretation, this "RNA World" understanding of life's origins imagines that life began with a particular RNA sequence capable of folding into a ribozyme which catalyzes construction of another copy of itself. This self-replicating RNA ("RNA replicase") could, in principle, evolve increasing length for additional ribozymes which influence local conditions into a controlled chemical environment that facilitates copying—the first shadow of metabolism. Such a system could evolve onward to eventually cede the work of folding and catalyzing to genetically encoded proteins.[27]

A major challenge for this version of events comes from the inference that an RNA replicase sequence would probably have to comprise a couple of hundred nucleotides, chemically bound to one another in the correct sequence. For chance alone to form a specific sequence of that length would require a total mass of RNA exceeding the total mass of the entire universe. In other words, we have the same objection at this deeper level of understanding as we did when considering cell theory as a possible starting point for life: our "solution" seems utterly improbable without a simpler, preceding state.

We can press even deeper: An ingenious potential solution for RNA replicase comes from work demonstrating that many small RNA sequences can interact to produce the same overall effect as one large sequence.[28] This drastically improves the odds of the development of self-replicating RNA. But how far does it strain an intuitive definition of "life" to think of a network of smallish RNA fragments, potentially lacking any cell membrane(s), which interact to reproduce one another? Or perhaps our very description of these entities as "reproducing" and "evolving" causes us to identify them as living.

Chemical evolution

Now we have pushed far beyond most traditional definitions of what it means to be alive—at least

those definitions informed by the world we experience today, some four billion years after the events under discussion. But we have found no obvious stopping point in the continuous process, and so we continue.

The process of natural selection is not limited to acting only on what we take to be alive.[29] The concept 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 in the absence of life, and exploration of chemical evolution seems increasingly important to investigate how life-as-we-know-it came into existence. Multiple ideas are still jostling to describe just how this may have happened.[30] Suffice it to say that somewhere between the RNA world and chemical evolution we have crossed over any clear divide between living and nonliving.[31]

Thinking in abstract terms about self-replication has led numerous researchers over the years to note a variety of well-known phenomena, from crystals to fire, which are quite different from what we intuitively consider alive but which could be said to harness energy so as to make copies of themselves. The existence of a class of nonliving phenomena, from among which at least one particular pathway leads seamlessly to life as we experience it, seems to us exactly what should be expected from a universe which produced life in a geologically rapid timeframe on a fairly ordinary planet in a fairly ordinary star system.

Viewed in this manner, abiogenesis becomes just one more subjectively chosen point on a continuum that now stretches back to the origin of the universe—which, according to current understanding, is also the origin of time. Maybe a cosmological physicist could, now or in the future, explain why it might be unhelpful to view the origin of the universe as a useful starting point, but for us this alignment between the origin of life and the origin of time is good enough.

Let us emphasize that, just as we claimed for the concept "species," we do not claim the concept of abiogenesis to be meaningless or unhelpful. Rather, there are many ways to define the idea, and no one choice is inherently superior to all the others. Each contributes something that is better or worse suited to a particular question and the context in which it is being asked.

Why Does the Perspective of Continuity Matter?

So far our argument might seem only to be advocating for a shift in perspective. Is there more at stake than perceptions? We claim so, on two different but overlapping fronts. One is the way in which scientific inquiry now proceeds regarding questions of "origins." The second is the way in which Christian theology connects with this scientific progress.

Practical implications for scientific progress

A typological or discontinuous view of abiogenesis is counterproductive to efficient progress on the topic. Put simply, patterns of thought that assume discontinuities and changes in type set us up to ask less-than-helpful questions and prevent us from asking the questions that may lead to new breakthroughs in understanding.

At an extreme, this discontinuous thinking leads to rejections of evolutionary science. For example, typological thinking about different species has repeatedly led some to question whether natural processes can account for the "jump" from one species to another.[32] Likewise, typological thinking about living versus nonliving entities causes some to perceive a gap so wide that it strains their credulity for any hope of a natural explanation.[33]

To all such reasoning, we would echo our brief critique of using cell theory as a guide to life's origins. Fully functioning cells are indeed implausible products of prebiotic chemistry in a single jump, but that was never the issue. We simply need to perceive fully functioning cells as a minor development of something earlier, which was a minor development of something earlier than that … and so on. It is the misplaced focus on one isolated point which leads to a wrong-headed question—or at least to a question that prevents us from asking more-productive, interesting questions.

