Biol Theory
DOI 10.1007/s13752-017-0280-8

THEMATIC ISSUE ARTICLE: ASTROBIOLOGY

Why We Should Care About Universal Biology

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Received: 27 January 2017 / Accepted: 28 June 2017

Abstract Our understanding of the universe has grown rapidly in recent decades. We've discovered evidence of water in nearby planets, discovered planets outside our solar system, mapped the genomes of thousands of organisms, and probed the very origins and limits of life. The scientific perspective of *life-as-it-could-be* has expanded in part by research in astrobiology, synthetic biology, and artificial life. In the face of such scientific developments, we argue there is an ever-growing need for universal biology, *life-as-it-must-be*, the multidisciplinary study of non-contingent aspects of life as guided by biological theory and constrained by the universe. We present three distinct but connected ways of universalizing biology—with respect to characterizing aspects of life everywhere, with respect to the explanatory scope of biological theory, and with respect to extending biological insights to the structure of nonbiological entities. For each of these, we sketch the theoretical goals and challenges, as well as give examples of current research that might be labeled universal biology.

Keywords Astrobiology · Cosmological natural selection · Definition of life · Extended evolutionary synthesis · Minimal genome · Universal biology

Introduction

Newton ushered in a new era of physics by removing the distinction between the terrestrial and celestial realms. Newton's *Principia*, first published in 1687, gave us one language and one system with which to investigate, understand, and explain not just our own planet, but the entire universe. Likewise, biology today faces a similar disunity when trying to reconcile our understanding of life on Earth with the life we may find in other parts of the universe. The accelerating pace of research in astrobiology spurs a need for a unified, universal approach to biological thought. Problematically, when drawing conclusions about the nature of life elsewhere in the universe, we cannot escape the fact that such claims are based on a single historical case, what has been called the "N = 1 Problem" (Sterelny and Griffiths 1999; Smith 2016). For understandable reasons, biology is often regarded as a historical science because most biological explanations are historical in nature: how life started, how the dinosaurs went extinct, whether humans came out of Africa, and so on. But there are also theories and models in biology that some have argued would apply to life elsewhere. It is, as yet, unclear how life on Earth may resemble life as it may exist in other worlds, or how such life might fit into biological theory. Nevertheless, several people have considered the possibility of presenting a universally applicable biology. These approaches span domains as disparate as artificial life (Langton 1989), evolutionary theory (Dawkins 1982), thermodynamics (Brooks and Wiley 1988), self-organization theory (Kauffman 1993, 1995), and so on. Each assumes a particular justification for studying the non-historically contingent aspects of life everywhere. But these disparate approaches prompt a more fundamental question: given our current epistemic limitations, why should anybody attempt a study of universal biology in the first place?

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One reason is that we are only now just beginning to understand the true expanse of the universe. The need for universal biology is fueled by scientific breakthroughs, including (1) the discovery that our galaxy is just one among the hundreds of billions of galaxies estimated to exist in the universe, with recent simulation evidence suggesting that there may exist as many as half a trillion galaxies in the universe; (2) the continual discovery of new exoplanetary systems and potentially habitable planets—of which at least 3200 have been verified from among about 5000 potential candidates identified so far (Chou and Johnson 2016); (3) the discovery of chemical diversity and complex organic molecules—the "building blocks of life"—in various solar systems including an infant solar system, leading to the conclusion that the chemical conditions necessary for life as we know it are fairly common (Öberg et al. 2015; Walsh et al. 2016; McGuire et al. 2016); (4) the discovery of water on Mars (Ojha et al. 2015); and (5) the discovery of creatures on Earth that can withstand and reproduce in very harsh environments, including interplanetary space (Jonsson et al. 2008). Such research is approaching or already engaging in the study of universal biology, creating a need for unification, and philosophical and theoretical input.

Simply put, universal biology is *the multidisciplinary study of the noncontingent properties of life as guided by biological theory and constrained by the universe*. Despite the diversity of approaches to such a study, we claim that research in universal biology can be characterized in three distinct but related ways: (1) with respect to generalizations about life everywhere, (2) with respect to the explanatory scope of biological theory, and (3) with respect to biological theory applied to the organization of nonbiological phenomena. Thus, in this article, we provide a way of understanding how these various research methods can be united under one common framework. We explore the questions that motivate the study of universal biology, and the research programs that consider those questions. Rather than go into any single approach in detail, or argue extensively about the merits or drawbacks of particular methods, our goal is instead to provide a primer of an exciting new research area. For each characterization we discuss the theoretical goals and challenges, and describe particular research programs and examples of current research in each that might be labeled universal biology.

