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The Cosmological Context of the Origin of Life: Process Philosophy and the Hot Spring Hypothesis

By Matthew David Segall and Bruce Damer

"It is mere rubbish thinking at present of [the] origin of life; one might as well think of [the] origin of matter."
–Charles Darwin[1]

"In itself such a material is senseless, valueless, purposeless. It just does what it does do, following a fixed routine imposed by external relations which do not spring from the nature of its being. It is this assumption that I call 'Scientific Materialism.' Also it is an assumption which I shall challenge as being entirely unsuited to the scientific situation at which we have now arrived. … Science is taking on a new aspect which is neither purely physical, nor purely biological. It is becoming the study of organisms."
–Alfred North Whitehead[2]

"[I]t is becoming increasingly clear that to understand living systems in any deep sense, we must come to see them not materialistically, as machines, but as (stable) complex, dynamic organization. … Our task now is to resynthesize biology; put the organism back into its environment; connect it again to its evolutionary past; and let us feel that complex flow that is organism, evolution, and environment united. … Thus, biology is at the point where it must choose between two paths: either continue on its current track, … or break free of reductionist hegemony, reintegrate itself, and press forward once more as a fundamental science."
–Carl Woese[3]

0. Introduction

The authors of this chapter—Segall, a process philosopher and Damer, an origin of life scientist—are grateful to the editors for the invitation to engage with other philosophers, scientists, and theologians about how best to approach some of the most consequential cosmological questions that biotic minds like ours are capable of imagining. *What is life? How did it originate?* These intimately related questions cannot be answered with metaphysics alone, but nor are they decidable purely on empirical grounds. After all, biologists cannot explain how life originated until they know what they are looking for.[4] These also are not merely academic questions, since the answers we give to them bear directly upon our own existence as conscious animals. Ultimately, we want to know more than just the *what* and the *how*. We also want to know *why*.

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[1] Darwin, Letter to Joseph Dalton Hooker (March 1863) in Peretó J, Bada JL, Lazcano A. *Charles Darwin and the origin of life*. *Origins of Life and Evolution of the Biosphere*, Vol. 39, No. 5 (2009), 395. As Peretó et al point out, Darwin's views on the scientific tractability of abiogenesis changed throughout the course of his life. Less than a decade later, he composed a letter to the same close friend speculating about a "warm little pond" wherein complexifying chemistry could have generated life.

[2] Whitehead, *Science and the Modern World* (Macmillan, 1925), 17, 105.

[3] Carl Woese, "A New Biology for a New Century" in *Microbiology and Molecular Biology Reviews*, Vol. 68, No. 2 (June 2004), 176, 179-180.

[4] See Scharf, Caleb et al., "A Strategy for Origins of Life Research" in *Astrobiology*, Vol. 15, No. 12, 2015, 1035. See also Pross, Addy, "Toward a general theory of evolution: Extending Darwinian theory to inanimate matter" in *Journal of Systems Chemistry*, Vol. 2, No. 1 (2011): "A coherent strategy for the synthesis of a living system is not possible if one does not know what life is, and one cannot know what life is if one does not understand the principles governing its emergence" (1).

The authors of this chapter have become convinced that a Kuhnian paradigm shift is afoot, not only in biology, but across the multiple scientific disciplines and methodologies relevant to studying the origin of life. Advances in complex systems science and the study of non-equilibrium thermodynamics have helped narrow the gaps between physics, chemistry, and biology, but many conceptual knots remain to be untangled. Indeed, making progress on the question of life's origin may require a fundamental transformation of traditional conceptions of the relations among the sciences and their varying methods of explanation. While in periods of normal science, master craftspeople and technicians make steady progress on precisely delimited problem-spaces, revolutionary science calls upon the aid of scientific seers, people who would have ended up as artists, philosophers, or theologians had they not become scientists.[5] In revolutionary periods, otherwise sharp boundaries between the *how* and the *why* questions begin to blur, thus encouraging closer collaboration between science and philosophy. The how questions constrain the imaginative speculations of philosophers, while the why questions pry scientists out of the shell of specialism, thus allowing, in philosopher of science Sebastian De Haro's terms, "the subject matters and methods of philosophers and of scientists [to] become entangled" such that "the relationship between science and philosophy becomes dynamical."[6]

The authors further affirm that continued progress in the effort to understand the place of life in the cosmos requires a transdisciplinary approach integrating the core insights and methodologies of not only astrobiology and philosophy, but also religious studies and theology. We value the freedom and autonomy of each of the special sciences to invent and test hypotheses unencumbered by the assumptions of other sciences (e.g., molecular biologists operate within a different paradigmatic context compared with evo-devo and systems biologists, etc.). We similarly insist upon the independence of science from theological orthodoxies (e.g., that life was designed and created from scratch by an omnipotent deity, or that the human soul is a supernatural substance existing in causal isolation from the rest of cosmic evolution). Scientific curiosity is to be checked only by the need for logical coherence and experiential adequacy (including ethical considerations).[7] While metaphysics and theology have been "warned off the premises"[8] of modern experimental laboratories, these ancient disciplines nonetheless retain an essential function in the effort to understand our cosmic origins. For one thing, philosophy and religion inevitably contribute to any final integration of scientific findings into a meaningful and motivating worldview for humanity at large. But even more significantly for natural science, metaphysics has a crucial role to play in shoring up science's own epistemological and cosmological conditions of possibility. Whitehead asks: "What is there in the nature of things which leads there to be any science?"[9] His answer is that trust in science requires a metaphysics explanatory of the insistent rationality of things. For Whitehead, cosmic rationality is a consequence of the inextricable causal entanglement of all

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[5] See Lee Smolin, *The Trouble with Physics: The Rise of String Theory, the Fall of Science, and What Comes Next* (New York: Houghton Mifflin Harcourt: 2006), 310.
[6] Sebastian De Haro, "Science and Philosophy: A Love-Hate Relationship" in *Foundations of Science* (2020) 25, 310.
[7] Whitehead, "First Lecture, 1924" in *Whitehead at Harvard*, 44; Whitehead, *Process and Reality*, 3.
[8] Whitehead, *Harvard Lectures of ANW: Philosophical Presuppositions of Science*, 3.
[9] Whitehead, "First Lecture, 1924" in *Whitehead at Harvard*, 43.

things: “there is an essence to the universe which forbids relationships beyond itself, as a violation of its rationality.”[10] Natural science thus assumes the universal communicability of the causal nexus across all scales of Nature. Science further presupposes that conscious organisms have arisen within this nexus who are capable of turning back to contemplate their own cosmic origins. It is imperative, then, that a way be found for scientific conceptions of physical causation, chemical reaction, and biological origination to hang together with our commonsense experience of conscious awareness and agency. For after all, if our consciousness is a total sham, then so are all our scientific inquiries and religious aspirations. Consciousness must somehow “[have] truck with the totality of things,” and it is the job of philosophy to critique and reconstruct the abstractions of the special sciences so as to recover a concrete sense of our connection with the cosmos as a whole.[11] Whitehead invites us to re-envision the modern clash between science and religion as “a sign that there are wider truths and finer perspectives within which a reconciliation of a deeper religion and a more subtle science will be found.”[12]

This coauthored chapter aims to contribute to origin of life research by approaching outstanding aporias from two complementary perspectives: 1) *the empirical*—explicating an emerging experimentally grounded hypothesis concerning the “progenitor” of living cells in the setting of wet-dry cycling in fresh water hot springs (written by Damer incorporating feedback from Segall), and 2) *the metaphysical*—leveraging the conceptual innovations of Whitehead’s organic process philosophy to overcome Kantian limits to knowledge so as to work toward better defining the cosmological conditions of life’s origin (written by Segall incorporating feedback from Damer). These two perspectives may find themselves in dialectical tension on some points. But the ultimate goal is to dynamically integrate the metaphysical and the empirical aspects of this research.