Beyond debate about the veracity of evolutionary science, something subtly similar can occur between different scientific disciplines. We noted above that

no serious, twenty-first-century scientist is attempting to research how prebiotic chemistry can lead directly to a fully functioning cell. But, instead, researchers may replace "fully functioning cell" with other isolated points, perpetuating the same unhelpful problem. The legacy of the Miller/Urey experiments serves to illustrate this point.

Miller and Urey in the 1950s succeeded in forming, within a matter of days, around half of the 20 genetically encoded amino acids from a simple chemistry representing prebiotic conditions.[34] This was enormously exciting and motivated a small army of chemists to attempt to produce the missing half. After three decades of work, 16 of the 20 amino acids had been accounted for by ingenious variations of reaction conditions (energy sources and gas mixtures).

Here, however, we see the footprint of a widespread mid-twentieth-century mindset about the proper relationship between scientific disciplines. Put crudely, when physics becomes sufficiently complicated it has moved into the domain of chemistry. When chemistry has become sufficiently complicated, it moves into the domain of biology. Under such thinking, the goal of organic chemists interested in life's origins can easily become "to account for the components of the central dogma as completely as possible" before handing over their results to biology and evolution. Another way of saying this is that chemists were motivated to form a "fully functioning amino acid alphabet" by any means necessary.

By the 1970s, other scientists were approaching the topic from a different disciplinary perspective: comparing the amino acids produced in spark tube experiments with those identified within meteorites. Meteorites are simply rocks that formed in space and underwent chemistry there before chancing to fall to Earth where they can be analyzed in laboratories. Considered as natural analogs for the spark tube experiments, meteorites revealed something interesting: they tend to contain more or less the same half of the "alphabet" of amino acids as the earlier spark tube experiments.[35]

It was left for scientists from yet another academic discipline, namely those studying the metabolic pathways by which amino acids are synthesized in contemporary biology, to notice an aligning pattern which led to a fundamentally different interpretation of the "missing half."[36] The half of the amino acid alphabet which forms plausibly under prebiotic conditions comprises molecules that are each found at the start of biosynthetic pathways. A series of sophisticated protein enzymes then act, one enzyme after another, to convert these prebiotically plausible amino acids into the missing half of the alphabet. A simple interpretation is to suggest that life's alphabet of genetically encoded amino acids began smaller—about half its current size. Then it was through biological evolution, not prebiotic chemistry, that the alphabet grew to incorporate amino acids absent from meteorites and difficult or impossible to produce through simulation experiments. The footprint of this ancient evolutionary history is seen, frozen through countless millennia, in present-day biochemical pathways—for much the same reason as a current version of Microsoft Windows contains fragments of code from 1980s MS-DOS. This idea of footprints of ancient evolution buried in modern metabolism resonates with one of the major directions of support for the RNA world hypothesis.[37]

Fast forwarding to the twenty-first century, this synthesis of different disciplinary insights has grown in strength and detail. Calculations of theoretical physics, empirical analysis of meteorites, simulations of organic chemistry, metabolic pathways of biochemistry, and computational reconstruction of ancient genomes all find unlooked-for alignment in the concept of a simpler, earlier stage of the genetic code which subsequently evolved a larger amino acid alphabet after protein enzymes were available to create useful, new amino acids. The problem of synthesizing missing amino acids in spark tube experiments has gone away. It is sobering, however, to remember the progress made by ingenious chemists in forcing "missing" amino acids into reluctant existence. The challenge, framed unhelpfully as it was, diverted time, skill, and resources away from the interdisciplinary breakthrough we now identify.

All ends well in the story of how we relate this history of science for the amino acids. But other potentially unhelpful points are alive and well within the origins community. "Fully functioning cell" and "complete amino acid alphabet" may have been left behind as targets for prebiotic chemistry, but "fully functioning RNA world," or "fully functioning RNA replicase molecule," or any other pinpoint can misdirect scientific efforts away from the fluid, open-

minded exchange of information between academic disciplines that yields progress.