Life

Theoretical Goal: Investigating the Nature of Life in the Universe

One motivation to study life in the universe is to develop a better understanding of life itself. By exploring universal biology in the sense of universal expectations for biology, many believe we can help define or develop a theory of life. This question, "what is life?" is central to disciplines as diverse as biology, philosophy, and public policy, but centuries of research into it have yielded only controversy. For example, when Edward Trifonov analyzed 123 distinct definitions of life across numerous disciplines, he found nine different categories of terms—system, matter, chemical, complexity, (self-)reproduction, evolution (variation), environment, energy, and ability (2011). In the past century, it has grown more relevant as new fields of research explore boundary cases: synthetic cells, operational criteria for Mars exploration, the RNA world, etc. According to Cleland and Chyba (2002), the reason we have not yet succeeded in defining life is because such a definition first requires an adequate theory of life, which we do not yet have. They maintain that definitions merely describe relations between words, so any definition of life is merely a statement on how we currently talk about the concept. Scientific theories, on the other hand, are what connect these words to specific meanings in the world. They agree with Shapiro and Feinberg (1980) when they argue that we can only hope to develop a theory of life by first discovering other examples of it. Until then, we will never be justified in any universal approaches to biology. In other words, both the exploration of universal biology and an understanding of life as a class are dependent on discovering other examples of life first.

Although the issues of theorizing about life and universal biology are related, we follow Smith (2016) and disagree with the view that universal biology must await a new discovery of life, much less a theory of life. If there are universal features of life, they are not conceptually linked to a clear division between life and nonlife, and in fact, such an assumption leads us astray.

First, it is unclear what it *means* to develop a theory of life. If it is an understanding of life that distinguishes all cases of "life" from "nonlife," then plenty of authors have stipulated such theories, they merely lack widespread scientific consensus (Gánti's chemoton or Maturana and Varela's autopoiesis models come to mind). If scientific consensus is required to be considered a genuine theory of life, the piecemeal approach found in most college textbooks has succeeded, though most researchers working in astrobiology find such a checklist approach unappealing. If it is to be a consensus on a holistic theory, such a consensus may remain elusive for sociological reasons. So, there is no consensus on what sort of consensus is needed to be considered a theory of life.

Second, life may not be the sort of phenomenon for which definitions or theories are appropriate (Machery 2011). The long history of searching for a clear definition of life can be viewed as the attempt to draw a precise line distinguishing life from nonlife—a distinction for which there is still no consensus. This assumption that there are only two possible answers guides our research toward searching for evidence of one or the other. It is possible for there to be a continuum between living creatures and nonliving creatures, or for there to be genuinely underdetermined cases. A few authors have even defended the notion that life is a cluster kind (Diéguez 2013), a process (Dupré 2014; Dupré and Guttinger 2016), a fuzzy category (Bruylants et al. 2010), a metaphysical individual (Hermida 2016), or outright denied that there *is* a distinction between living and nonliving entities (Descartes [1633]2010; Jabr 2013).

Finally, biological explanations do not need to refer to *all and only* living phenomena. We are comfortable with biological explanations that do not apply to *all* life, as when referring to particular species or populations. We are also comfortable, to some extent, with biological explanations that do not *only* apply to biology, as with biological models that do not necessarily fit the world as we see it. Astrobiologists model life on other worlds based on plausible assumptions about universal aspects of physics, chemistry, and evolutionary theory (e.g., Irwin and Schulze-Makuch 2011). Such simulations deal with possible environmental conditions and physical constraints, rather than an understanding of the specific requirements for life on Earth. This is good work even though it is speculative and inconclusive.

There is a distinction between historical explanations (which are common in biology), how-possibly explanations (typical in such models), and how-universally explanations (which we take would hold true for all life everywhere) (Dray 1957; Scharf et al. 2015). These universal explanations apply to *all* life, though not *only* life. Such explanations can range from trivial (e.g., life must always have finite mass and velocity) to more interesting (e.g., as size increases, the impact of microscopic forces inversely correlates with the impact of gravitation (Bonner 2011)). None of these approaches requires a theory of life beyond the assumption that it is a natural phenomenon explainable by laws of nature. Unless we entertain the possibility that *no* aspect of Earth life will resemble life in other parts of the universe, we must be open to a universal biology of the sort that infers the likely noncontingent properties of biology based on what we know about life and the universe. We discuss this point more in the third section, "Biological Theory."