1. The Empirical Evidence for a Hot Spring Progenitor of Life

Opportunities for philosophy to connect with science in a mutually respectful and closely collaborative way are not common. Indeed, much of the normal problem solving of day-to-day science finds no need for the big picture ontological reframing proposed by philosophers. Some scientists go further than simply stating the uselessness of philosophy, declaring that “unquestioned philosophical preconceptions have at times been hampering factors of scientific progress.”[13] However, when a special branch of science finds itself in the midst of a revolutionary transition or Kuhnian paradigm shift[14], it then becomes apparent that scientific disciplines are themselves founded upon a background of philosophical preconceptions. For this reason, paradigm shifts alert us to the urgent need for collaboration between scientists and philosophers. When scientists discover a new system which is complex or opaque enough that

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[10] Whitehead, *Process and Reality*, 4.
[11] Whitehead, *Process and Reality*, 15.
[12] Whitehead, *Science and the Modern World*, 184.
[13] See De Haro, “Science and Philosophy: A Love-Hate Relationship” in Foundations of Science, Vol 25 (2020), 302.
[14] See Thomas Kuhn, *The Structure of Scientific Revolutions* (Chicago University Press, 1962).

it defies formal treatment and testing with existing tools, a period of fervent creativity ensues, generating new thought experiments, explanatory models, and laboratory instruments. It is easy enough to point to historical examples of philosophy's contributions to new paradigm science, like Kepler's Pythagorean-inspired discovery of planetary harmonics in the seventeenth century or the emergence of quantum mechanics in the twentieth under the influence of Vedic wisdom and western philosophers as diverse as Plato, Kant, and Schopenhauer.[15] When such shifts are afoot, the specialists and technologists of normal science must endure the wild speculations of their more holistically minded, visionary colleagues. Often those colleagues come in from other disciplines, bringing fresh perspectives but encountering strong resistance until their contribution shines new light upon the obscure questions at hand. These "seer" scientists are open to entertaining and developing ideas beyond the strictly reductionist approaches which had guided the puzzle solving approach of day-to-day science. Scientific seers engage with a wide range of thinkers, going beyond strict disciplinary boundaries to entertain proposals from non-specialists and from philosophers.

This situation is exactly what we find in the field of origin of life science, which is currently undergoing a very public and controversial paradigm shift from an old scenario to new models. The long-held view that life began in the oceans 4 billion years ago is being supplanted by the approach that life could only plausibly begin in land-based freshwater bodies.[16] One of the leading thinkers in this transition, biochemist David Deamer, discovered that polymers such as RNA and DNA could be self-assembled from their component monomers through a process of repeated hydration and dehydration. Such cycling through wet and dry phases has now been adopted as a common chemical protocol by multiple groups internationally who have repeated and extended the work by demonstrating the formation of polymers from amino acids called peptides. Deamer's approach is based upon five decades of research on membrane biophysics which he also incorporated into the wet-dry cycles to form the cell-sized compartments which can contain and concentrate these polymers. The co-emergence of membranous compartments and their polymer cargo form "protocells," the basic units which can undergo the stepwise transition from non-living to living processes.

a. A Time Portal to the Hadean

The following story is offered for the layperson and non-specialist alike to comprehend the proposed scenario of life's origin. The hope is that it captures our latest thinking on how simple biological life can emerge from the background of the sterile but dynamic physics and chemistry of a newly formed world, eventuating in the establishment of an entire microbial biosphere.

> Two scientists, a geologist and a biologist, buy tickets to travel back through a time portal four billion years to the end of the Hadean eon. Their destination is one of the large volcanic land masses rising up through the rusty brown oceans of a turbulent

[15] De Haro, "Science and Philosophy," 308. See also Bitbol, Michel, "Schrödinger and Indian Philosophy" in *Cahiers du service culturel de l'ambassade de France en Inde* (Allahabad, 1999).

[16] See Russell MJ, "The 'Water Problem' (sic), the illusory pond and life's submarine emergence—A review" in *Life*, Vol. 11 (2021), 429. doi.org/10.3390/life11050429

young Earth. After donning environment suits to provide a breathable air supply (free oxygen, a product of life, would not become available for a few more billion years[17]), they grab their kit bags for sampling and step through the portal. In a flash, they tunnel through time and find themselves walking out onto the crunchy black landscape of a lava-filled volcanic caldera. A line of volcanoes roars forth ash as heat is dumped from the mantle of the newborn world. The scientists head for a more quiescent field of geysers jetting forth and filling multi-colored steamy pools interconnected by streams. The orange-brown haze of the atmosphere is lit by a faint young Sun itself surrounded by a brilliant disc of dust and larger rocks from the still-forming solar system. Some of this material enters Earth's atmosphere, painting streaks across the sky and flashing with sonic booms as it hurtles toward the surface. This remarkable scene is conceptually represented by the computer-generated image in figure 1 below.

[17] See Luo, Genming, Ono, Shuhei, Beukes, Nicolas J., Wang, David T., Xie, Shucheng, Summons, Roger E. "Rapid oxygenation of Earth's atmosphere 2.33 billion years ago" in *Science Advances*, Vol. 2, Iss. 5 (2016).

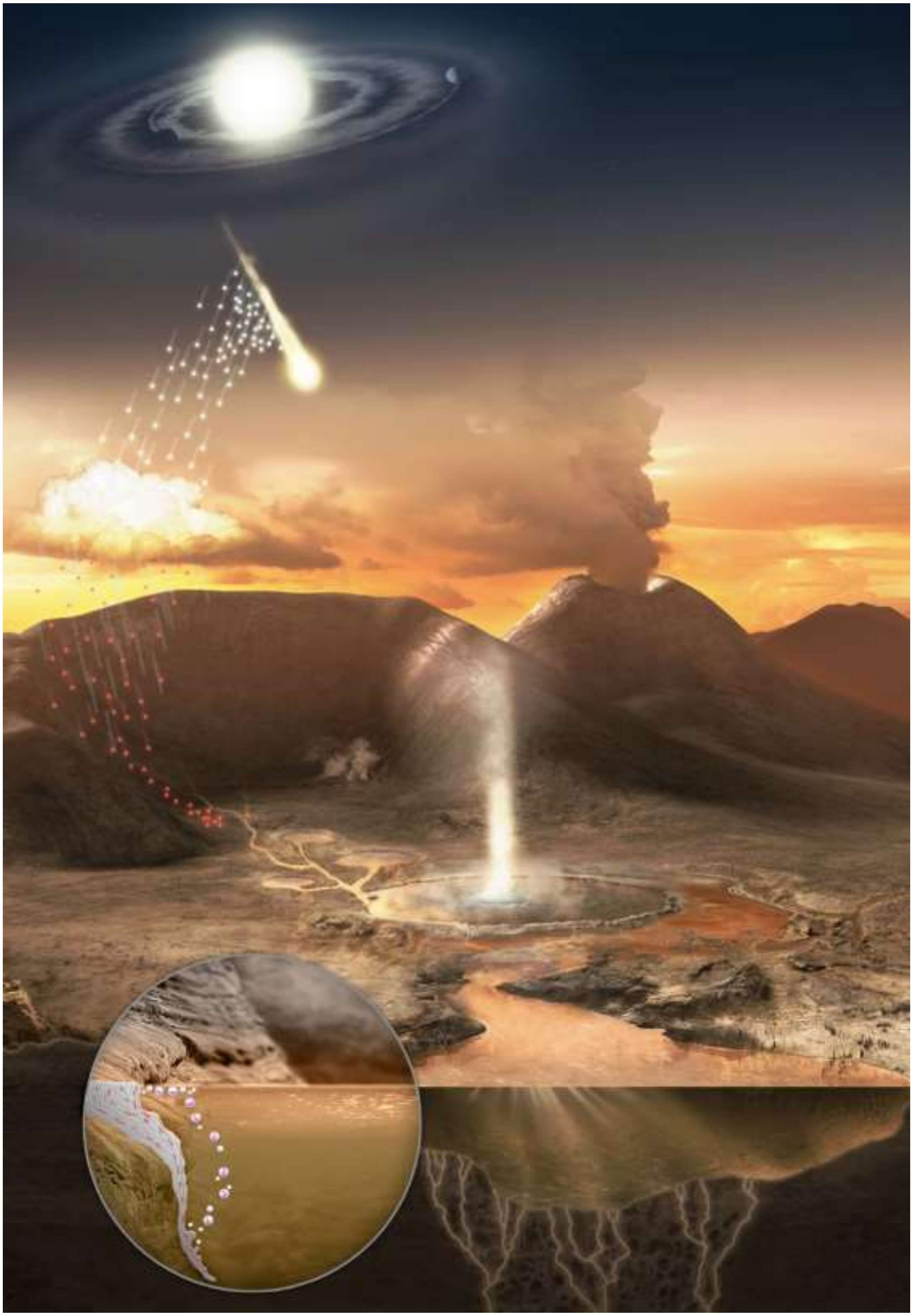

Fig 1. Artist conception of a geyser-fed fluctuating hot spring pool on the Hadean Earth, 4 billion years ago. Credit: Ryan Norkus and Bruce Damer

The explorers make their way over to a set of pools and notice that along the edges of some of them a silvery sludge is forming. The geologist has his rock hammer in hand but finds that there is nothing to break. He decides the sludge is not made of minerals and determines that their nature is beyond his disciplinary ken. The biologist leans in to consider the sludge, determining that it is somewhat reminiscent of pond scums formed by bacteria or algae. She scoops up a sample, placing it under a microscope. The view is remarkable: a seething mass of membranes forming ballooning layers which entrap a soup rich in mineral particles and dissolved organics. The biologist looks to the sky, wondering if this material was sourced partly in the dust and meteorites falling all around, accumulating in the hot spring pool at their feet. She determines that the sludge is not merely geological, but also not yet biological. On a hunch, they return to the time portal to turn the dial a few thousand years closer to the present and revisit the same site.

