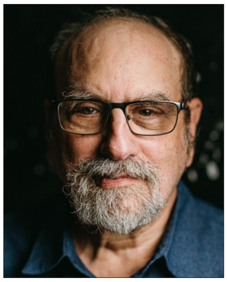

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Continuity, Simplification, and Paradigm Shifting in Biological Evolution

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The principle of continuity in evolution is often violated by discontinuous saltations leading to "punctuations" in evolutionary history. Highly accurate cellular replication fidelity is a requirement for biological evolution. In previous work, I have used a statistical theoretical model to demonstrate discontinuity in the evolution of high replication fidelity. Depending on the granularity of approach, both a continuous and a saltational view of evolutionary history are consistent with a scientific worldview of creation, and with the concept of simplification in biology as articulated by Emily Boring et al. The apparent contradiction between the complexity of biological systems with the idea of evolutionary simplification can be resolved by considering the globally simplifying selection of single systems and the local evolution of increasing system complexity. Explanations of thresholds and discontinuities during evolution might require the inclusion of paradigms such as teleology and agency in biological science, with theological implications.

Keywords: self-replication, discontinuity, convergence, teleology, teleonomy, agency, agonomy, origin of life

Continuity in Evolution

The role of continuity (sometimes referred to as gradualism) has been an important aspect of biological evolutionary theory since its inception. Charles Darwin famously wrote:

> If it could be demonstrated that any complex organ existed, which could not possibly have been formed by numerous, successive, slight modifications, my theory would absolutely break down. But I can find out no such case.[1]

Eugene Koonin defined evolutionary continuity as the "general Darwinian principle … [that] evolution must proceed via consecutive, manageable steps, each one associated with a demonstrable increase in fitness."[2]

Continuity involves a process that progresses in steps, whereby each step produces a meaningful difference in an outcome compared to the previous step. Meaningful differences can be assessed statistically for measurable outcomes. Continuity can thus be determined by the smallest number of fixed-size steps that result in a statistically significant difference in outcome. If a large number of steps is required before a significant outcome difference is observed, then continuity is broken, and the best explanation is saltation. This approach was used in my previous work on discontinuity in replication accuracy.[3]

Evolution, including its detailed biochemical and molecular mechanisms, is a cogent, strictly biological theory that operates only in the biological world. If we examine the evolutionary history of

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life on this planet, we can see strong evidence for discontinuity at many points.[4]

The great paleontologist Stephen J. Gould proposed the concept of punctuated equilibrium based on fossil data. Gould and Niles Eldredge found many examples of long periods of slow or negligible evolution, interrupted (or punctuated) by dramatically rapid and unexpected leaps of sudden alterations, including the birth of new phyla.[5] "Sudden" here is, of course, meant in evolutionary time scales. Some of these leaps, or saltations, resulted, at least partially, from rare kinds of mutations, such as whole-genome duplications in the origin of vertebrates,[6] or from insertions of transposons as in the development of mammalian pregnancy.[7]

Even the origin of eukaryotes, which apparently happened through the endosymbiosis of energy-producing bacteria by larger cells resulting in mitochondria and chloroplasts, must be considered an enormous leap through discontinuous evolutionary space.[8] While such examples of discontinuity clearly contributed to the evolutionary history of life on Earth, they should generally be viewed as part of that history, along with simultaneous gradual changes. The complexities of evolution of plants and animals do not allow any single mechanism to entirely account for the enormous diversity of structural and functional characteristics of any form of biota.

However, all of these (and many more) discoveries of discontinuity in the large-scale evolutionary stage in biology did *not,* as Darwin feared, destroy the value of the theory of evolution by natural selection. Gradualism by itself is not a required feature for evolution to work, since we now know (as Darwin did not) the mechanisms required for the variation that evolution depends on, and there is no reason to exclude those mutations that produce rare and impactful changes in phenotype from the overall theory. Biochemical mechanisms for dramatic evolutionary changes have been elucidated by James Shapiro under the rubric of "natural genetic engineering,"[9] as well as by many biologists working in several newer fields of evolutionary biology called the "Extended Evolutionary Synthesis."[10]

Self-Replication

When most people, including most biologists, think about evolution, they generally start and finish with the Darwinian concepts of variation (gene mutations) and natural selection as the principle drivers of evolution. But there is another crucial component to the evolutionary process that is often overlooked, assumed, or taken for granted. That component, as Darwin well understood, is inheritance:

> But if variations useful to any organic being do occur, assuredly individuals thus characterized will have the best chance of being preserved in the struggle for life; *and from the strong principle of inheritance these will tend to produce offspring similarly characterized* (italics added).[11]

Evolution requires that alleles be inherited in order for natural selection to work. It is the inherited alleles that determine the phenotype, which is the target of natural selection. And, as we now know, inheritance is produced by the highly complex biochemical processes of cellular self-replication, which are unique to biological cells.

