

The Impact of Discovering Life Beyond Earth

Steven J. Dick

Former NASA Chief Historian



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University Printing House, Cambridge CB2 8BS, United Kingdom

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www.cambridge.org

Information on this title: www.cambridge.org/9781107109988

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First published 2015

Printed in the United Kingdom by XXXX

A catalogue record for this publication is available from the British Library

Library of Congress Cataloguing in Publication data

The impact of discovering life beyond Earth / [edited by] Steven J. Dick,
former NASA Chief Historian.

pages cm

Includes bibliographical references.

ISBN 978-1-107-10998-8

1. Life on other planets. 2. Exobiology. I. Dick, Steven J.

QB54.I47 2015

576.8'39 – dc23

2015014815

ISBN 978 1 107-10998-8 Hardback

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7 Universal biology: assessing universality from a single example

CARLOS MARISCAL

Avoiding the $N = 1$ problem about life

Is it possible to know anything about life we have not yet encountered? We know of only one example of life: our own. Given this, many scientists are inclined to doubt that any principles of Earth's biology will generalize to other worlds in which life might exist. Let's call this the " $N = 1$ problem." By comparison, we expect the principles of geometry, mechanics, and chemistry would generalize. Interestingly, each of these has predictable consequences when applied to biology. The surface-to-volume property of geometry, for example, limits the size of unassisted cells in a given medium. This effect is real, precise, universal, and predictive. Furthermore, there are basic problems all life must solve if it is to persist, such as resistance to radiation, faithful inheritance, and energy regulation. If these universal problems have a limited set of possible solutions, some common outcomes must consistently emerge.

In this chapter, I discuss the $N = 1$ problem, its implications, and my response (Mariscal 2014). I hold that our current knowledge of biology can justify believing certain generalizations as holding for life anywhere. Life on Earth may be our only example of life, but this is only a reason to be cautious in our approach to life in the universe, not a reason to give up altogether. In my account, a candidate biological generalization is assessed by the assumptions it makes. A claim is accepted only if its justification includes principles of evolution, but no contingent facts of life on Earth.

When biology's sample size became problematic

The discussion of the $N = 1$ problem has a long history. Some Greek and Roman thinkers spoke of infinite worlds, while others, notably Aristotle, ruled it out (Dick 1982, pp. 9–11). In the Western world, many early key figures touched on the issue. Giordano Bruno, Johannes Kepler, and even Immanuel Kant were all optimistic about the existence of many life-bearing worlds. Meanwhile, others, the anti-pluralists, denied the existence of other life, usually from theological principles (Dick 1982, pp. 63–9). Intimately related to the question of other worlds is the question of the origin of life here on

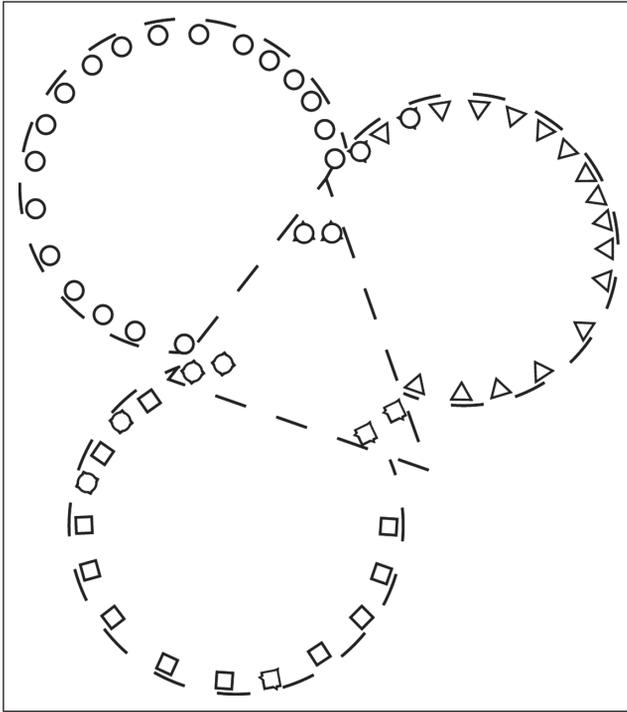


Figure 7.1 In a world in which spontaneous generation is accepted, it might be plausible to view the diversity of life (the triangles, circles, and squares in this figure) on Earth as representative of life in the universe. It might even be expected for enterprising scientists to find predictive generalizations unifying distinct kinds of life (represented as the dashed lines encircling the triangles, circles, and squares). Thus, scientists might see similarities among species and form predictive groupings expected to hold for as-yet-unknown life. Artwork by Carlos Mariscal.