As the study of noncontingent aspects of life, universal biology is approachable independently of clearly distinguishing life from nonlife, since features of the universe that *also* apply to living phenomena may be relevant to such research.[1] For example, the flow of energy in a food web limits the ratio of predators to prey sustainable in any constant environment. This effect could be spelled out in detail and is universal under plausible assumptions about the nature of predation, energy, and selection. It would be hard to imagine an ecosystem composed entirely of apex predators persisting for very long. So, rather than focus on answering the question of "what is life?" a universal approach to biology focuses on identifying nonarbitrary properties that *must* apply to life, as with the general laws and trends found in mechanics, thermodynamics, chemistry, evolution, and so on. Universal biology thus circumvents the life question and builds a firm foundation upon which we can better investigate the nature of life on other planets. In fact, as we show in the following example, there is already a growing literature exploring universal biology with respect to expectations for life everywhere.

Research Example: A Better Understanding of Life Based on its Necessary Features

Recently, Sir Richard Roberts, the 1993 Nobel Prize winner in biology, said, "The goal of completely defining what it means to be considered alive has taken a giant step forward" (Kowalski 2016). He was referring to Craig Venter's now 20-year research project of trying to create life, synthetically. One of the Venter lab projects involves searching for the smallest DNA genome, which, when inserted into bacteria, will produce a living organism. Their latest press release claims they have succeeded in creating an organism simpler than any found in nature (Kowalski 2016). By setting a minimum threshold of genes necessary for life as we know it, researchers purport to investigate life as it *must be*. This project is one of discovering the necessary (and thus universal) aspects of life, or universal biology in the sense described above.

This minimal genome research may be helpful to identify necessary genes on the assumption that they (or their functions) *must* be present in all organisms; however, as Coyle et al. (2016) point out, the distinction between the organism and the environment is often blurred. Organisms on Earth depend on other organisms to survive. In fact, most known organisms are parasites (Lafferty et al. 2006), and most of life's genetic information is probably viral in nature or origin (Breitbart and Rohwer 2005). Venter's research begins with *Mycoplasma mycoides*, which contains one of the smallest known genomes (Waters et al. 2003; Kowalski 2016). Interestingly, some of the reason that *M. mycoides* has so few genes is that it relies on the tissues in which it resides for many of its key functions. So while it may be the smallest known genome, there's no sense in which it is independent. In fact, many of the genes necessary to its survival are found in the human cells in which it resides. It is an organism on life support. An extreme version of such a dependency is our

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[1] As an anonymous reviewer points out, this section accepts the scientific interest of biologists as demarcating biology. Baryons are largely irrelevant to the features biologists study, so they would not be investigated within universal biology, but thermodynamics may yield many interesting principles of ecology, for example.

own mitochondria, which descend from a once free-living alpha-proteobacterium and have since transferred many of their own genes to the nuclear genome (Gray and Doolittle 1982). A synthetic mitochondrion would not tell us much about the features necessary to life in general because it is "merely" an organelle, not an independent organism capable of independent survival. However, this reasoning would also apply to all organisms incapable of independent survival, which would, we are now realizing, include most organisms on the planet.

Koonin gives operational criteria, defining a minimal genome as "the minimal set of genes that are necessary and sufficient to sustain a functioning cell under ideal conditions, that is, in the presence of unlimited amounts of all essential nutrients and in the absence of any adverse factors, including competition" (2000, p. 99). This metric is interesting and intuitive. But theoretical research suggests some biological functions will be poorly contained within cell membranes, and so complex interdependencies may evolve among microbes (Morris et al. 2012). That prokaryotes are so open to genetic exchange and interdependencies has long been used to challenge prokaryotic species concepts (e.g., Nesbø et al. 2006). Perhaps cell membranes are just a poor way to identify evolutionary individuals (Bouchard and Huneman 2013). Living creatures have always depended on other organisms in a robust biosphere and minimal genomes appear to be of mere academic interest. Ignoring complex metabolic interplays in favor of merely the genes located within a membrane threatens to push us in the direction of considering viruses as minimal genomes, which have merely exported most of their metabolic processes. But some extant viruses have as few as four genes (Fiers et al. 1976). Clearly, a standard of presence within a membrane will quickly lead us astray.