Only living cells can copy themselves with high accuracy. A factory can make thousands of identical widgets, but no widget and no factory has ever made even a single copy of itself. Crystals grow, but they do not copy themselves. No chemical, including DNA or RNA, can copy itself without help from a myriad of enzymes.

Each cell contains thousands of molecules: nucleotides, proteins, lipids, carbohydrates, metabolites, precursors, breakdown products, cellular structures, and organelles. When a cell divides, the two new cells contain copies of all these molecules, and each of the two new daughter cells is almost exactly the same as the parent cell.

In all of life there is a mechanism for the accurate replication of the genotype and a mechanism for the conversion of the genotype information into the phenotype. The central dogma of molecular biology states that only the genotype can be directly replicated, and only the phenotype can interact with the environment to allow for natural selection. (Of course, as in all of biology, no "dogma" is without exceptions, as epigenetics research shows in this case.) Genes made of DNA are not only replicated themselves, but they also code for the replication of all the cellular constituents, including all the enzymes (proteins) and RNAs that produce other cell constituents. In modern cells, genes and (indirectly) proteins are replicated, with over 99.9999% accuracy.

Evolution by natural selection depends on this high degree of replication fidelity from a parent organism to its offspring. If this value were much lower, then errors could have the potential of not accurately copying and transmitting beneficial alleles to the offspring. At lower levels of replication fidelity, an "error catastrophe"[12] would affect many genes, and thus many crucial proteins, and lead to death. If life requires a very high replication fidelity in order to survive and evolve, we can ask how this extraordinary feature of all life came to be.

Discontinuity in Evolution of Self-Replication in Early Life

Given the enormous complexity of the systems required for accurate replication of all the cellular components, questions about the origin of self-replication are likely to be very difficult to approach. Rather than focus on the molecular biological details, or assume any hypothetical scenario for protolife, I decided to try to develop a theoretical and statistical model. The goal was to investigate whether the evolution of high replication fidelity could have followed the continuity principle.[13] The model deals with two critical biological features possessed by all living cells, and presumably by protocells at the origin of life as well: the probability of cell survival between cell divisions and the degree of fidelity of replication.

Using a Monte Carlo approach to convert probabilities into simulated experimental findings, I found that a measure of population survival, the growth rate constant K, was a function of the two parameters described above. Values of K greater than 1.0 will allow for expansion and survival of a cellular population, whereas growth rates below 1.0 lead to population extinction. Both simulation data and theoretical derivations produced a relation between growth rate, survival probability (P_s), and replication fidelity (F), given approximately by the formula: $K \approx P_s (1 + F)$. Details of the model and methodology are given in two papers.[14] The main conclusions were that, in early life, continuous growth of a population of protocells requires minimum threshold probabilities of both survival and accurate replication.

The evidence for phase transitions with thresholds below which improvement of either survival or replication fidelity by evolution is not possible are consistent with saltation rather than a continuous, gradual process. Once these probabilities surpass the thresholds in the development of replication fidelity and survival, evolution to the very high levels of both parameters that we see in all modern life is possible, and in fact inevitable, by continuous evolution.

Biological Evolution as Simplification

In an article published in *PSCF* by Emily Boring, Randy Isaac, and Stephen Freeland, the case is made for life being a simplification of the nonliving universe.[15] This might at first appear to be counterintuitive and opposite to what most biochemists and molecular biologists would think. Every advance in understanding the detailed mechanisms by which living cells operate seems to point to a fractal-like picture of ever-increasing complexity at every scale of organization. Systems biology, neuroscience, and gene regulation are some of the areas under intensive study that exhibit astounding levels of complexity.

Yet, with further thought, I believe that there is truth in the simplification view, especially in the "filtering" or focusing sense that was stressed in the article.[16] Of all the possible genetic codes, there is only one (with a few very minor exceptions). Of all the possible mechanisms to translate the information in the DNA to make proteins, only one exists. The same is true for many of the basic required cellular systems in modern biological life. This narrowing down to one single system is probably traceable to, and helps support, both common ancestry and a selective mechanism for weeding out less efficient or reliable alternatives. The complexity of the successful systems is beyond controversy, but the biological process of selecting single complex systems is clearly a process of simplification to the best scenario. Perhaps one way of approaching this is to recognize that what biology does is simplify the possible collection of complex systems, resulting in simultaneous global simplification of systems with locally increasing complexity.

Simplification and Continuity

Both increasing complexity of systems and simplification by reduction of the number of systems can occur either by a continuous process of natural selection of variants, or by rapid saltations that are also selected for.