Earth. For nearly two millennia, natural philosophers assumed life regularly originated from non-living material. It is easy to see how such a view of spontaneous generation might seem to justify a universal scope for biology, even independent of evidence of life elsewhere. If life arises spontaneously, then each new example provides a new test case for generalizations claimed to hold for life everywhere (Figure 7.1).

Two of the biggest changes in our conception of life came in the 1800s in the forms of Louis Pasteur and Charles Darwin. With Pasteur, the theory of spontaneous generation was, if not refuted, marginalized (Lahav 1999, pp.

23–29). If life does not form readily, then perhaps our evidence is not as diverse as it might seem – and the origin and existence of species must be explained by appeal to some other process. The process given by Darwin in the *Origin* (Darwin 1859) gave a naturalistic explanation of the genesis of species without spontaneous generation. Species descended with modifications from earlier species, which in turn descended from earlier species. This induction, given the difficulty of spontaneous generation, implies all life descended from some last universal common ancestor.¹ Nevertheless, Darwin is non-committal about universal common ancestry (Darwin 1859, p. 484):

I believe that animals have descended from at most only four or five progenitors, and plants from an equal or lesser number. Analogy would lead me one step further, namely to the belief that all animals and plants have descended from some one prototype. But analogy may be a deceitful guide. Nevertheless all living things have much in common . . . Therefore I should infer from analogy that probably all organic beings which have ever lived on this earth have descended from some one primordial form, into which life was first breathed.

The single origin of all life on Earth naturally leads to the $N=1$ problem. If all organisms had arisen independently via spontaneous generation, biology would be the study of many distinct objects. It would be reasonable for scientists to concern themselves with discovering universal principles governing these distinct phenomena. So, before Darwin, biology could reasonably be considered a universal science on par with physics and chemistry.² But given the realization that the sample size of biology is 1, it seems difficult to see how any universality can be justified. See Figure 7.2.

Exploring new ways to address $N = 1$

Not everybody takes the $N = 1$ problem to be insurmountable. In the century and a half since Darwin, many authors have attempted to show the universality of biology in various ways. Herbert Spencer, infamous for the ideas behind social Darwinism, attempted to show evolution was a natural law of universal application (Spencer 1864). Others have maintained we can show aspects of biology are universal from evolutionary principles (Dawkins 1982, 1992), due

¹ Darwin is not the originator of the concept of common descent. British biologist John Ray first introduced the concept (Serafini 1993, p. 128), but it was Pierre-Louis Moreau de Maupertuis who first postulated *universal* common descent, the view that all life originated from a single organism (Harris 1981, p. 107). Still, after 1859, arguments for and against common descent tend to trace their roots to Darwin.

² Granted, the appearance of a non-mechanistic teleology and the lack of a naturalistic paradigm posed other, major problems for early biologists.

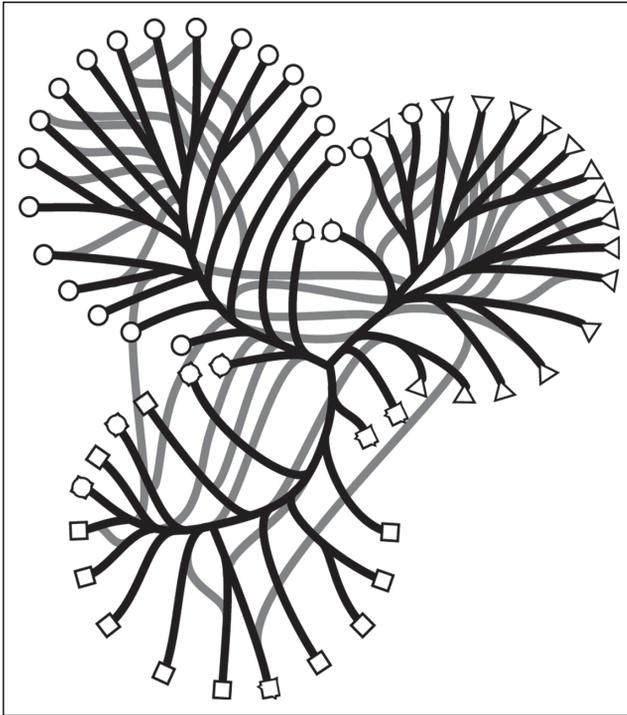


Figure 7.2 We now know all of life on Earth shares common ancestry. In other words, all of our biology forms a single sample. Thus, it appears unjustified to consider life on Earth as representative of life elsewhere. In this case, we can see the explanation for any similarities is due to common descent (black lines connecting the triangles, circles, and squares) or lateral transfer (gray lines) and likely not from underlying universal principles. Artwork by Carlos Mariscal.