To address life as it *must* be elsewhere, to do universal biology, minimal genome research must (appropriately) also favor a minimal conception of its own approach. Coyle and colleagues (2016) distinguish between Venter's approach, which begins with an extant cell and works at reducing it further ("top-down"), and contrast it with an approach that attempts to construct the minimum number of genes necessary and sufficient for macromolecule polymerization and genome replication ("bottom-up"). They seem to believe these will be localized in a cell, but, as we've seen, this requirement is rarely met by most organisms. If we relax that assumption, we can see an advantage for the bottom-up approach in the context of universal biology. By not starting the minimal genome project with extant organisms, we can better identify traits likely to be universal features of biological systems.

For example, one of the properties needed for genome replication on Earth relies on DNA's famous double helix structure. To form such a structure, DNA requires chiral or "handed" molecules. While alternative methods of heredity exist (e.g., RNA), and others have been proposed (see Kay 1992), most biochemists believe complex macromolecules are more likely in homochiral scenarios (but see Sczepanski and Joyce 2014). If this is true, then the prevalence of chiral molecules in the universe becomes relevant to entities we would call "living" in the universe.

As it turns out, a group of researchers recently reported the discovery of chiral molecules in other parts of the universe for the first time (McGuire et al. 2016). Although expected, such a discovery is a huge step in the mining of molecules in the universe, hopefully leading to further discoveries and research about how prevalent such molecules are, where they are found, how they come about, and perhaps how such molecules may form different types of primitive replicators throughout the universe. The discovery of chiral molecules helps us better understand which aspects of life on Earth are likely to be present in life elsewhere. Thus, by finding chiral molecules in space, we eliminate one variable in research of life in the universe. We can assume biology in the universe beyond Earth will probably use such molecules and move on to theorize about which kinds and how they might be the same as or differ from life on Earth.

In sum, there are philosophical assumptions implicit in minimal genome research that unnecessarily restrict research in universal biology. Although minimal genome concepts may yet discover necessary features of biological systems, the underlying assumptions about the nature of life must be seriously considered in a study of universal biology.

Biological Theory

Theoretical Goal: Investigating the Universality of our Biological Theory

Another approach to universal biology focuses on biological theory rather than on biological entities. One of the oldest debates in the philosophy of biology is about the status of biology as a science. Some have argued that biology is not theoretically autonomous, and so it is much more akin to engineering than it is to the physical sciences (Smart 1963, 1968; Rosenberg 1984). In this view, biology is merely an applied form of physics, chemistry, or even probability theory. Thus, to the extent that biology is universal, it is not biology, and to the extent it is biology, it is not universal (Beatty 1995). In response, others take biological theory to be at least somewhat autonomous and accept biological generalizations as having a degree of counterfactual stability comparable to the physical sciences (Munson 1975; Brandon 1997; Mitchell 1997; Lange 2002). Much of these debates focused on the question of whether biology has laws or whether universal aspects of biology are "distinctively" biological. But these debates overshadow the question of whether the models and theories of biology are universal in scope. Ron Munson argues many are universal because they are not restricted in range of application to a certain region of space or time, do not contain individual names or constants, and are supported by evidence of the quantity and diversity to make them reliable in novel scenarios (Munson 1975, p. 429). In short, there exists a subset of biological theory whose explanatory scope is not limited to individual populations, and this subset is *universal biology*.

Unlike the understanding of universal biology in the "Life" section above, in this approach, biology may still count as universal even if Earth life is the only life in the universe. Biological theories may be universal in scope and thus not limited to life's history on Earth (Powell and Mariscal 2015). This notion of universal biology is complementary to the approach discussed above, of course, although it focuses on biological *theory* rather than on potential life-forms elsewhere in the universe.

Evolutionary theory has often been lauded as universal, to the extent that some authors have regarded it as trivially true. Famously, Popper claimed that natural selection is tautological (1976).[2] Darwin did not argue for a universal approach to his theory explicitly, yet it is not uncommon to interpret the idea as such. For example, according to Sean Rice, "Since the initial work of Darwin and Wallace, it has seemed to many people that at its core evolution has simple and universal principles" (2004, p. 188). Even the US National Aeronautics and Space Administration (NASA) appears to agree with this viewpoint as they define life as, "A self-sustaining chemical system capable of Darwinian evolution" (Joyce 1994). Suggested by Carl Sagan in 1994 (Benner 2010), NASA has held this view ever since, solidifying the idea that life and Darwinism are conceptually linked. Taking the idea further, Richard Dawkins (1976, 1982) popularized the theory that all living systems in the universe will obey Darwinian principles of evolution. In other words, he claims that *all* life in the universe will evolve via natural selection and other processes.