The island is still recognizable. A few more lava fields have formed, and the hot spring system has grown into a larger network of pools and geysers. The scientists can't find their original pool but notice that the sludges now encircle the edges of many more pools in the hydrothermal field. The biologist, fascinated by this apparent growth, takes a knee next to the nearest pool to study the material forming these distinct "bathtub rings." Instead of the uniform silvery-white observed on their first trip, the sludge is now infused with something resembling black ink. She scoops some new samples and inserts them into several instruments to analyze their chemical structure. She notes surprising spikes revealing the presence of polymers, some which are chains dozens of units in length. She then employs a pocket-sized nanopore sequencer to sequence the polymers and is even more astonished to discover that there are whole families of repeating sets of polymers. Some are composed of nucleic acid cousins resembling those making up the RNA and DNA present in all living organisms today. Others are built up from amino acids strung together into families of peptides, the short precursors of proteins. On a whim she subjects a blob of the pond sludge to a powerful UV lamp. A probe records a drop in the pH as the blob becomes more acidic, and resampling shows a surge of polymer production along with a slurry of other molecules, including glucose. She realizes that the sludges have somehow incorporated a means of capturing UV light to turn it into useful products, including repeating sets polymers and sugars. She suspects that the inky black fluid is a kind of pigment enabling photon absorption, much like chlorophyll in the cyanobacteria that will emerge millions of years in the future. She is not sure if this particular sludge sample is "alive," but the extant evidence of its growth and adaptive capability suggests it is well on its way to evolving into the first living, dividing cells.

Before heading back to the portal to travel home to the terminal phase of the Cenozoic era for a lunch break, the scientists exchange preliminary hypotheses. The geologist remarks that perhaps life organized itself around a liquid form of crystal called a lipid membrane, cycling and growing within small pools formed by the hard geological crystals of silicates, clays, and lava. The biologist wonders in turn what energetic and selective processes may be driving the changes in her soft sludges and what primitive proto-biological feedback loops may be sparking the transition to full-fledged life. She gathers some samples to place in a simulation chamber back in her lab hoping to continue to observe their evolutionary adventure.

The story of this humble sludge and how life can emerge from it is the subject of the rest of Part 1.

b. Foundations of a New Hypothesis

Fifteen years ago, David Deamer began testing his intuition that life could begin in hot springs by visiting bubbling volcanic landscapes in distant Kamchatka, Russia and closer to home at Bumpass Hell in California. These hot springs possess the chemical composition and rhythmic energetic cycling capable of driving *away from equilibrium* chemical interactions. These interactions occur because polymers cycle in what chemists call a "kinetic trap," wherein the rate of their synthesis exceeds that of their hydrolysis (breaking apart).[18] All life today exists in a series of cycles supporting kinetic traps. Geysers and other sources of hot water can fill and refill small pools on a repeating, rhythmic basis, facilitating wet-dry cycling and the emergence of communities of protocells.

Recent analysis of carbonaceous meteorites and missions to asteroids and comets have established that abundant organic molecules for protocell formation would have been delivered to landmasses on the early Earth during the time proposed for life's origin.[19] By focusing on *warm little ponds* on land, where Charles Darwin intuited that life began[20], the hot spring hypothesis suggests that these organic materials would concentrate in freshwater pools. In contrast, any material landing in the oceans would be diluted and lost to further chemical processes. Furthermore, such geyser fed hot spring pools not only would have existed on the early Earth, but have been discovered on Mars, and are likely ubiquitous on many rocky exo-planets, so they provide a plausible candidate environment for life's beginnings.

In 2009, while working on a PhD on molecular simulation approaches to the origin of life[21], coauthor Bruce Damer met Deamer. Coming from a computational and systems background, Damer added a new understanding of how Deamer's wet-dry cycling system could repeat, couple its contents through distinct phases, and generate a protocellular population capable of supporting multiple levels of combinatorial selection, eventuating in the emergence of bonafide

[18] See David Deamer, *First Life: Discovering the Connections Between Stars, Cells, and How Life Began* (University of California Press, 2011), 100.

[19] See Pearce B.K.D, Tupper A.S., Pudritz R.E., Higgs P.G. (2018). "Constraining the Time Interval for the Origin of Life on Earth" in *Astrobiology*, Vol. 18, No. 3, 343-364.

[20] Darwin, Letter to Joseph Dalton Hooker, February 1, 1871. See Introduction note 1.

[21] Damer B.F. (2011). THE EVOGRID: An Approach to Computational Origins of Life Endeavours (Doctoral dissertation). University College Dublin, Dublin, Ireland. doi: 10.13140/RG.2.1.4800.7206

biological functions.[22] Deamer and Damer have since engaged in a decade of collaboration on new laboratory science and field trips to hot spring sites at several locations including Bumpass Hell, Lassen Volcanic Park in California, Yellowstone National Park, and Rotorua in New Zealand. They also visited sites in Australia containing fossil evidence of some of the oldest signs of life on Earth, found in preserved hot spring minerals from the Archaean period, 3.5 billion years ago. Their collaboration with colleagues around the world resulted in a number of pivotal publications developing the new scenario and reporting on mounting empirical evidence. This effort culminated in their 2020 *Astrobiology* journal lead article "The Hot Spring Hypothesis for an Origin of Life"[23] which laid out the entire scenario with testable predictions for the next generation of investigators. Deamer and Damer are now developing an approach to determine which worlds are potentially "urable," a new term denoting zones on rocky planets or moons capable of starting life. While many worlds could be deemed "habitable," i.e., able to support life, fewer would have the proper conditions for initiating it.

[22] Damer B.F. and Deamer D.W. (2015). Coupled phases and combinatorial selection in fluctuating hydrothermal pools: a scenario to guide experimental approaches to the origin of cellular life. Life 5(1): 872-887. doi:10.3390/life5010872

[23] Damer B.F., Deamer D.W. (2020). "The hot spring hypothesis for an origin of life" in *Astrobiology*, Vol. 20, 429-452.