In the past ten years, there has been a series of claims from one extraordinary research group about how prebiotic chemistry might have produced RNA. Those involved wrote openly in an early paper about motivations: "support [for] the 'RNA world' hypothesis … provide[s] a mandate for chemistry to explain how RNA might have been generated prebiotically on the early earth."[38] The resulting chemistry has been careful and ingenious, and has gathered considerable attention from scientific journalism. But oddities remain that seem to echo the amino acid history.

Neither RNA nor its constituent nucleotide building blocks have ever been identified in meteorites. RNA has likewise never been detected in spark tube experiments (or their ilk) unless these experiments were explicitly configured to detect RNA. (Indeed, the ingenuity lay in figuring out what configuration could possibly yield RNA!) The reaction pathway for plausibly prebiotic formation of RNA looks nothing like the pathway by which RNA is synthesized in contemporary biology. If we know that RNA once played the role of enzyme because the reaction pathways are still buried in modern metabolism, then why do we see nothing of the sort for RNA synthesis? Perhaps most intriguing, direct prebiotic synthesis of RNA does nothing to explain why RNA shows properties ideal for the role of genetic material in comparison with slightly different, simpler molecular analogs.

Voicing skepticism for the prebiotic synthesis of RNA, we are duty bound to admit, is the point at which our argument probably strays furthest from a mainstream view of current science. The RNA world hypothesis still reigns within the origins research community, and the spectacular series of claims for prebiotically plausible RNA was published in far more prestigious scientific journals by a group with far more funding and scientific authority than any of the authors of this manuscript can boast. But our purpose is less to make a judgment call than to ask the reader a question. Is a prebiotically plausible pathway for RNA synthesis really closing a gap between pieces of the puzzle for life's emergence? Or does it reflect the sort of problems that come from pinpointing abiogenesis? Put another way, does "support [for] the 'RNA world' hypothesis" really "provide a mandate for chemistry to explain how RNA might have been generated prebiotically on the early earth"? Or does it provide a mandate to ask what precursors might have been upgraded to RNA by natural selection for an optimal genetic molecule, and what precursors led to these RNA precursors, and so on, until we find answers that mesh with the chemistry that emerges easily and from a wide variety of spark tube experiments, meteorites, metabolic pathways, and other approaches?

Whatever you decide about RNA, one way to generalize our overarching point is to suggest that a discontinuous or typological view of abiogenesis can place different academic disciplines out of right relationship with one another. Right relationship in this sense means something like a humble open-mindedness and equality of disciplines which encourage objective integration of disparate knowledge. Preconceived hierarchies between disciplines or even preconceived notions of a discipline's legitimate domain stray from this notion of right relationship. For example, evidence in favor of a smaller, earlier amino acid alphabet would be hard to notice for any scientist who perceived only the chemical challenge ("How could the amino acid alphabet have been synthesized?"). However, this evidence would be easy to spot for a community of scientists comparing meteoritics, biochemical physiology, and chemistry with similar, shared questions in mind.

Expressed in this way, right relationship defines, to a large extent, the emerging interdiscipline of "astrobiology," which has encompassed and, in our view improved, the health of origins research.[39] In our direct experience, astrobiology is more a statement of community than it is an identity of an individual researcher. To the extent that individual scientists are astrobiologists, it seems to mean something like "open to the breadth of science telling me things I did not know" or "seeking unexpected connections between disparate dimensions of science." Happily, there are signs that the major funding sources increasingly favor this sort of approach for the study of life's origins.

For example, NASA and the National Science Foundation recently entered into a novel collaboration to jump-start fresh thinking within the origins community by putting thirty leading scientists from different disciplines through a commercial training process designed to break down preconceptions in

order to form interdisciplinary teams.[40] Readers who are interested in exploring this unusual initiative in greater detail are warmly welcomed to browse a full description of outcomes, as gathered two years after the initial event.[41]

Interface of science and theology

On the surface, our framing of evolution and abiogenesis may appear to challenge some widespread interpretations of Christian doctrine. We have argued that all life stretches back in an unbroken continuum, and that any starting point is best understood in relation to all previous points. Christian ideas of creation, on the other hand, have often tended to emphasize discrete and discontinuous events: the special creation of humans, or each of the species according to their "kinds," for example.