Whether "Universal Darwinism" is justified as universal depends entirely on what is included in the view, the details of which have been debated since Darwin himself. The issue came to a head during the Modern Synthesis, but debates about evolutionary theory continue to this day. Recently, some authors have put forth an understanding of evolutionary theory that is at cross-purposes with universal approaches to biology. These authors argue biology needs a *new synthesis* that incorporates discoveries and theoretical developments since the Modern Synthesis (Pigliucci 2009; Pigliucci and Müller 2010; Laland et al. 2014, 2015). They call this the *Extended Evolutionary Synthesis* (EES) and argue biologists should incorporate new theoretical developments into evolutionary theory. These theoretical apparatuses include epigenetic inheritance, niche construction, developmental bias, and phenotypic plasticity. Without including such phenomena, they argue biological theory is disunified and each of its parts are impoverished as a result.

The response to these arguments has focused on the inclusion/exclusion of biological processes and the desirability of wholescale theoretical change as opposed to an incremental approach. Wray et al. (2014) argue many important processes are left out even in the EES (epistasis, cryptic genetic variation, extinction, adaptation to climate change, the evolution of behavior, etc.). They argue the EES caricatures contemporary biological theory and deny an extended synthesis is needed anyway: biological theory does not undergo paradigm shifts by fiat. Booth et al. (2016) argue the theoretical unification central to EES downplays most of life on Earth–microbes. They point out that many theoretical tools in the EES are unnecessary in individual research programs and so a piecemeal, "evolutionary toolbox," approach may be more conceptually helpful than a unificationist approach.

We may add another criticism of the EES here: many of the theoretical apparatuses being considered are unlikely to be universal (or have not been claimed to be so). But by including non-universal theoretical tools, the EES is a provincial theory of biology. In fact, as Wray et al. and Booth et al. point out, some of the theoretical tools considered are not even explanatory for all taxa on Earth, let alone as part of a universal biological theory. As with our discussion of minimal genome research, here, too, it seems the EES may undermine the very study of noncontingent aspects of life.

An approach like the EES can be unifying for biology if an explicit effort is made to distinguish those processes that may be universal from those that are not. An eye toward universal biology can help point out the differences in explanatory scope of the theoretical tools that make up our "evolutionary toolbox." Some are expected to apply to all life in the universe, such as natural selection, while others are almost certainly limited to particular leaves on the tree of life, such as epigenetic inheritance.[3] It's true, of course, that it is possible to be hyper specific about natural selection so that it is unlikely to be universal (e.g., defining natural

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[2] He soon retracted the statement, saying, "I have changed my mind about the testability and logical status of the theory of natural selection; and I am glad to have an opportunity to make a recantation" (Popper 1978, p. 345).

[3] This discussion is slippery, as epigenetics and other relevant terms (e.g., plasticity, niche construction) are sometimes used in a nontechnical, metaphorical sense. We try to use only the specific understanding of epigenetic inheritance as described in Laland et al. 2015: chemical changes that alter DNA expression but not the underlying sequence.

selection as a change in gene frequencies and identifying genes as sequences that begin with AUG/GUG/UUG and end with UAA/UAG/UGA). Conversely, we may subscribe to a sufficiently vague notion of epigenetic inheritance so that it is trivially true for all life in the universe (e.g., non-genetic inheritance). Our point is that some of the processes included in EES may be interpreted as being highly contingent outcomes of evolution on Earth, which can pose problems from the perspective of universal biology. A universal formulation of evolutionary theory must be neither trivially true nor arbitrarily specific.

By taking the notion of universal biology seriously, we see that not only are calls for extending the evolutionary synthesis unnecessarily impoverished, so, too, was the original Modern Synthesis. In neither case have we considered the potentially universal scope of elements of biological theory.