to their sheer utility (Dennett 1995), from common patterns or recurrent causal mechanisms (Sterenly and Griffiths 1999), or from an understanding of the physics, complexity, and probability theory that underlie them (Kauffman 2000). Some biologists have pointed to the long history of life on Earth as a series of natural experiments, from which we might be justified in assessing some generalizations as more robust (e.g. McGhee 2013, Powell and Mariscal in press). Still others have attempted to explore universal biology through discovering a second example of life (e.g. Davies and Lineweaver 2005) or creating it (e.g. Langton 1989, Gibson *et al.* 2010).

The most interesting modern approach to the $N = 1$ problem comes from astrobiology. Astrobiology is the scientific investigation designed by NASA in the wake of several discoveries in the mid 1990s.³ Periodically, key astrobiologists gather to produce “roadmaps” intended to serve as assessments of astrobiology’s progress and guides for future directions. Continuing in the most recent roadmaps, the authors propose beginning a new science of “universal biology” (Des Marais *et al.* 2008, p. 6):

We must move beyond the circumstances of our own particular origins in order to develop a broader discipline, “Universal Biology.” . . . we need to exploit universal laws of physics and chemistry to understand polymer formation, self-organization processes, energy utilization, information transfer, and Darwinian evolution that might lead to the emergence of life in planetary environments other than Earth. Clearly an inventory of molecules must exist that is capable of gaining chemical, structural, and functional complexity and eventually assembling into living systems. This is strongly conditioned on temperature, solvent, energy sources, etc.”

Astrobiology’s approach is clearly grounded on physical and chemical principles. Given the assumptions that life is based on chemistry and physics, which we accept as universal, the project seems justified. Within these constraints, there is active debate in the astrobiological community as to specifics – if any– are essential to life. Astrobiologists worry about assuming that life elsewhere would require water, carbon, or other chemistry important to life on Earth. The astrobiology research program is both speculative in questioning our “Earth chauvinism” and constrained by the conditions we expect to exist in the universe. For astrobiologists, possibility is grounded in actuality. Astrobiologists focus on hypotheses testable through astronomical techniques, modeling, Earth analogs, or robotic space travel. With a few stellar exceptions (e.g. Irwin and Schulze-Makuch 2012), astrobiologists disregard large-scale ecological and evolutionary effects such as major transitions, increasing trends in complexity and diversity, or mass extinctions, which could have major implications for life everywhere. In the next section, I will describe an approach that accepts contributions from physics, chemistry, and biochemistry, while allowing for insight from evolutionary and developmental biology, ecology, philosophy, and other disciplines. I hope my account becomes accepted as an expansion of the universal biology project in astrobiology.

³ The change of direction was spurred by the discovery of suspected water on Mars and Europa, increased research into extremophiles, the discovery of extrasolar planets in 1992, and the Allan Hills 84001 meteorite, which was thought to contain microscopic fossils of Martian bacteria in 1996 (Dick and Strick 2004).

Separating universal biology from non-universal biology

Consider two generalizations, commonly made about life on Earth, but which could apply to all biology in the universe:

- (1) The genetic code holds for all life.
- (2) Hereditary information is digital not analog. That is, all life will use *some* biochemical code (Maynard Smith 1986, p. 21; Dawkins 1992, p. 26).

For the sake of argument, let us grant both are true.⁴ What justifies them? By understanding the justification of these generalizations, we will be better able to assess *why* they hold, *how* they hold, and to *what* extent may hold in the future.

Generalization (1) refers the usual set of 20 amino acids coded for by the 64 possible sequences of three nucleotides (codons). Francis Crick (1968) argued (1) is only true because all life on Earth shares common ancestry to the point in history when the genetic code was settled (though Vetsigian *et al.* 2006 have convincingly shown lateral gene transfer is also necessary in this story). Since the genetic code's success at producing amino acids depends on its consistency and stability, any changes would introduce new amino acids into established proteins, many of which would have proved lethal. It is akin to swapping the letters "e" and "r" on a keyboard: *it eaisrs the peobability mrssagrs will br misundrestood*. Crick's historical explanation accounts for both the generality and rigidity of the genetic code. If this is true, it follows that with different starting points or different contingent factors, the genetic code could have been different.⁵ So even if we expect (1) to be true everywhere on Earth, we do not expect it would apply to any organisms that lack this shared history. If scientists ever create life in a laboratory or discover alien genetic material on Mars, they would not be surprised if (1) did not hold.