But such notions of creation do not exhaust what is found in the Christian tradition. Indeed, to escape charges of deism (or at least a semi-deism or episodic deism), any Christian account of God's activity must acknowledge what God is doing between the moments of special creation.[42] Sometimes this is described merely as God's upholding or sustaining the world, but there is a rich tradition of referring to God's *creatio continua*, particularly in the writings of Maximus the Confessor, Gregory Palamas, and Hildegard von Bingen. On this view, God's creative work is ongoing and continual, and thus brings God into more direct relationship with all of the created order.

Emphasizing the continuous aspect of God's creative activity over the episodic does not diminish God's role but, rather, extends it.[43] Beyond a conception of intervention at narrowly defined starting points, God's role and presence expands to the continual, integrated, and coherent pattern of an unfolding universe. The relationship between such theological statements of *creatio continua* and the explanation of continuity in scientific language as presented above merits further exploration.[44] The theological challenge—and, we believe, the invitation—lies in a challenge to think about the origins of humanity, of life, or even of the universe itself as a *process.* We have described a framework of evolutionary thinking in which the primary themes are relationship, continuity, and pattern rather than linearity and discrete categories. What would it look like to extend these ideas to their theological application?

A good place to start might be with the thought of St. Bonaventure, a thirteenth-century theologian and contemporary of St. Thomas Aquinas. Bonaventure belonged to the Franciscan order, and just as St. Francis saw all creatures in the light of Christ, Bonaventure insisted that Christian thinkers must see the world through Christ—the creative Word through whom and for whom all was created. He claimed that Christ is the medium or Center of all the sciences.[45] As such, God is necessarily expressed through the created world, not at one or more points of origin but continually and continuously.

Bonaventure gave a series of proofs, in the sense recognized by medieval philosophy, that every individual creature proclaims the existence of God, and Bonaventure delighted (again like St. Francis) in what he saw as vestiges of the Trinitarian God manifested in the world. These vestiges were not limited to living creatures, though, as Bonaventure revived the idea first found in Augustine of *rationes seminales*. These are potentials with which God seeded the world, which would develop and unfold over time. For Bonaventure, matter itself is a kind of seed bed out of which later corporeal forms would bloom, not on their own accord, but precisely because God acts continuously at each moment.[46] This should not be understood as a scientific explanation in our modern sense, but it does resonate with the continuity of creation we have described here.

This view changes our priorities about the way we describe the created world. Investigating God through nature does not require or even benefit from rigid categorization with finite events such as a formal, and human-defined, origin of life. Instead, the study of ongoing and unbounded relationship—not only between different branches of life, but also between life and the universe within which it exists—is not only compatible but also helpful, and perhaps even necessary, in approaching questions about the nature of God. And our article provides one way to begin this investigation.

We suspect that this example is no more than one gesture to many specific ways in which a perspective of evolutionary continuity, far from threatening important theological tenets, instead invites a richer conversation between theology and science. In addition to uniting disciplines of physics, chemistry, and biology, we hope that the "right relationship" we

have advocated will allow us to revisit traditional theological ideas with new scientific insight. ∞

Notes

[1]See, for example, Austin Cline, "Abiogenesis and Evolution," *Learn Religions*, updated June 25, 2019, https://www.learnreligions.com/abiogenesis-and-evolution-249875; and "Abiogensis," *RationalWiki*, https://rationalwiki.org/wiki/Abiogenesis.

[2]Sy Garte, "Teleology and the Origin of Evolution," *Perspectives on Science and Christian Faith* 69, no. 1 (2017): 42–50.

[3]Tom Siegfried, "Top 10 Scientific Mysteries for the 21st Century," *Science News,* January 28, 2015, https://www.sciencenews.org/blog/context/top-10-scientific-mysteries-21st-century; and Lauren Cahn, "15 Science Mysteries No One Has Figured Out," *RD.com >culture,* https://www.rd.com/culture/science-mysteries-no-one-has-figured-out/.

[4]Stephen J. Freeland, "Could an Intelligent Alien Predict Earth's Biochemistry?," in *Fitness of the Cosmos for Life*, ed. J. Barrow et al. (New York: Cambridge University Press, 2008), 289–91; and see Garte, "Teleology and the Origin of Evolution," for a discussion of the reasoning behind the semantics of "evolution" and what is meant by evolutionary change.

[5]This legacy is clear from the ancient Greeks (particularly Aristotle) through Linnaeus in the eighteenth century, and the intuitions remain today.

[6]We acknowledge that some people may have theological reasons for identifying a first member of the human species. We bracket this topic of discussion as irrelevant to the bigger point we are making in this article.