Research Example: A Better Understanding of Biological Theories Based on Their Necessary Consequences

In addition to the aforementioned approach to universal biology, which relies on the context of evolutionary theory, there is another common approach to universal biology focused on entirely different theoretical aspects of biology: complexity theory and self-organization. Stuart Kauffman is perhaps the most well-known developer and proponent of such views. In his *Investigations*, Kauffman develops a novel, substrate-neutral understanding of biology (2000). He declares life is a molecular "autonomous agent," or a system capable of self-reproduction and capable of performing at least one constrained release of energy that returns to its initial state (2000). Autonomous agents can exist anywhere energy and processes exist. Kauffman holds that the principles of autonomous agents are necessary features of life. For Kauffman, "life is an expected, emergent property of complex chemical reaction networks" (2000, p. 35). Wherever we may discover life in the universe, it will be composed of autonomous agents, he contends.

Kauffman builds up his account from the concept of autonomous agents. He imagines a "catalytic system space" uniting all catalytic reactions (2000, p. 61). Reactions closer to each other in catalytic system space are more similar. In this context, an autonomous agent can now be defined as a set of paths through catalytic system space that can create new paths and perform at least one cycle through that space. From this formulation, Kauffman thinks he can derive general laws. So, for Kauffman, universal biology is the study of the networks in which molecular autonomous agents participate. There is a worry his definition is too stringent: it says little about the aspects of biology most often touted as universal, such as carbon, homochirality, and senescence. To the extent that we want a universal biology that accounts for these regularities (as discussed above), Kauffman's approach is a poor fit. Yet if viewing biology as a network proves fruitful, the student of universal biology may wish to explore Kauffman's proposals. Among the interesting consequences of his view, Kauffman proposes four candidate "laws" of such systems. They are:

- Life will not evolve toward a highly orderly state (as in crystals, where change in one area is localized and has no lasting consequences for the system as a whole) or a disorderly state (as in weather, in which any change completely disrupts the system). Instead, life will be just at the "edge" of the orderly state—near the disorderly state.[4] This is because only systems at this edge are able to discriminate between signals while still being significantly noise-resistant.
- On short timescales with respect to coevolution, species will tend to "fill" their environment and occasionally push each other to extinction along a power law distribution.
- On long timescales with respect to coevolution, life will tend to couple to and change its environment. This will yield a power law distribution of extinctions, speciation events, and species lifetimes.
- Biospheres expand their diversity and their constructed, coevolved complexity increases, on average, "as fast as it can" (2000, p. 160; but see England 2013).

Whatever the status of these proposals, Kauffman's approach is a version of universal biology, although his approach is so specific it may not appeal to all researchers interested in universal biology. Even if his approach has a different justificatory base than others (e.g., the EES), such inquiries are also biologically guided and motivated by finding nonarbitrary principles of life, constrained only by the universe.

Stuart Kauffman's theory of the self-organization of life is a good example of how a framework of universal biology not only improves the status of biology as a science, but also clearly demonstrates how such a theory can incorporate physics and chemistry, yet still be a discussion about biology. Research on biology from such basic principles helps allay concerns that research in biology must be about contingent facts of life on Earth. Instead, we may study the parts of biological theory that can be universally applied throughout the universe.

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[4] This may be a direct consequence of his definition of life—neither very ordered nor disordered systems can complete "work cycles."

The Universe

Theoretical Goal: Using Biological Tools to Investigate the Structure of the Universe

The concepts and tools of biology have regularly been deployed on nonbiological phenomena, such as chemistry, economics, and artificial (digital) life, sometimes with mixed results (Bagg 2017). This may be because some nonbiological phenomena share formal similarities with biology, but it also may be due to an innate human tendency to see patterns where none exist. About 20 years before publishing the *Origin of Species*, Darwin wrote in a notebook that, "Our faculties are more fitted to recognize the wonderful structure of a beetle than a Universe" (Barrett et al. 1987, p. 573). Nevertheless, there are those who view universal approaches to biology as implying a stronger analogy between a beetle and the universe. For Lee Smolin (1992, 1997), or followers of his theory of Cosmological Natural Selection (CNS) (e.g., Gardner and Conlon 2013; Gardner 2014), there is clear design in both the beetle and the universe, because of the optimizing effect of natural selection. Whereas a beetle might be explained as optimized or well adapted in terms of being resistant to a number of plant defenses, according to CNS, the universe is optimized or well adapted in terms of its production of black holes. In short, evolutionary principles, broadly construed, apply to both cases, although behind these descriptions there is an odd sense that both a beetle and a universe are fine-tuned toward a clear purpose. And perhaps Darwin's quotation is about just that—a remark on the human inclination to think teleologically.