Meanwhile, generalization (2) is based on an argument from evolutionary principles to the conclusion that an analog system of heredity would prove catastrophic. Suppose I make a photocopy of a poem. Then I make a

⁴ There are many examples of (1) being violated, but none of these violations are wholesale new examples of genetic codes (Elzanowski *et al.* 2000). And it is not obvious that all genetic information is digital (2). Some epigenetic and environmental methods of inheritance seem perfectly analog. A charitable, understanding of (2) would see it as claiming all life in this universe requires *some* digital process, regardless of any analog processes surrounding it.

⁵ It has since been argued that 99.97% of codes are less robust than our current code, when accounting for such features as hydrophobicity and production of physicochemical-similar amino acids (Wagner 2005, p. 25. See Philip and Freeland, 2011 for a review). Nevertheless, there are thousands of equally optimal possible codes and it is possible one of those possible codes would have evolved given a replay of the tape of life. Thus, the case for (1) is stronger than Crick makes it out to be, but his explanation is still apt.

photocopy of the resulting photocopy (and so on). After enough iterations, the latter photocopies will accumulate enough specks and noise as to prove incomprehensible. If faithful inheritance is a universal goal in biology, then analog reproduction is a terrible way to do so ~~(but see Mariscal 2014)~~. If we expect some element of heredity to reproduce in a potentially endless way, then it follows that all biochemical life would use some sort of lossless code.

We can see that (1) depends on contingent events in the early history of life, but (2) is justified by principles that are independent of the foibles of Earth's history. So if (1) is true, it's sensitive to initial conditions in a way unlike (2). In this sense, (1) is less robust and less general than (2). Since the justification for digital codes does not depend on Earth's initial conditions, (2) would be expected to hold wherever life exists. If (2) is true, it has nothing to do with the contingencies of evolution on Earth. An Earth-based explanation wouldn't even make sense.

In the next section, I propose a way of drawing a sharp distinction between generalizations like (1) from ones like (2). By assessing the underlying justifications of purported universal features of biology, we can adequately address the $N = 1$ problem. My proposal is an account of how to discover, understand, and justify generalizations in biology. It is *not* a defense of the generalizations themselves, which must be defended by the relevant kinds of scientists.

On universality given a single sample

I have proposed defining universal biology as “the study of evolutionary generalizations whose justification does not assume contingent facts about Earth's history (and so are expected to apply elsewhere in the universe)” (Mariscal 2014). This section will explain, clarify, justify, and expand that definition.

Consider the *kinds* of justifications biological claims can have. I propose six major divisions based on the kind of necessity each is taken to invoke:

- a. claims that are applications of *a priori* concepts such as logic or probability theory;
- e. claims based on or derivable from *natural necessity*, such as laws of physics or chemistry;
- i. claims based on or derivable from *principles of evolution*, including natural selection and drift;⁶
- o. claims that follow from the *initial state* of the universe or planet as a whole;

⁶ Some have argued that evolution is derivable from physics and so *i* is contained in *e* (cf. Rosenberg 2014). In Mariscal 2014, I argue against this view.

- u. *historically contingent* claims following from more recent events in the system; and
- y. *state-dependent* claims, which occur as a result of other co-occurring factors (whether external or internal).

Roughly, each division sets an envelope by which the subsequent category is constrained. These categories are neither exclusive nor exhaustive and I will only consider claims that make reference to all and only their justifications. A claim can only have as wide a scope as the least general justification it invokes. My definition can now be restated in these terms: universal biology is “the study of generalizations that are (*i*) evolutionary and whose justification does not make reference to (*u*) contingent facts about Earth’s history.” A generalization must reference (*i*) to count as “biological” in this view.⁷ The claim “all organisms face entropy” might be universal, but it is not based on evolutionary principles.

Additionally, if an explanation in biology makes reference to a historical explanation (*u*),⁸ it will be excluded. This exclusion demarcates the difference between universal biology, the study of life as it *must* be, and possible biology, which I take to be the study of life as it *could* be. The $N = 1$ problem is a bigger problem for universal biology, which strives to be more conservative in its claims. I disallow mere possibilities in universal biology because possibilities are infinite and I worry that without an explicit limitation, possible biology could be wildly speculative (but see Schulze-Makuch in this volume for interesting, scientific, and fruitful ways to delimit possible biology). Those seeking to understand life *as it must be* should proceed in a cautious manner, if we are to address the concerns raised by the $N = 1$ problem.