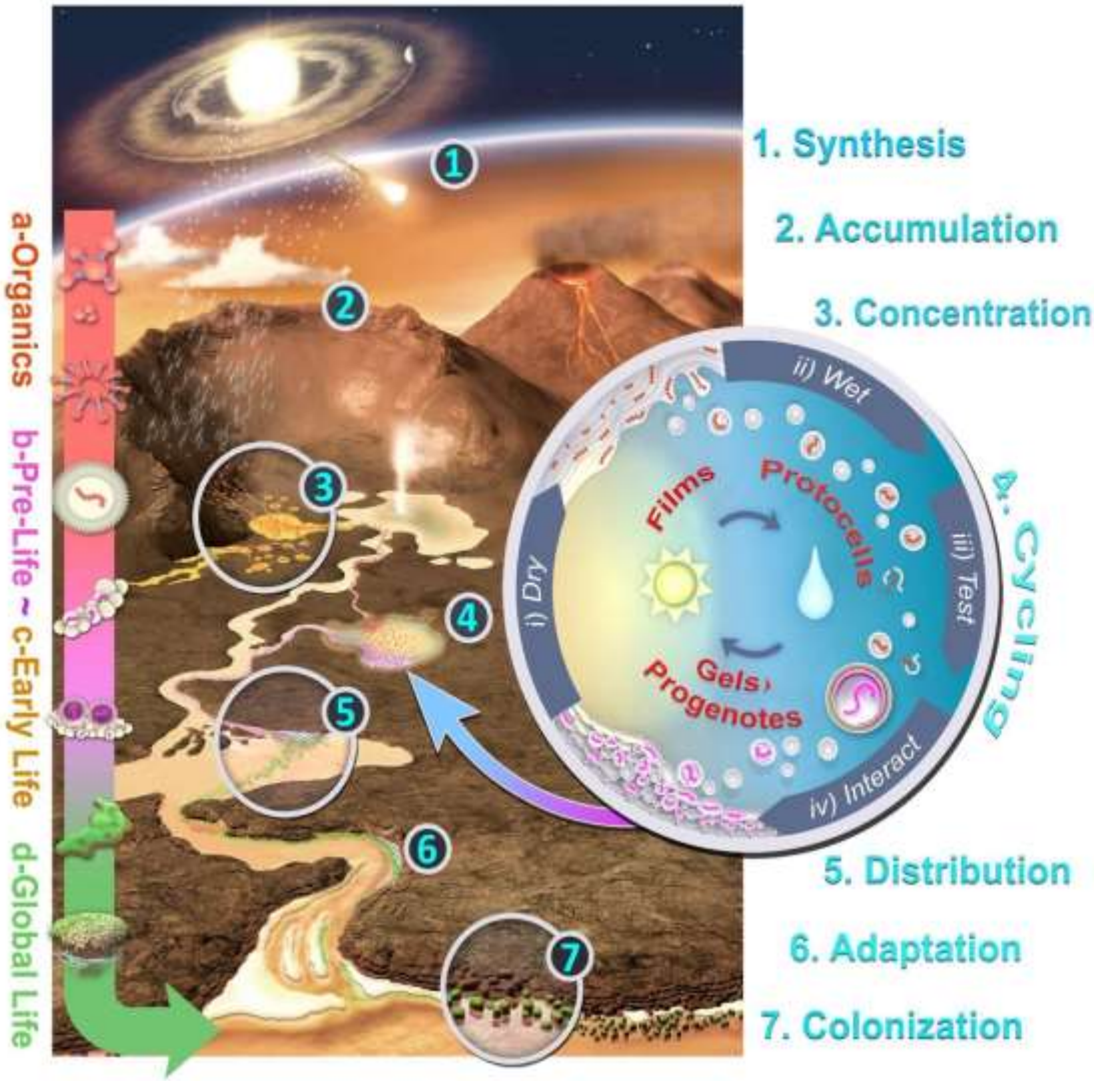

Fig 2.

Consolidated model for life's origins on land with fluctuating hot springs playing a central role, from (Damer and Deamer, 2020). Credit: Ryan Norkus and Bruce Damer

Figure 2 above details the scenario in one dynamic picture starting in the first three steps with sources of organics delivered from space and atmospheric and terrestrial sources to hot spring pool networks on a volcanic island. The fourth stage introduces cycling of these materials which can self-assemble and form polymers as they transition through wet-dry-moist phases. The resulting populations of protocells budding off from the dry into the wet phase are chemically selected for stability with each new test run through the watery medium. As water evaporates, the moist phase allows protocells to form collaborative networks of chemical interaction that Carl Woese called "progenotes," which are aggregates of prebiotic processes "in the throes of evolving the genotype-phenotype relationship."[24] These progenote and protocell populations would eventually become robust enough to be distributed across the landscape. Steps five

[24] Woese, C.R., Fox, G.E. "The concept of cellular evolution" in *Journal of Molecular Evolution*, Vol. 10, No. 1–6 (1977), 3. https://doi.org/10.1007/BF01796132

through seven show those aggregates evolving and exchanging material in various settings across the landscape, flowing downhill and gradually adapting to the more hostile, salty, and disruptive environments of the seashore. On the left side of the figure, the increasing levels of chemical and structural complexity are represented. The assemblage of starting materials which acts as a cradle for the emergence of protocells and progenotes is defined as the "progenitor" and is discussed in detail below.

As this work was emerging and more groups adopted a land-based, wet-dry cycling approach to their prebiotic chemical experiments, controversy erupted in the science media among proponents of the hypothesis that life began in the deep oceans along hydrothermal vents.[25] "Ventists" and those favoring a land-based scenario weighed in, culminating in the December 2020 feature in the journal *Nature*[26], which was widely considered to be confirmation that the paradigm shift had occurred. This transformative moment in the field has opened the door to new thinking, especially from computer science, complex systems theory, and new speculative cosmological proposals from philosophy. Damer met co-author, Matt Segall and began collaborating in earnest in late 2019. Segall was intuitively attracted to the process of rhythmic cycling evident in the evolution of protocells in the hot spring setting. Damer was interested in the big picture thinking offered by Segall and Whitehead's process philosophy (see Part 2).

c. The Dawn of the Progenitor

While scientific colleagues debate and test the biochemical minutiae of the stages of various origin of life scenarios, the bigger picture of where life fits into the cosmos as a whole may fade from their view. Stepping back to consider the cosmic context allows us to ask a core metaphysical question: What generative process animated matter? Taking this question apart we can ask what is *animation,* what do we mean by *matter*, and how might we define and describe a *generative process*? This is the problem space that is ripe for renewed twenty-first century collaboration between science and philosophy. These questions are not new, but for the first time perhaps, they can be informed by an empirically testable artifact, namely a proposed *progenitor* at the origin of life. A dictionary definition of the term progenitor brings up three principal meanings: 1) an ancestor in a direct familial line (e.g., a forefather); 2) a biologically ancestral form; 3) a precursor or originator.[27] The further back we search for a universal, common ancestor the more muddied the waters become. Phylogenetic studies of microbial DNA can only hint at the form, possible lifestyle, and basic functional components of the most ancient cells as there exists no fossil record of their molecular composition. To further complicate matters, microbial life was fundamentally communal, with cells sharing genes horizontally not only within their own species but across extended ecosystems. Woese's prediction and our recent proposal of a physical model of the progenote, the form which preceded cellular life, could well bring the curtain down on the consensus that life started as

[25] See Nicholas Wade, "Meet Luca, the Ancestor of All Living Things" in *The New York Times* (July 25, 2016). https://www.nytimes.com/2016/07/26/science/last-universal-ancestor.html
[26] Michael Marshall, "The Water Paradox and the Origin of Life" in Nature, Vol. 588 (10 December 2020). https://media.nature.com/original/magazine-assets/d41586-020-03461-4/d41586-020-03461-4.pdf
[27] Merriam-Webster. https://www.merriam-webster.com/dictionary/progenitor. Accessed March 23, 2022.

simple *protocells*.[28] After tallying up all of these obstacles to understanding, we might be permitted to suggest that the question: *what was the first form of life?* itself breaks down and that there was in fact never a common ancestor. Like the uncertainty of the properties and positions of particles at smallest subatomic scales of matter, the medium and process of life's origination may be stranger than we can yet suppose. If we cease asking ourselves to imagine a distinct, common ancestor of all of life we are liberated to consider an alternative: that cellular life arose through interactions within a complex medium. Drawing from our above dictionary meanings, we could adopt the following definition of an *abiogenesis progenitor* as: *the precursor to and originator of all biological forms.*

Another commonly held belief in origin of life research emerges from the day-to-day practices of *solution* chemists, the majority of workers studying life's origins. Their paradigm is that complex forms can emerge from reactions occurring in relatively simple liquid mixtures called solutions. Such systems work in practice in the laboratory and in industry as long as a continuous supply of reagents and energy are engaged over one or more serial stages. Each stage, if simply left to percolate on its own without further inputs, will run down to what is termed a state of equilibrium, in which bonds forming are balanced with those broken, and no net increase in yield is observed. Applying their skills to origins of life, these same chemists test and publish numerous down-to-equilibrium reactions. However, the bigger picture of life is that cells, bodies and ecosystems continue to produce novel products and continuously move away from equilibrium to what is called a steady state. This is achieved by a fiendishly complex set of interactions far beyond the simple serial enrichments of solution chemistry. The interactions are catalyzed by enzymes—gigantic molecules tuned to their tasks of fixing broken links and synthesizing new polymers in an exquisitely choreographed dance. Without this dance of enzymes maintaining a steady state away from equilibrium, Deamer notes that "we would dissolve when taking a shower."[29]

This long-held presumption of a simple, serial start to life, with few inputs and variables, is now yielding to a more complex view that life's origin involved many molecular actors and environmental factors.[30] Leading researchers now consider it plausible that major players resembling DNA and RNA were present together with peptides built out of chains of amino acids, all encapsulated in a membranous housing which facilitated their interaction. This is a stunning refiguring of the process by which life is thought to have emerged. No longer are we constrained to simple reactions winding down to equilibrium or limited to scenarios of protocells with a handful of polymers and other solutes in interaction. Science thus finds itself at the threshold of novel conceptions and facing new questions. It is here that philosophers might no longer fear to tread and offer their best contributions to a field in flux.