As an example of the latter, the discontinuities or phase transitions in the history of evolution may be directly related to the simplification process proposed by Boring, Isaac, and Freeland.[17] They represent barriers or roadblocks to straightforward, gradually improving solutions to biological problems in the course of evolution. In the case of high-accuracy self-replication, early life was faced with an almost insurmountable problem: how to replicate all the phenotypic components of a cell to allow for the inheritance required for evolution. The solution was the highly complex protein synthesis system, including a replicable information storage molecule (DNA) containing the information in the form of the genetic code to reproduce each of the enzymes necessary to create the phenotype. Once this system came into existence, evolution could proceed, and every living creature uses the same system.

It has been suggested that at one time there may have been other genetic codes, other protein synthesis systems, and only the most successful one survived in a standard evolutionary process. While this is certainly possible, an alternative view is that the difficulty in passing the self-replication barrier might have severely restricted the number of times such systems could arise. For example, the genetic code requires the simultaneous presence of aminoacyl-tRNA synthetases, tRNAs, transcription of DNA to mRNA, the ribosome, and a host of enzymes and other components. Therefore, when any working solution did arise, it became the universal process in all of life. Further refinement of the system then could occur through a gradual evolutionary process.

We can see something similar in many other examples of discontinuity in biology. The problem of survival in an increasingly toxic oxygen atmosphere was resolved by the saltation of endosymbiosis, whereby a cell engulfed an oxygen-metabolizing bacterium alive, which then allowed the cell to use the toxic gas to perform energy conversion far more efficiently than the original anaerobic creature could. Much later, the appearance of the vertebrate body plan followed a rare whole-genome duplication mutation event that allowed for the four-limbed bilateral body plan, which remained universal in all land animals.

An additional mechanism that clearly contributes to simplification during evolution is the process of convergence,[18] wherein common evolutionary pathways and solutions for specific problems are found in diverse phylogenetic branches. The evidence for this (including the degree of continuity) is found in multiple systems (the vertebrate eye, radar and sonar, flight using wings, and so on) that evolved independently in different phylogenetic lineages.[19]

A major biological innovation in this category was the origin of multicellularity. This required a difficult transition of cells from being independent units susceptible to all the rules of natural selection and individual fitness, to becoming parts of a greater organism whose fitness overrode that of the individual component cells. While an in-depth understanding of this major transition (including the degree of continuity) remains elusive, it apparently occurred at least twenty different times in early evolutionary history, and some postulate a fairly simple mechanism to explain its widespread occurrence.[20]

Contrary to the traditional neo-Darwinian gradualist view, these findings suggest a nonrandom direction in evolution and possibly the existence of unknown laws that can account for the constraints seen in the data (see below). It is notable that while operating with different mechanisms, the end result of convergence is the same—increasing simplification by constraining possible outcomes to a smaller set than might be expected.

Discontinuity and "God of the Gaps"

Saltational events should not be seen as leaps over "gaps" in what is known as a "God of the gaps" argument. In some cases, these unexpected punctuations in the process of evolution may be explained simply as rare events that needed to happen only once to have dramatic effects on the history of life. In many cases, detailed mechanisms for these events are known.[21] In other cases, including such phenomena during the origin of life as the development of high-accuracy self-replication, our level of ignorance is more profound. Stating that these kinds of gaps imply a divine intervention or the work of a designer does little to address the scientific issues involved.

Need for Paradigm Shifts in Biology

As happened with physics starting in 1905, we may be seeing for such biological problems a need to employ new kinds of methods, new perspectives, and perhaps to bring back some concepts that might have been prematurely expelled from biological thought. As I have previously written,[22] teleology is one prime candidate for such a banished concept. Another is agency. To be clear, I am not advocating for "bringing religion" into science—these ideas have been put forth by nontheist biologists such as James Shapiro and Denis Noble.[23]

Teleology and agency are everywhere in biology.[24] Both terms have several definitions. Ernest Mayr has used the term "teleonomy" to mean purpose conveyed by a program rather than a conscious agent as the best way to describe biological teleology.[25] I have previously noted that the complex biochemical systems that had to be present in the first protocells in order to allow for the origin of evolution are a sign of teleological processes at the dawn of life.[26] There is also strong evidence that agency can be found throughout biology. While I am not aware of a suitable term to refer to unconscious agency (analogous to teleonomy), clearly such a term would be helpful. I would propose "agonomy" and the nonconscious agent (such as bacteria, plants, or primitive animals) as "agonomists" (from the Latin *agere*—to act).