This account is broader in scope than that which astrobiology currently investigates. It is able to accommodate any understanding of “polymer formation, self-organization processes, energy utilization, information transfer, and Darwinian evolution,” as well as universal elements of ecology and development. A justification-centered approach makes explicit the degree to which we expect these factors to exist elsewhere in the universe. The constraints of my

⁷ We do not have a good definition for life and there is reason to suppose that a consensus on a definition for life will prove impossible (Cleland 2011, Machery 2011, Tsokolov 2009, Mariscal 2014). On the other hand, we have a decent grasp of how evolution works and we think it will apply to all naturally arising living systems. There is good reason to suppose the kind of life we will find will be complex and reasonably well adapted to its environment. The concept of “life” adds nothing to the issue that cannot be better accomplished by a concept of adaptive complexity, which is best explored in terms of (*i*) the principles of evolution.

⁸ I will only consider claims that make reference to all and only their justifications. I could reference the price of tea in China (*u*) when I explain why I wasn’t able to subdivide a prime number of fruits equally, but that detail is inessential in the explanation, which only requires math (*a*) to be explained (see Lange 2012).

account are designed to make it clear in which biological systems our generalizations are expected to apply. A universal generalization that depends on other states in the system (y) might no longer apply if that system is disrupted, while one that depends solely on conditions a , e , and i will likely continue holding true until the living system goes extinct.

More concerns for a universal biology

Discussing a related issue, Carol Cleland draws lessons from the early history of alchemy in which some alchemists classified various liquids as water, including nitro-hydrochloric acid (HNO_3+3HCl) and a solution of nitric acid in water ($\text{HNO}_3+\text{H}_2\text{O}$) (Cleland 2011). They even referred to these liquids as strong water (*aqua fortis*) and royal water (*aqua regia*), respectively. It makes a certain sort of sense to think of them as unified since all three are clear, liquid, and serve as solvents. But these characteristics are not essential to water; it is the chemical structure of H_2O that is the essential determinant. A study of the necessary and sufficient conditions for the set of water, strong water, and royal water would have been pointless. Similarly, Cleland looks at the debate about definitions of life as premature. She argues the features of life we think are essential, such as replication, metabolism, or Darwinian evolution,⁹ might rest on mistaken assumptions and we cannot say anything definitive about life until we discover a second genesis.

Cleland proposes a situation in which we are tasked with uncovering the essential features of mammals based on a single species, such as a zebra (Cleland 2012). A scientist could study the zebra forever without truly understanding mammals. She might disregard mammary glands, for example, because only half of zebras – the females – have mammary glands. Instead, the scientist might infer all mammals are hooved, striped, or walk on four legs. This, she argued, is the plight of biologists doing universal biology. If we can't generalize from zebras – what hope does any such project have?

The objections Cleland raises are interesting and well worth addressing. Not only do we not know the essential features of life, but life itself may also be a spurious category (see Jabr 2013, Mariscal 2014, ch. 4). Still, with respect to

⁹ Darwinism has been amended and augmented numerous times since the first publication of the *Origin*. Many scientists now use the term “Darwinian” with some fluidity to refer to some kind of evolution by natural selection. Current biological theory only accepts a portion of Darwin's work. Darwin's notion of heredity was superseded by Mendelian genetics, his acceptance of gradualism was complicated by punctuated equilibrium (Eldredge and Gould 1972), his principle of divergence has been challenged by notions of random-walks (Kimura 1984, McShea and Brandon 2010, Fleming 2013), and the tree of life has been cut down (Doolittle 1999). What's left of Darwinism is unclear.

zebras, plenty of scientists *would* find mammary glands relevant. They would be fascinated to study a subject in which half the population had one set of traits and the rest had a different, but complementary set of traits. Perhaps the scientist might refuse to conjecture such traits were universal, but she might correctly infer such traits would probabilistically apply to half the individuals of any similar population.