Returning to our original three-part question, the progenitor must be an operating medium capable of supporting a *generative process* which supports the emergence of minimally viable

[28] Damer, 2016.
[29] Deamer, *First Life*, 100.
[30] Marshall, M. (2020). *The Genesis Quest*. University of Chicago Press.

living cells. The current philosophical refiguring of the origin of life is that the progenitor, the medium within and through which life emerged, is plausibly far more complex than the initial emergent biological processes themselves. "Complex" in this context means that the medium possesses a very large number of distinct components in a network of substantial density supporting a great variety of possible encounters and copious means of testing, selecting, and amplifying those components to further densify the network. A related notion emerging from this conjecture is that novel, finely tuned processes like living cells can only emerge and persist within such a richly endowed environmental context. This leads to a conundrum for scientists working on the problem: how can something more complex than the first primitive expressions of life exist before life itself? This seems like a fine exemplar of the age-old "chicken or egg?" question.

We are fortunate to have the time, instruments, and collegial support to pursue the question of life's origin. Following biochemist Albert Eschenmoser, this pursuit is not simply an undertaking to discover life's origin, but an attempt to reinvent it.[31] It is therefore necessary to run numerous experiments in simulated conditions indicative of conditions on the urable early Earth. The most effective way to do this is to start in a carefully designed laboratory setting to get experiments to work, and then take those experiments out to try them again "in the wild" at field sites which are analogs to those which would plausibly have existed on volcanic landscapes four billion years ago. An advantage of field work is that when leaving the clean confines of the laboratory and attempting to perform experiments in much messier natural settings, Mother Nature becomes both teacher and a tough peer reviewer challenging hoped-for outcomes. Damer and Deamer have spent a decade testing their conjectures by traveling to diverse field sites on the flanks of volcanos or overlying magma plumes where fumarole vents steam and hot spring pools bubble and pulse with geysers.

To justify any argument that the progenitor environment must be extremely complex (and capable), one must simply take a step back and look upon the task this hypothesis is called to perform. This cycling chemical system must, through innumerable trials driven solely by chemical selection, drive systems of polymers across a vast chasm of molecular evolution to the emergence of a minimally viable living cell capable of self-maintenance, growth, and reproduction through fission. The end product is a living organism far simpler and more fragile than your average staphylococcus, but it is still a breathtakingly complicated molecular system. Working backwards from first life, the sheer number of finely timed and tuned processes operating in lock step which must line up to enable the most primitive biotic entity defies our comprehension. To the sixteenth century alchemists of Prague Castle a substance capable of transforming base compounds into life would surely be a candidate for their long-sought *philosopher's stone*. Even if a plausible chemical progenitor might be synthesized in twenty-first century science laboratory conditions, it would fall far short of the full creative capacity (and time!) to realize a second genesis. Despite the limitations of our ability to realize Eschenmoser's dictum, it is worth trying our hand to see if we can synthesize candidate progenitors, trying them out both in the lab and in the field.

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[31] A. Eschenmoser. (2007). "The Search for the Chemistry of Life's Origin." *Tetrahedron* Vol. 63, 12822.

Fig 3. Films comprising lipid, dissolved silicates, and RNA monomers in a dried sample at Fly Geyser, November 2021. Credit: Bruce Damer

Fig 4. Wet-dry cycling of repeat and new experiments, Little Pot geyser at Fly Geyser, Nevada, December 2021. Credit: Bruce Damer

In late 2021, Deamer and Damer made two site visits to Fly Geyser in northern Nevada. There, while being filmed for science documentaries, they ran experimental panels of wet-dry cycles by setting their instruments down in the hot spring environment and applying drops of hot spring water, allowing the solutions to dry down, and then hydrating them again, for to 3-4 cycles. As is shown in figure 3 above, dried films became visible on the slides. Microscope studies later revealed that these films were composed of membrane-forming lipids and a mixture of two RNA monomers (which were introduced) together with silicate minerals which had crystallized out of the hot spring waters. Further analysis revealed that long chain polymers up to 100 units or more had formed from the RNA monomers. Thus, it was shown that an important biopolymer of life can be linked together from its nucleic acid components, all through a process of dehydration, and in a hot spring setting. The stitching together of some of the biopolymers from which life can emerge must be possible without the need for enzymes which life evolved later to accomplish the same task. This demonstration was only a first step toward life, but a compelling one. As Deamer, Damer, and coresearchers add more ingredients and variables to these tiny primordial soups and cycle them under a variety of conditions, more complex biochemical systems are expected to form and even to begin evolving.

A highly dynamic environment presents itself as the products from the Fly Geyer experiments are viewed under the microscope. Figure 5 below shows the assemblage of lipid membranes, dissolved silicates, and RNA monomers which assemble into protocell compartments (left). When stained and subject to fluorescence microscopy some of these compartments are observed to have captured polymers of RNA (large blue volume, figure right). As can be clearly seen, complicated spherical compartments, tubes, tendrils, and layers form as lipid membranes self-assemble and start to become animated by the dynamics of the water bath around them. Each microscopic scene unfolds into a complex configuration that will never be exactly repeated anywhere in the entire future of the universe.

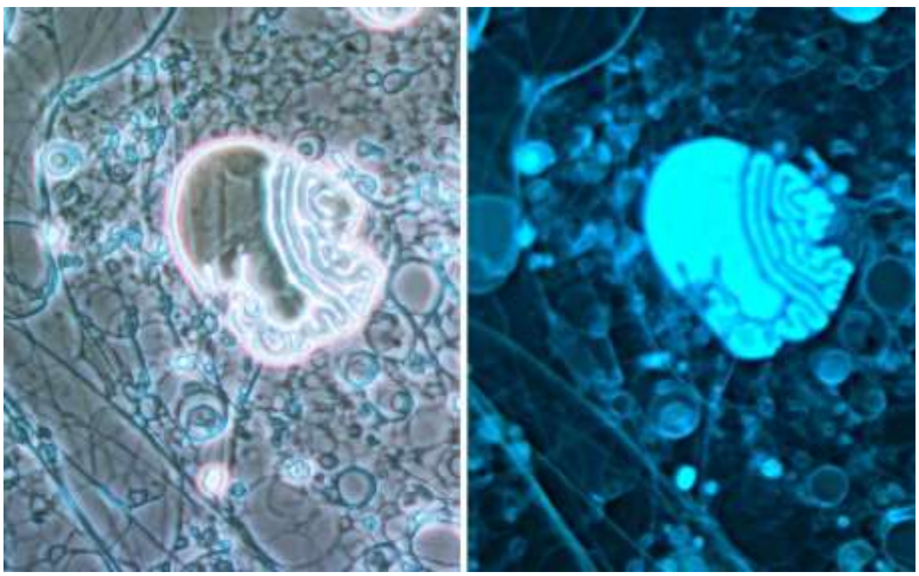

Fig 5. Protocell forming from a mixture of RNA components. Left: phase contrast view of the lipid aggregate with vesicle compartments. Right: fluorescent image of the protocell stained with acridine orange, indicating RNA polymers present within some of the protocell interiors. Credit: David Deamer

At the level below what the microscope can reveal flows a labyrinthine matrix of interacting channels and compartments with concentrated molecules in continuous dynamic interaction. Likely dwelling within such labyrinths would be sets of potentially information-conveying polymers similar to RNA and DNA. When water is present, these move around, coming into contact with other monomer building blocks or polymers, forming bonds and growing new chain links, or sometimes cleaving apart. During dry-down these polymeric tendrils can come into close contact with each other. Other species of polymers, such peptides made from amino acid chain links, are also players on this stage. As some have polar ends, they can affix themselves to surrounding membranes and ride around on those membranes.[32] Peptides are the precursors to the proteins of our cells, the complex macromolecules essential for the formation of all biological structure and function. These peptide populations, initially formed spontaneously as non-functional chance sequences, would travel about in their trillions coming into contact with other riders on the membranes. Significantly, they could also brush against trillions of RNA and DNA-like polymers sandwiched between membrane layers. This dynamic setting might therefore host a stupendously large set of combinatorial possibilities, meshing together life's two primary actors, peptides and

[32] Cornell C.E., Black R.A., Xue M., Litz H.E., Ramsay A., Gordon M., Mileant A., Cohen Z.R., Williams J.A., Lee K.K., Drobny G.P., Keller S.L. (2019). Prebiotic amino acids bind to and stabilize prebiotic fatty acid membranes. *PNAS*, 201900275; doi: 10.1073/pnas.1900275116

oligonucleotides, side-to-side and head-to-tail, providing opportunities for creative synthesis. "Creative" here means the emergence of function-forming integrations which benefit the players involved by allowing them to grow and replicate.