Despite the fact that Darwin's theory of natural selection was heralded as ridding biology of purpose-driven thinking, such a mentality is certainly alive and well in our biological explanations—traits adapted *for* something, behaviors evolved *with the purpose* of accomplishing something, gene frequencies shift *in order to* optimize a population. This teleological mindset is one of the largest challenges facing novel approaches to biological thinking, as well as the creation of a unified universal biology. There is a stark difference between the goal-driven nature of earthly biology and the purely mechanistic nature of astronomy, which will need to be reconciled before we can assess to what extent biological principles apply to the "wonderful structure" of both. This is a distinct interpretation of universal biology: understanding biological organization and structure as applied to other entities in the universe, or even the universe itself. Whereas in the "Life" section above the driving concern was finding universal traits of life, and in the "Biological Theory" section it was identifying universal principles of our understanding of life, here the emphasis is on recognizing universal structures other phenomena share with life.

Such inquiry needs to be free of teleological thinking; but, as illustrated with CNS, it is not easy to apply biological theories to the structure of the universe without bringing along the unfortunate biological assumptions of design and purpose. One way of doing so is by comparing life and the universe via the structural hierarchy that is apparent in both, which can appear designed, yet be explained mechanistically. This approach is based on the understanding that the life that we observe on Earth is structured hierarchically. The beetle is made of cells, cells contain chromosomes, chromosomes are made of genes, and so on. It goes the other direction too: beetles can group together and form a colony, and a group of beetle colonies can—hypothetically—form a beetle supercolony. Typically, the question in biology that follows is "how did such structural hierarchy emerge (in living organisms)?" One answer that is free of teleological thinking is that such structural nestedness is expected, or in some sense, inevitable, among groups of living things because there is an underlying tendency for accidents—variations—to accumulate. As entities vary over time, so do the number of possible interactions among those entities, eventually causing groups and new levels of hierarchy to form (Fleming 2012; Fleming and Brandon 2015; NB: a similar claim can also be found in Newman 1970). This fundamental assumption that variations accumulate is the idea behind the Zero-Force Evolutionary Law (ZFEL), which states that in a system with variation and heredity, variance among entities will increase (McShea and Brandon 2010). Such a theory, although initially presented with the biological context in mind, can easily be applied to other entities in the universe as long as there is measurable variation and some kind of entity-persistence and change over time. Thus, the ZFEL is one method for applying biological theories about organization to the universe, in other words, pursuing universal biology in this third and final sense.

Although the universe is not typically explained as consisting of multiple levels of hierarchy, it is fairly easy to understand it in terms of structurally nested groups. For example, a protostar, because of its self-sustaining fusion, can be seen as a group forming out of a molecular cloud (which could be seen more like a loose group). These protostars can form low-mass, intermediate-mass, and high-mass stars, which can be the stellar level of hierarchical organization. The next level up is the galaxy level, which includes groups of diverse stars (in terms of mass) and various kinds or organization among them. Galaxies can interact in many different ways and form clusters, which is yet another level of the structural hierarchy, and even these galaxy clusters can group into galaxy superclusters. Rather than following Smolin (1992, 1997) and trying to explain the universe in terms of an optimization process (for which the standard of optimization is somewhat of a mystery), this approach to universalizing biology instead illuminates the way in which complex multilevel systems can form—whether the system in question is on Earth or in other parts of the universe. There is no sense in which Smolin's model is identical to life on Earth, but there are enough similarities for it to share a family resemblance.

Exploring this resemblance, then, is a task for this form of universal biology.

Research Example: A Better Understanding of the Universe Based on its Necessary Structure

A good illustration of how structural hierarchy can serve as a neutral and useful framework for comparing life and the universe is Dan McShea's naturalistic account of teleology (2012, 2016). McShea's work can provide a useful middle ground where biological accounts are more scientific in their purpose-driven language, and astronomical or astrophysical accounts gain an additional layer of explanation by emphasizing the importance of the hierarchical structure of the universe.

McShea, recognizing the problem with teleological thinking in biology, explains that (the appearance of) teleological behavior is merely a result of structural hierarchy in a system. Higher-level structures constrain the movement of lower-level structures, a phenomenon McShea calls "upper directedness."[5] Upper directedness should not be confused with progression; instead it refers to the fact that in a nested hierarchy, lower-level entities are contained in a larger object or field that restricts or constrains them. This makes their behavior appear teleological or "upper directed." For example, as thousands of bacteria in a pond swim toward a food source, their behavior is both persistent—if thrown off course they can return to it—and plastic—there are multiple routes for reaching the food source—and thus it appears purpose-driven because of the guiding upper-level food gradient (NB: the ideas of persistence and plasticity are often considered "signatures" of teleology, and as McShea points out, they are rooted in Nagel 1979 and Sommerhoff 1950). As another example, "Ecology might direct a population of birds toward, say, medium-sized beaks so that they can crack a range of seed sizes" (McShea 2016, p. 5).