[7]Per E. Ahlberg, "Follow the Footprints and Mind the Gaps: A New Look at the Origin of Tetrapods," *Earth and Environmental Science Transactions of the Royal Society of Edinburgh* 109, no. 1-2 (2019): 115–37, https://doi.org/10.1017/S1755691018000695.

[8]Jack Lester King and Thomas H. Jukes, "Non-Darwinian Evolution," *Science* 164, no. 3881 (1969): 788–98, https://doi.org/10.1126/science.164.3881.788; Motoo Kimura, *The Neutral Theory of Evolution* (New York: Cambridge University Press, 1983); and Tomoko Ohta, "The Nearly Neutral Theory of Molecular Evolution," *Annual Review of Ecology and Systematics* 23 (1992): 263–86.

[9]P. L. Forey, B. G. Gardiner, and C. Patterson, "The Lungfish, the Coelacanth, and the Cow Revisited," in *Origins of the Higher Groups of Tetrapods: Controversy and Consensus*, ed. Hans-Peter Schultze and Linda Trueb (Ithaca, NY: Comstock Publishing Associates, 1991), 145–74; and Colleen Farmer, "Did Lungs and the Intracardiac Shunt Evolve to Oxygenate the Heart in Vertebrates?," *Paleobiology* 23, no. 3 (1997): 358–72, http://farmer.biology.utah.edu/manuscripts/1997%20Paleobiology23.pdf.

[10]The 1000 Genomes Project Consortium, "A Global Reference for Human Genetic Variation," *Nature* 526 (2015): 68–74, https://doi.org/10.1038/nature15393.

[11]Richard Dawkins, "Immortal Coils," in *The Selfish Gene* (New York: Oxford University Press, 1989), 21–45.

[12]Kevin De Queiroz, "Species Concepts and Species Delimitation," *Systematic Biology* 56, no. 6 (2007): 879–86, https://doi.org/10.1080/10635150701701083.

[13]Ramon Rosselló-Mora and Rudolf Amann, "The Species Concept for Prokaryotes," *FEMS Microbiology Reviews* 25, no. 1 (2001): 39–67, https://doi.org/10.1111/j.1574-6976.2001.tb00571.x; Ping Xie, "A Brief Review on the Historical Changes in the Concept of Species," *Biodiversity Science,* September 2016, http://en.cnki.com.cn/Article_en/CJFDTOTAL-SWDY201609006.htm; and Richard A. Richards, *The Species Problem: A Philosophical Analysis* (Cambridge, UK: Cambridge University Press, 2010).

[14]Tatiana Korshunova et al., "Multilevel Fine-Scale Diversity Challenges the 'Cryptic Species' Concept," *Scientific Reports* 9, no. 1 (2019): 6732, https://doi.org/10.1038/s41598-019-42297-5.

[15]Johanna Kovar-Eder et al., "Palaeontological and Biological Collections—Bridging the Gap," *Biodiversity Information Science and Standards* 3 (June 18, 2019), e37183, https://doi.org/10.3897/biss.3.37183.

[16]Konstantinos T. Konstantinidis, Alban Ramette, and James M. Tiedje, "The Bacterial Species Definition in the Genomic Era," *Philosophical Transactions of the Royal Society B, Biological Sciences* 361, no. 1475 (2006):1929–40, https://doi.org/10.1098/rstb.2006.1920.

[17]Patrick Forterre, Simonetta Gribaldo, and Celine Brochier, "LUCA: The Last Universal Common Ancestor," *Medical Sciences* 21, no. 10 (2005): 860–65.

[18]Patrick Forterre and Herve Philippe, "The Last Universal Common Ancestor (LUCA), Simple or Complex?," *The Biological Bulletin* 196, no. 3 (1999): 373–77, https://doi.org/10.2307/1542973.

[19]Tamir Tuller et al., "Reconstructing Ancestral Gene Content by Coevolution," *Genome Research* 20, no. 1 (2010): 122–32, https://doi.org/10.1101/gr.096115.109.

[20]Antonio Lazcano et al., "The Evolutionary Transition from RNA to DNA in Early Cells," *Journal of Molecular Evolution* 27 (August 1988): 283, https://doi.org/10.1007/BF02101189.