Pulling up from our speculative reverie for a moment, we can ask: Is what is being observed in these early micrographs a first scientific view of the proposed progenitor of life? Given the already observed capacity of this system to support the polymerization and lengthening of strands of RNA, DNA, and peptides while organizing them within lipid compartments called protocells, we propose it as a plausible, if greatly simplified, candidate progenitor. Following this first view, let us engage in another extended thought experiment to speculate on the possible properties and processes which might arise within such a progenitor. These imaginings might shed some light on what was going on in the silvery sludges studied by our two time traveling scientists as they bent over the Hadean hot spring pool.

> *The progenitor environment is fed constantly with new organic chemicals and infused with energy from heat in the hot spring, from dehydration, and from the Sun's ultraviolet radiation which can drive important chemical reactions. Flows of electrons and small molecules stream across openings in membranes where momentary dislocations are made by appropriately folded peptides. Meanwhile, the entire system is undergoing continuous transitions between wet, dry, and moist phases. As water is reintroduced onto a pool, the dried layers are contacted and neatly ordered sheets of lipid erupt, budding off into compartments in uncountably large numbers. Some of these compartments contain sets of polymers stitched together during the dry phase, forming protocells. During the flooded, aqueous stage, these protocells engage in a pre-Darwinian "struggle for existence," some holding together through all the stresses they experience in the pond and some falling apart. Each protocell compartment is a distinct chemistry experiment searching for the stability that prevents it from going to pieces. If the protocell pops, then its contents are lost to the dilute watery environment where they break down. If it holds together, the protocell and its polymers have a shot at participating in another cycle. This process may be analogous to the account of evolutionary novelty offered by Whitehead's concrescing "drops of experience," a proposal explored by Segall in Part 2. The physical affinity of polymers and membranes creates a more stable overall package so that both survive. As the pool dries down, the protocells clump together into a moist gel-like aggregate along a mineral surface edge or at the bottom of the pool (the sludge in our time portal story). This gel aggregate of lipid and molecular cargos compresses down as water evaporates. Populations of surviving spherical protocells begin to flatten out into sausage shapes which can spontaneously fuse with each other. The whole system then returns to a layered phase with polymer contents flowing and mixing within vast two-dimensional sheets. During each of these three distinct phases—dry layering, wet protocellular testing, and moist sharing (further unpacked below)—different chemical cycles can be tested and amplified, a very small chance subset of them synthesizing the basic components of life.*

The progenitor environment would not be very impressive to the naked eye—a shiny thin white slick at the boundary between mineral, water, and air—but it is a powerful catalytic medium capable of generating the first echoes of a lifecycle, and ultimately, cellular life itself. The progenitor would be the deepest ancestral form which generates all subsequent lineages of living organisms. This ancestral form is itself not alive but has the capacity to carry a self-assembled system of prebiotic molecules all the way to self-maintaining, reproducing living cells. The progenitor is indivisible from its environment as it arises through processes of concentration and self-assembly within quite specific surrounding conditions.

The exact composition of the actual original progenitor or progenitors aggregating and cycling on the early Earth will never be known. Laboratory and computational simulacra of progenitors will inevitably be missing some components and environmental influences. Its primary organizing construct is membranous layers and compartments derived from carboxylic acids delivered by carbonaceous chondrite meteorites at the time of life's origination. One such meteorite, over four billion years old and known as the *Murchison* for the town it fell near in Australia, has been shown by Deamer and others to contain these membrane forming molecules.[33] Other exogenously delivered organics such as amino acids and nucleobases have been found on such objects and even generated through atmospheric synthesis[34] are also viable additives to the progenitor soup. The conditions of pools into which the ingredients are assembled can be inferred from current day volcanic environments, and also from the preserved Archaean rock record as far back as 3.5 billion years.[35] Estimates of atmospheric composition, weather patterns, day-night cycles of radiation under a fainter young Sun, and the underlying geological platform can be pieced together from models and the Archaean rock record. Therefore, while pieces of the puzzle are certainly missing, we can assemble a plausible if still rough picture of the likely progenitor conditions on a rocky volcanic planet with fresh water hot springs.

Prebiotic chemists typically explore simpler systems with reduced variables to create clean and publishable outcomes. However, a minimally viable progenitor is going to be extremely complex, its internal processes and products very hard to track and analyze during laboratory trials. Of course, future investigators will have to decide where to set the bar for a minimally viable progenitor, which could simply start as a system which can amplify and diversify polymer populations, If these workers are truly lucky (and patient), they might observe some selected sequences which can perform functions and even self-replicate. From outside, such a system would seem to grow in physical dimensions and self-stabilize in the face of stresses which would otherwise degrade and return the whole structure to an undifferentiated chemical broth.

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[33] Deamer, D. Boundary structures are formed by organic components of the Murchison carbonaceous chondrite. Nature 317, 792–794 (1985). https://doi.org/10.1038/317792a0

[34] Pearce BKD, Ayers PW, Pudritz RE. (2020) CRAHCN-O: A Consistent Reduced Atmospheric Hybrid Chemical Network Oxygen Extension for Hydrogen Cyanide and Formaldehyde Chemistry in CO2-, N2-, H2O-, CH4-, and H2-Dominated Atmospheres. *J P Chem A*, 124, 8594

[35] See Kranendonk, Martin, Bennett, Vickie, and Hoffmann, Elis (eds.). *Earth's Oldest Rocks* (2nd Edition). Elsevier, 2018.

For future astrobiologists, presented next is an educated guess of the form and properties of progenitor environments. The films on the slides at Fly Geyser provided an early suggestion of how they can emerge. We can attempt to coax them toward growth, adaptation, and even some emergence of function using the best techniques available to chemistry and synthetic biology, all informed by computer models. We can use our best thought experiments and supercomputer simulations to predict some of the outputs and behaviors of model progenitors. The epoch of the progenitor and its emergent progeny, protocells, may have lasted tens of millions of years. Such an epoch may constitute the process by which biology emerged from physics and chemistry.

d. Summarizing and Speculating on the Progenitor Hypothesis

The following list is an initial set of speculative propositions concerning the properties of the progenitor. The first few could be demonstrated through laboratory and field testing in the next few years.