The generalization from traits found in *zebra* females to traits found in all *mammalian* females is likely a tenuous one, but this is only problematic if we accept the analogy as representing the situation. In fact, the analogy is suspect. Mammals are a historically contingent evolutionary group, unified solely by a common origin. There is still an open debate in the philosophy of biology as to whether broad categories, like “mammal,” are philosophically *real* in any sense that matters to biology (Claridge *et al.* 1997, Mishler 2009). So why should biological generalizations be limited in such a way? It’s true we cannot know if Earth-life is representative of life in the universe or an extreme outlier among all possible life worlds, but that is not the issue under investigation. Rather, the question is about whether there is *anything* we could know about life in the universe *whatsoever*. Universal factors can intersect with biology in a number of different ways: geometric constraints, probability theory, physical laws, and so on. A scientist studying zebras might infer some facts about the environment in which they arose: why all four limbs are roughly the same length, that vision is an adaptation, and the role that grass has in producing energy. This scientist would be perfectly justified in inferring all similar creatures facing similar ecological pressures would have corresponding adaptations. Such justifications would be independent of whether these inferences lined up with the kinds of generalizations we initially might have wished a universal biology would provide.

There is a broader concern alluded to in this discussion. What bothers us about the zebra thought experiment is that it suggests our inferences might be unjustified, *no matter how thorough our methodology*. We can always imagine a biological system violating generalizations we think hold true for all of biology. If we can imagine it and evolution is cleverer than we are, then biology in the universe will surely be far stranger than our conceptions of it will allow. Skepticism about any particular claim or about the utility of the project is fair. But appeals to the $N = 1$ problem implicitly assume *any* biological generalization can potentially be understood as local phenomenon. This cannot be true. There are features of biology for which a purely local explanation is inadequate. The explanation for why there are few large predators relative to the number of primary producers is fully captured by the way energy is passed along the food chain (Colinvaux 1979). If an opponent were to deny the

universal scope of this phenomenon, she would have to show how local features of life on Earth— but not evolution or thermodynamics— explain each instance of it. If such an alternative is unpalatable, then, to some extent, biology *must* be universal.

One might be justified in being skeptical about these and other generalizations, but the move toward stopping universal biology is too quick. We could be wrong about how we characterize a biological phenomenon or the justifications we presume underlie a biological phenomenon, of course, but the enterprise is not flawed simply because it may produce claims of which we might be skeptical. Certainly we are going to be wrong about *some* claims of universal biology, but the same holds true for any other branch of inquiry. Universal biology might be in a more difficult situation than many sciences, but it is a difference of degree, not a difference in kind.

Ending thoughts regarding the $N = 1$ problem

The $N = 1$ problem should be viewed as merely an explanation of why we should be cautious about confounding evidence, not the stronger claim that any biological generalizations are at base unjustifiable. By stating the justification of each claim and being conservative in accepting new claims, my approach provides sufficient caution. In my view, if the explanation of a certain biological phenomenon makes no reference to any contingent facts here on Earth, includes causal or constitutive factors, and its conditions are expected to hold in other places in which life might develop, then we are justified in accepting the biological phenomenon as being universal in scope, regardless of our sample size of one. In a sense, I move away from claims like, “robin’s eggs must be blue” and toward claims like “eggs must be spheroid.”

Some claims will be sufficiently justified by the history of life on Earth. For instance, Earth has suffered several mass extinctions. Shortly after each of these, diversity has increased (Erwin 2001, Krug and Jablonski 2012). With many independent natural experiments showing the same phenomena and a causal explanation (perhaps dealing with niche construction and energy available in the environment), a biological generalization of some sort might be justified. However, for universal biology, it is necessary to specify the underlying assumptions in order to make any justified predictions about other life in the universe. This and other examples from the various biological sciences need to be taken seriously for astrobiology’s approach to be maximally effective. Other claims might be justified by new science. A biologist interested in universal biology would find no shortage of candidate biological generalizations to test in the deep ocean or in the microscopic world. Finally, a good

number of these claims are not yet testable, allowing for future work and development to render them good science.

Because the kinds of claims made in biology are so varied, it is key to seek a precise statement of a generalization and its assumptions before we can test it, assess it, and, hopefully, accept it. I hope to have proposed a worthy project in astrobiology that explores universal biology from a number of different sciences and methods, including experimenters, modelers, and theorists. Independent of whether we ever create new life or discover life elsewhere, there is a benefit for practicing scientists in knowing whether a biological feature is expected without exception or only given certain preconditions. This is not merely a speculative or hypothetical pursuit— it should have real consequences for practice and theory in the study of life.

Acknowledgments

I would like to Robert Brandon, Alex Rosenberg, Stephen J. Dick, and Zoë Lewin for help with earlier versions of this paper. I am also grateful to the Katherine Goodman Stern Fellowship and the Natural Sciences and Engineering Research Council of Canada (grant GLDSU/447989) for support of this research.

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