Such an approach can work in astrophysics as well, considering the structural levels of the universe—stellar, galaxy, galaxy group/cluster, supercluster. Parallel to the ecology example above, galaxy features can be interpreted as directing the distribution and type of star populations that form; for example, it has been found that in denser galaxy cluster environments, star formation is suppressed or "regulated" by the environment (Welikala et al. 2016). Just as birds with medium-sized beaks can be seen as adaptive, molecular clouds that form hot, massive stars in gas-rich regions of the galaxy can similarly be seen as adaptive. Although it may seem like a step backward to reintroduce some teleological language into how we discuss the structure of the universe, McShea's naturalized teleology is a big improvement upon CNS in terms of its range of explanation, as well as providing a way to explain and investigate the area of overlap between the structure of life and the structure of the universe—opening the door for a more coherent universal biology that may serve to link the two.

Conclusion

Universal biology is the multidisciplinary study of the noncontingent properties of life as guided by biological theory and constrained by the universe. It is not merely the attempt to simplify biology to general laws nor is universal biology the attempt to broaden all aspects of earthly biology to environments beyond Earth. Instead, there are many approaches and motivations for this research. In this article, we've presented three separate but compatible ways of characterizing the study of universal biology: (1) generalizing from our understanding of life on Earth and our knowledge of the universe to life everywhere, (2) assessing the explanatory scope of biological theory and the extent to which its elements are universal, and (3) using biological principles to explain the structure and organization of other phenomena in the universe and perhaps the universe itself.

The first approach begins with an understanding of life. Rather than define life, we advocated an approach to biology that begins with well-accepted universal principles, such as those derived from physics, chemistry, and probability theory. These, we argued, are likely to apply to phenomena we would recognize as "life" everywhere in the universe regardless of whether we have a well-accepted theory of life's nature. As an example of this approach, we discussed minimal genome projects in this light and argued a bottom-up approach may be fruitful from the perspective of universal biology.

Next, we explored the potential universal scope of biological theory, especially with respect to evolutionary theory and broader principles of self-organizing complexity. With respect to evolutionary theory, we argued that calls for a new synthesis of evolutionary theory must take into account the explanatory scope of various evolutionary processes. By lumping potentially universal models and theories with more limited ones, we lose conceptual clarity. A piecemeal, or toolbox, approach to evolutionary theory may be a better alternative. We also explored Stuart Kauffman's

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[5] As an anonymous reviewer points out, McShea's theory is very much compatible with R.E. Ulanowicz's (2003) notion of "ascendancy," which refers to autocatalytic forms, and the idea that the complexity of configurations and reactions among molecules can help explain the emergence of life.

self-organizing approach to biology, arguing it was an interesting approach to universal biology, which may be done in tandem with an evolution-focused approach.

Finally, we explored how biological principles may inform us with respect to the structure of phenomena not typically considered biological. Some authors describe culture, chemistry, computer viruses, and even star formation by invoking biological processes. We explored Smolin's cosmological natural selection argument, and the difficulties of applying biological theories of organization to the universe without bringing along teleological notions of purpose and design. We explored more mechanistic accounts of biological hierarchy, such as McShea's, and rendered arguments for the general hierarchy of processes in the universe, which may be justified using tools developed to explain biological phenomena.

Many scientists are already doing universal biology, albeit under a variety of different names and across many disciplines. When investigating the universal features of life, the route of inquiry can be guided by the pursuit to find universal traits, identify universal principles, or recognize universal structures. In a larger sense, one benefit of having a clear research program of universal biology is that much of the diverse work that is already being done in various fields can be united under one common framework. This way, it can be better understood, compared, categorized, and justified. By investigating life as it must be (and why it must be that way), we gain a better foundation upon which we can search for life on other planets, examine the status of our biological theories, and better explain the unknown. We can gain a new understanding of oddities on Earth and throughout the universe.

Acknowledgements The authors would like to thank Kelly C. Smith and several anonymous reviewers for helpful comments and suggestions.

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