1. Like ecosystems supporting the living world today, the progenitor is an *environment* which provides a *kinetic trap*, in which systems of molecules composed partly of polymers can grow and become complex enough to ultimately accomplish a primitive form of replication. Outside of the supportive environment of the progenitor, these molecules would lose complexity, fragment, and return to a chemical equilibrium of inactive components and short, non-functional polymers.
2. Through processes of self-assembly and self-organization, the progenitor supports the arising of primordial versions of the capacities of living cells: capturing energy and incorporating external feedstocks, growing, adapting, and constructing additional niches as it is distributed into and colonizes new environments.
3. The progenitor would begin without any biological functions operating within it, but over time it would be gradually taken over (but never completely) by such functions. Even today, some proportion of matter and energy in the construction of ecosystem niches is not caught up in the activities of living cells.
4. The progenitor undergoes a cycling physical metamorphosis between individual protocell units containing sets of polymers and a conjoined indivisible whole formed through an aggregate of protocells termed a *progenote*.
5. In the unit phase, sets of polymers budding off into membrane bounded protocells enter bulk solution and are tested for stability and longevity. In the conjoined moist and dry phases, these protocells and their contents clump together within the progenitor environment wherein network interactions through diffusion, concentration, fluxes of energy, and forms of molecular competition can then occur.
6. The progenitor environment consists of an organizing matrix of layered membranous material composed of prebiotically plausible fatty acids. Within this matrix, polymers can be formed from monomers through dehydration synthesis. These polymers inhabit interior spaces or become affixed to membranes. The biophysics of the environment would then rapidly transport polymers, moving between and on membranous layers. Akin to a highway system running through a city, the vehicles of polymers travel on the

high-speed thoroughfares of lipids, or move more slowly along intervening surface streets represented by interior volumes, or concentrate in parking areas represented by vesicular lumens. With this view, the progenitor could be formally modeled as a *directed graph*[36] and bears a resemblance to the living world which emerges from it, from cells to bodies to brains and their progeny: cities and networked computer systems.

7. Ironically, the progenitor would be a much more complex environment than any of the initially primitive life functions or protocells emerging within it. Specific events within a progenote aggregate might include: molecule-to-molecule encounters on the membranous highways or between these highways and interior volumes; transiting of molecules and ions carrying energetic potentials across membranes; and budding of new compartments and fusing together of membranous volumes, carrying sets of molecules with them. We hold that the combinatorial potential of these interactive events is large enough to support the arising of biological processes.
8. The progenitor undergoes a down-selection of its own combinatorial expansiveness as proto-living systems take over from its less efficient self-assembling processes. Protocells and their aggregates, progenotes, "grow" within the supporting matrix of the progenitor and eventually fully colonize it, transforming it into the first living microbial communities, represented in the fossil record as stromatolites.
9. Progenitor substrates would spontaneously form in many watery environments on landscapes on the early Earth and or on similar exoplanets. Defined in the narrative at the beginning of this section as an "effusion" or "byproduct" of the elemental interactions between air, water, and rock, the progenitor represents an intermediate form between geology and biology. The progenitor is effectively a form of proto-niche construction[37] and becomes the substrate into and from which the super-niche of the biosphere eventually emerges.
10. Progenitor aggregations would assemble with a variety of chemical and structural variations, subsets of which could support polymer accumulation and interaction, combinatorial selection, and stepwise evolution toward cellular life. The evolutionary journey toward life would take many twists and turns within progenitor niches, with many search pathways petering out as conditions change and environmental stresses become too great. Two factors would support the eventual emergence of life against substantial odds, particularly the forces of degradation on a challenging landscape:
    a. progenitor environments would continue to form in abundance supporting new starts toward life, and

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[36] See for example Pavlopoulos, G. A., Secrier, M., Moschopoulos, C. N., Soldatos, T. G., Kossida, S., Aerts, J., Schneider, R., & Bagos, P. G., "Using graph theory to analyze biological networks" in *BioData mining*, Vol. 4, No. 10 (2011). https://doi.org/10.1186/1756-0381-4-10

[37] See F. John Odling-Smee, Kevin N. Laland, and Marcus W. Feldman, *Niche Construction: The Neglected Process in Evolution* (Princeton University Press, 2000). See also Bruce Damer, "The Hot Spring Hypothesis for the Origin of Life and the Extended Evolutionary Synthesis" (2019). Essay for Extended Evolutionary Synthesis project. Available online: http://extendedevolutionarysynthesis.com/the-hot-spring-hypothesis-for-the-origin-of-life-and-the-extended-evolutionary-synthesis/ (accessed 31 December 2021).

   b. material from a progenitor in one physical locale could be distributed to nearby environments by wind or water overflow, spreading and recombining molecular innovations with other progenitors.
11. At some point in the progenitor's history, members of its protocellular population could transition from being entirely dependent on external inputs to begin to source some of their essential processes and products in house. Such a point or points might be referred to as the stage of life's "ignition," i.e., the transition to active work, self-determination, and autopoiesis.[38] Protocells would then begin taking on some of the functions provided by the progenitor surrounds with more efficient, enzyme-driven replacements. Some of the ignition points might include the appearance of the following:
    a. capturing of solar radiation through pigments and coupling it into an energy system represented later by ATP;
    b. the selection and amplification of efficient catalysts which are coupled to the copying of informational templates (the proto-ribosome); and
    c. the collection and division of coherent sets of informational and functional polymers colocalized on membrane surfaces as a first primitive kind of reproduction.
12. The progenitor yields to protocells forming aggregate communities which Woese referred to as a "progenote." Progenitor environments become more "alive" as more efficient biological functions replace earlier stochastically driven and unreliable prebiotic processes. New progenitor aggregates continue to assemble and provide a "feeding" medium as progenote populations colonize them and construct niches.
13. Supported by the surrounding medium of the progenitor and in networked relationships with other protocells occupying a distinct progenote, a key milestone is reached when the first fission of a protocell into two viable daughter compartments occurs. This is another point that some may decide to mark as the event originating life on Earth. These cellular divisions could never happen outside of the protective and nutritive environment of the progenitor. Indeed, many such attempted divisions would fail resulting in the disgorging of protocell contents. This would not present a net loss of that line of polymeric evolution, however, as the contents are reabsorbed into the progenitor to be used again.
14. With cellular fission comes true reproduction, allowing living cells to protect an increasing proportion of their heritable traits. Vertical descent has begun and with it specialization. The specialization leads to the fundamental division of labor seen in microbial mat communities today: sun-gathering photosynthetic organisms in the top layer, metabolizers below, and detritus digesters toward the bottom. Horizontal sharing of genetic innovations which was completely dominant in the protocellular world continues to be an important factor in microbial communities.
15. We can estimate that the coming of increasingly autotrophic communities enhances their robustness to distribution, allowing them to escape the confines of hydrothermal pools and, especially after some form of photosynthesis was selected for, to lead lives

[38] See Varela, F.G., Maturana, H.R., and Uribe, R. "Autopoiesis: The organization of living systems, its characterization and a model" in *Biosystems*, Vol. 5, Iss. 4 (1974), 187-196.

independent of the chemical feeding zones of hot spring pools and meteoritic organic accumulation.

16. These increasingly robust early microbial communities adapt to a range of settings including desiccated rock surfaces and interiors, osmotically challenging saline lakes and marine shores, dilute water bodies such as oceans, and extreme environments like deep sea hydrothermal vents and the subterranean crust.
17. Progenitor-like environments would continue to arise under similar conditions for billions of years (as has been demonstrated in the above-described Fly Geyser field work). However, as Charles Darwin suspected[39], the presence of atmospheric oxygen and competition from hungry extant cellular life prevents these substrates from becoming the cradles of a second genesis. Nonetheless, the synthesis of such conditions in modern laboratory settings could perhaps recreate from sterile ingredients an original "genesis" progenitor, allowing us to observe and test some of the propositions proposed here.

e. Why the Progenitor Matters

Part 1 concludes with some metaphysical musings. As is witnessed everywhere in the biosphere today, death and extinction play an instrumental role in driving the selection of more efficient functions required for life. Therefore, any system proposed for life's origins must include a great deal of dead ends for a few travelers to reach more successful outcomes. The proposed substrate for life's beginning, the *progenitor*, instantiates a "try and try again" molecular search engine that is planetwide across a multitude of environments, all potentially interconnected and sharing their material innovations. Passage through multiple treacherous probability landscapes to the seemingly miraculous emergence of a living, dividing cell can only be undertaken by a very potent and persistent combinatorial selection process. Life's beginning was far from simple. It was nurtured in a spontaneously emergent, self-assembled progenitor system whose capacity for novel interactions vastly exceeded the complexity of the prebiotic geosphere upon which it rested.

Why should the human species go in search of our deepest biogeochemical ancestor? Perhaps the similarity of the progenitor environment to other complex systems arising later in biological and technological evolution suggests that through its study and laboratory re-creation scientists may be able to tease apart the fundamental principles underlying all emergent, adaptive phenomena. This could initiate a Copernican-class revolution, particularly if such knowledge is applied to the development of more powerful artificially intelligent computing systems. Further, witnessing a lab synthesized simulacrum of the enormity of the challenge faced by our biotic ancestors would surely contribute to enriching our cosmological perspective, giving us a new insight into the probabilistic unlikelihood, and therefore the preciousness of all life.