[21]In our argument thus far, we have assumed that the origin of life is closely linked to the origin of the process of evolution itself. In other words, studying the development of the process by which genetic information is encoded and passed on is equivalent (or at least a necessary step) to studying the development of life itself. Here we point the reader to an alternative view expressed in Garte, "Teleology and the Origin of Evolution." Garte argues that the origin of life and the origin of natural selection are best considered as two separate issues. He advocates that "evolution" as a process is a purely biological phenomenon, characterized by a linkage between genotype and phenotype. This distinction is important, in his view, when it comes to questions of teleology. The protein-synthesis/translation system that bridges the gap between genotype and phenotype allows us to conceive of a new definition of biological teleology—one in which meaning is found not in the action or outcome of evolution, but in the "fabric" of the process of evolution itself.

[22]Albert Eschenmoser, "Chemical Etiology of Nucleic Acid Structure," *Science* 284, no. 5423 (1999): 2118, https://doi.org/10.1126/science.284.5423.2118.

[23]Edward N. Trifonov, "Consensus Temporal Order of Amino Acids and Evolution of the Triplet Code," *Gene* 261, no. 1 (2000): 139–51, https://doi.org/10.1016/s0378-1119(00)00476-5; Paul G. Higgs and Ralph E. Pudritz, "A Thermodynamic Basis for Prebiotic Amino Acid Synthesis and the Nature of the First Genetic Code," *Astrobiology* 9, no. 5 (2009): 483–90, https://doi.org/10.1089/ast.2008.0280; and H. James Cleaves, "The Origin of the Biologically Coded Amino Acids," *Journal of Theo-*

retical Biology 263, no. 4 (2010): 490–98, https://doi.org/10.1016/j.jtbi.2009.12.014.

[24]David Deamer, "The Role of Lipid Membranes in Life's Origin," *Life* 7, no. 1 (2017): 5, https://doi.org/10.3390/life7010005.

[25]In his article, "Biological Information, Molecular Structure, and the Origins Debate" (*Perspectives on Science and Christian Faith* 63, no. 4 [2011]: 231–40), Jonathan Watts expands on the mechanisms of this "upgrading": how new information can be added to biological molecules via natural processes. He describes the modern laboratory technique SELEX (Systematic Evolution of Ligands through Exponential Enrichment) to show how the physical properties of nucleotide sequences can be exploited to artificially develop molecules with desired properties from a random pool of starting material. In Watts's view, new information can be incorporated into life-forms purely from the interaction of molecules with their environment, without a necessity for direct intelligent design. This capacity arises from the tight relationship between the information of a molecule and its physical structure, which in turn makes it difficult to separate the information in a biomolecule from the information in the rest of the environment. As we do, Watts explores how this relational and situated view of evolution expands rather than threatens theological conceptions of God's role in the development of life.

[26]"The Nobel Prize in Chemistry 1989," *NobelPrize.org*, accessed September 13, 2019, https://www.nobelprize.org/prizes/chemistry/1989/summary/.

[27]Stephen Freeland, Robin Knight, and Laura Landweber, "Do Proteins Predate DNA?," *Science* 286, no. 5440 (1999): 690–92, https://doi.org/10.1126/science.286.5440.690.

[28]Nilesh Vaidya et al., "Spontaneous Network Formation among Cooperative RNA Replicators," *Nature* 491, no. 7422 (2012): 72–77.

[29]Addy Pross, "The Evolutionary Origin of Biological Function and Complexity," *Journal of Molecular Evolution* 76, no. 4 (2013): 185–91, https://doi.org/10.1007/s00239-013-9556-1.

[30]Chrisantha Fernando and Jonathan Rowe, "Natural Selection in Chemical Evolution," *Journal of Theoretical Biology* 247, no. 1 (2007): 152–67, https://doi.org/10.1016/j.jtbi.2007.01.028; Andrés de la Escosura, "The Informational Substrate of Chemical Evolution: Implications for Abiogenesis," *Life* 9, no. 3 (2019): 66, https://doi.org/10.3390/life9030066; Bruce C. Gibb, "Abiogenesis and the Reverse Hofmeister Effect," *Nature Chemistry* 10, no. 8 (2018): 797–98, https://doi.org/10.1038/s41557-018-0111-y; and Don L. Armstrong, Doron Lancet, and Raphael Zidovetzki, "Replication of Simulated Prebiotic Amphiphilic Vesicles in a Finite Environment Exhibits Complex Behavior That Includes High Progeny Variability and Competition," *Astrobiology* 18, no. 4 (2018): 419–30, https://doi.org/10.1089/ast.2016.1615.