Under stress, bacteria undergo directed hypermutation, a process whereby specific parts of the genome, for a limited time, experience a drastic increase in replication errors, leading to an increased chance of producing specific mutations to alleviate the danger of population collapse due to severe stress such as starvation or exposure to toxicants.[27] These experimental findings are backed up by theoretical treatments of the role of replication fidelity and survival probability in extreme stress.[28]

Teleology and agency are undeniably part of life, and they appear as indispensable to an understanding of evolution. Asa Gray and Darwin himself considered teleology to be part of the beauty of the evolutionary theory,[29] as attested to by the following quotes. Gray wrote about "… Darwin's great service to Natural Science in bringing back to it Teleology: so that instead of Morphology *versus* Teleology, we shall have Morphology wedded to Teleology."[30] According to Francis Darwin, his father Charles quickly responded to Asa with, "What you say about Teleology pleases me especially and I do not think anyone else has ever noticed the point.[31]

However, in the decades following, and especially with the modern attempt to divorce any semblance of vitalism, religious connotation, or anything other than strict reductionism and materialism from the science of biology, all hints of such things as purpose and agency have been expunged from scientific vocabulary related to biology, more so than for any other (perhaps less defensive) scientific field. Throwing out the baby of teleology along with the bath water of unscientific metaphysical ideology has been, in my view (shared by many such as Haldane, Mayr, and Dennett), a terrible mistake. Biological agonomy does not mean that (for example) bacteria decide based on free will to hypermutate; the hypermutation reaction is built in by standard evolutionary mechanisms and the process of natural selection to increase survival probability in the face of severe stress. But it remains true that bacteria act.

By the same token, denying that animals and plants act with purpose, or that the function of an enzyme is devoid of purpose is, to me, the essence of denial of the reality of existence. As stated above, bringing teleology and agency back into biological theory is not an attempt to shove the camel's nose of design or creationism into the tent, but a much-needed solution to a fuller understanding of how life works and evolves.

The Theology of Paradigm Shifts

Many of the phenomena that I have labelled as discontinuous (for example, endosymbiosis, multicellularity) are used as examples of continuity in another article by Boring, Stump, and Freeland, who proposed that evolutionary continuity is a fundamental principle in the universe that can be applied to all emergent phenomena since the big bang, including life and consciousness.[32] These authors were focused on how "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."[33]

This view of overall continuity in the history of our universe employs a different meaning of the word compared to my own discussion of continuity restricted to an evolutionary mechanism implying gradualism. One way to think of the difference is in the granularity of our respective perspectives on change. The unfolding of God's purposes may indeed be seen in the coarse-grained, overall, continuous process of change in the cosmos, the galaxy, and the origin and evolution of life on Earth.

My point is that a more fine-grained examination of biological origins and evolution reveals striking discontinuities that require scientific explanation. Unlike some intelligent design advocates, I do not see these phenomena as direct evidence of divine miracles, places where God steps in to correct or revise his original creation. Instead, I see them as opportunities to search for new laws and new paradigms that will ultimately bring us closer to understanding divine creation as a whole.

Findings of science that are consistent with a divine Creator have historically followed major paradigm shifts and the application of novel scientific approaches or methodology. These include the discoveries of natural laws governing the physical world that came with the new experimental approaches of methodological naturalism (the scientific method); the awareness of the majestic size of our universe following the use of telescopy; the appreciation of the wonders of the living world following discoveries in the new fields of physiology, microscopy, and biochemistry; the sense of overarching mystery about the nature of the universe following discoveries in physics using new mathematical and theoretical approaches in relativity and quantum mechanics; and the finding that the universe, as stated in Genesis, did indeed have a beginning and was not past-eternal—that is, this same idea of a "beginnning" also followed from the new theoretical and experimental physics, as did the discovery that many cosmological constants appear fine-tuned to allow for the kind of universe we see.

Perhaps the time has come for the science of biology, like the science of physics, to accept some new scientific perspectives in order to make further progress in areas where breakthroughs appear to be needed, such as the origin of life, the understanding of unknown biological laws that may be responsible for convergence in evolution, the nature and origins of consciousness, the mechanisms of gene regulation, and others.[34] It is my belief that, as in the past, such new understanding will serve as an inspirational pointer to the majesty of the divine Creator. Both teleology (or teleonomy) and agency (or agonomy), two potentially useful new paradigms for a new scientific philosophy of biology, are also of major theological and philosophical significance, as related to divine purpose, human free will, and determinism. Like teleology, agency is in general rejected by current science as part of natural law; this rejection is appropriate for the behavior of molecules and physical objects. But humans as well as animals (even plants, bacteria, and cells) make decisions and act, using either conscious will or biochemical receptor and effector systems. We are agents with purposes, as is the original Agent who created the universe, the Lord God.

Biology is a wonderful science, but, as the study of all aspects of life, it is also more than a scientific discipline—it is a window into something beautiful and transcendent in our universe.[35] It needs to be explored with every tool given to us by our Creator. Adam was given the task of naming the animals. We, his descendants, have the task of learning all we can about God's gift of life. ▼

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