[31]We depart, for example, from Garte's argument that life's origin may be usefully distinguished from the origin of Darwinian evolution, with the latter as a true, typological innovation. See Garte, "Teleology and the Origin of Evolution."

[32]Bodie Hodge and Georgia Purdom, "Zonkeys, Ligers, and Wolphins, Oh My!," *Answers in Depth* 3 (2008): 71–73, https://assets.answersingenesis.org/doc/articles/aid/v3/zonkeys-ligers-wolphins.pdf.

[33]Douglas Axe, *Undeniable: How Biology Confirms Our Intuition That Life Is Designed* (San Francisco, CA: HarperOne, 2017).

[34]Stanley L. Miller, "A Production of Amino Acids under Possible Primitive Earth Conditions," *Science* 117, no. 3046 (1953): 528–29.

[35]Keith A. Kvenvolden, "Natural Evidence for Chemical and Early Biological Evolution," *Origins of Life* 5, no. 1–2 (1974): 71–86, https://doi.org/10.1007/BF00927014.

[36]J. Tze-Fei Wong and Patricia Bronskill, "Inadequacy of Prebiotic Synthesis as Origin of Proteinous Amino Acids," *Journal of Molecular Evolution* 13, no. 2 (1979): 115–25, https://doi.org/10.1007/BF01732867.

[37]Harold White, "Coenzymes as Fossils of an Earlier Metabolic State," *Journal of Molecular Evolution* 7 (1976): 101–104, http://hoffman.cm.utexas.edu/courses/cofactors_molecular_fossils.pdf.

[38]Carole Anastasi et al., "RNA: Prebiotic Product, or Biotic Invention?," *Chemistry and Biodiversity* 4, no. 4 (2007): 721, https://doi.org/10.1002/cbdv.200790060.

[39]G. Scott Hubbard, "What is Astrobiology?," *NASA*, October 1, 2008, https://www.nasa.gov/feature/what-is-astrobiology.

[40]Julie Fletcher, "Joint NASA-NSF Ideas Lab on the Origins of Life," *Astrobiology at NASA: Life in the Universe,* June 7, 2016, https://astrobiology.nasa.gov/news/joint-nasa-nsf-ideas-lab-on-the-origins-of-life/.

[41]"Assessment of the 2016 Origins IdeasLab: A Fresh Approach to Generating Scientific Research," https://inds.umbc.edu/files/2019/01/Ideaslab-Booklet_FINAL-1.pdf

[42]Aubrey L. Moore, "A Theory of Occasional Intervention Implies as Its Correlative a Theory of Ordinary Absence," in *Science and the Faith: Essays on Apologetic Subjects*, 6th ed. (London, UK: Kegan Paul, Trench, Trübner & Co., 1905), 184.

[43]As Denis Lamoureux describes, Darwin himself reflected on this topic, advocating that a God who creates life via natural processes is "far grander" than a God who relies on dramatic divine creative acts. He argues that biological evolution need not threaten the concept of teleology and divine intention in the development of life; it merely shifts the power of God to the creation of underlying "laws." For a thorough review of Darwin's writings in the context of debates of origins and intelligent design, see Denis O. Lamoureux, "Darwinian Theological Insights: Toward an Intellectually Fulfilled Christian Theism. Part 1: Divine Creative Action and Intelligent Design in Nature," *Perspectives on Science and Christian Faith* 64, no. 2 (2012): 108–20; and ___, "Darwinian Theological Insights: Toward an Intellectually Fulfilled Christian Theism. Part II: Evolutionary Theodicy and Evolutionary Psychology," *Perspectives on Science and Christian Faith* 64, no. 3 (2012): 166–79.

[44]See James Stump, "Does God Guide Evolution?," *Perspectives on Science and Christian Faith* 72, no. 1 (2020): 15–24.

[45]Frederick Copleston, *A History of Philosophy, Vol. 2, Mediaeval Philosophy, Part 1: Augustine to Bonaventure* (New York: Image Books, 1962), 271.

[46]Ibid., 306.

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