Before we leave the purview of the progenitor, let us take the opportunity to pose some compelling questions, perhaps best taken up by philosophy:

[39] Darwin, Letter to Joseph Dalton Hooker, February 1, 1871. Darwin Correspondence Project, "Letter no. 7471," accessed on 6 January 2022, https://www.darwinproject.ac.uk/letter/?docId=letters/DCP-LETT-7471.xml

1. Are the matter and energy engaged in the processes of living organisms something truly different from what came before? By discovering a means to utilize primitive instructional templates acting as the first genes, does life introduce a nonlinear leap in creative potential in the universe? Or is biological life a less remarkable phenomenon, more of a step in a continuum beyond the previous creative assemblages of the prebiotic cosmos?
2. If science can establish that a medium like that proposed for the progenitor is required for life to emerge, then is it a given that life must share some of the same properties of that progenitor? If so, how does this recast our understanding of organisms as an indivisible set of units in densely interconnected relationships?
3. Can we gain an understanding of the nature of conscious experience, including our most inexplicable and extraordinary states, by scaling up the fundamental processes operating in the earliest stages of life's origin? For one example of this, let us take it as a given that the progenitor had to be a system for shaping probabilistic outcomes and moving the bar of thermodynamic equilibria. Therefore, in the subsequent four billion years since life's beginning, a planetwide system has dramatically shaped probability in its favor, at all scales. At the same time, that system has generated a vast store of linear instructions, from genes to memes, from which probabilistic outcomes are increasingly shaped. It is perhaps this collective power to alter the future in nuanced and highly complex ways that best characterizes life, all the way up to the seemingly miraculous products of the conscious minds of human beings. What can such a view teach us about the nature and potency of the living world? Might this understanding of life's origin provide a new explanatory context for our own remarkable capacities, aiding us in our evolutionary bid to become a flourishing planetary civilization?

2. The Metaphysical and Cosmological Context of Life's Origin

In Part 2, Segall argues that the task of explaining the origin of life is made more tractable by overcoming classical mechanistic-materialistic metaphysical assumptions. In place of the now defunct mechanistic world-picture, Whitehead's more general conceptions of both organism and evolution are extended beyond just the biological domain. These metaphysical generalizations reframe the emergence of living organization in the course of cosmic and Earth evolution, allowing scientists to reconceptualize the threshold of "life" as more a matter of degree than of kind.[40] The scientific goals of the interdiscipline of astrobiology, and Damer et al.'s hot spring progenitor hypothesis in particular, are interpreted as implying such a conceptual shift. The metaphysical approach Whitehead called "organic realism"[41] also shows the way out of the epistemological quandary first formulated by Immanuel Kant. Recounting Kant's transcendental treatment of biological phenomena thus serves to bring Whitehead's cosmological contributions into relief. The controversial question of whether formal and final

[40] Whitehead, *Process and Reality*, 102.
[41] Whitehead, *Process and Reality*, 309.

causation—what Whitehead described in terms of “aims at satisfaction”—play any selective role in the evolution of complexity and the emergence of living organization is also addressed. Finally, in conjunction with expanded notions of organism, evolution, and teleology, Part 2 unpacks Whitehead’s account of the role of environmentality[42] in sheltering the otherwise highly improbable chemical pathways responsible for igniting biological self-organization.

Since our understanding of abiogenesis bears directly upon the meaning of human existence, the cultural and spiritual implications of process-inflected origin of life science become salient. The hope is that a new kind of collaborative transdisciplinary research can contribute to healing the rift between the sciences and the humanities, thus allowing us to better appreciate, in Arran Gare’s words, “what it means to be free conscious agents as part of and creative participants within a dynamic, creative nature.”[43]

a. The Limits of the Mechanistic Paradigm

It is widely accepted among physicists that “there is nothing in physical law which implies the existence of [biological] organisms.”[44] For Whiteheadian or Whitehead-inspired researchers, as well as many systems biologists, this means only that the mechanistic metaphysical framework underlying such an interpretation of physical law is not generic enough to account for the reality of life and mind. If there is to be a scientific explanation for the origin of biological cells (not to mention the possibility of scientists), then it cannot just be that the more fundamental laws of physics and chemistry *happen to allow for* the emergence of biological organisms as an accidental collocation of molecules. Rather, there must be some set of principles of organization and complexity at play—some “all-embracing relations”[45]—linking prebiotic to biotic modes of existence. Contrary to Jacques Monod’s claim that living beings on Earth simply got lucky (“Our number came up in the Monte Carlo game”[46]), random chance must be understood to be the opposite of a causal scientific explanation. Evan Thompson articulates this point while summarizing Immanuel Kant’s treatment of organisms:

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[42] See Joana Formosinho, Adam Bencard, and Louise Whiteley, “Environmentality in biomedicine: microbiome research and the perspectival body” in *Studies in History and Philosophy of Science*, 91 (2022). The term “environmentality” has recently been used in several contexts, including environmental governance and ecocriticism. In this case the reference connects with new research by Formosinho, et al., which though focused on the biomedical implications of the microbiome and limited to epistemic or operational use rather than ontology is none the less of great relevance to Whitehead’s environmental conception of cosmic evolution. Formosinho et al. draw on work by Whiteheadian philosopher of science Isabelle Stengers to define environmentality as “the locally described state or quality of being a causal context for something else…over time and across scales, from micro to macro” (149, 152). This definition contrasts with the dominant sense of “environment” as something fixed and external, opening the door to more processual, relational, and situated analyses of evolutionary novelty.

[43] Arran Gare, “Approaches to the Question ‘What Is Life?’: Reconciling Theoretical Biology with Philosophical Biology” in *Cosmos and History: The Journal of Natural and Social Philosophy*, Vol. 4, Nos. 1-2 (2008), 55.

[44] As the theoretical biologist Robert Rosen put it. See “Relational Biology and the Origin of Life,” 421.

[45] Whitehead, *The Concept of Nature* (Cambridge University Press, 1920), 32-33.

[46] Monod, Jacques, *Chance and Necessity* (Vintage Press, 1972), 146.

> "We cannot explain organisms mechanistically because their organized forms are contingent, not necessary, with respect to the mechanical laws of inorganic nature."[47]

Given classical assumptions about the metaphysical status of matter, the Monodian approach requires viewing the emergence of life as so gratuitously improbable that it borders on the miraculous.[48] To give a scientific explanation is to give a rational account, while an *accident* is said to occur for no reason. It is not that chance plays no role in the unfolding of the universe, nor that biological organization must be understood to be strictly entailed by the laws of physics.[49] The problem is that Monod's influential bifurcation between blind "chance" and iron-clad "necessity" stacks the deck so as to leave no room for life in the universe except as an alien anomaly. A more concrete rendering of the facts of Nature would recognize that, in ontological terms, physical laws are statistical tendencies rather than transcendent impositions, thus softening the dichotomy between randomness and determinism. As in unpacked below, this allows "laws" to be reformulated as widespread cosmic "habits."[50] Further, Whitehead's panexperiential vision of cosmic creativity allows us to re-define chance occurrences in a non-reductionistic way as (to varying degrees depending on the complexity of the system in question) the expression of self-organizing *aims*. Such aims are not imported into Nature from a supernatural beyond, but are understood to be intrinsic to self-organizing processes at whatever scale they emerge. Accepting the reality of such "natural purposes" in the universe (further defined below) allows for a naturalistic treatment of human agency and intelligence, features which would otherwise appear even more absurdly anomalous than the emergence of life.

Materialism proposes to explain life as nothing more than an especially complicated chemical reaction that is ultimately a fluke byproduct of physical law under special highly improbable conditions.[51] From a process philosophical perspective, this alleged explanation looks more like a deflationary metaphysical redefinition than a legitimate scientific finding.[52] Life has not been rationally explained, but reductively explained away. An *a priori* definition of life that excludes the aims and feelings of organisms makes it a good deal easier to explain their arrival in purely

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[47] Evan Thompson, *Mind in Life: Biology, Phenomenology, and the Sciences of Mind* (Harvard, 2007), 132.
[48] See Christian de Duve, "Life as a cosmic imperative?" in *Philosophical Transactions of the Royal Society A*, Vol. 369 (2011), 622.
[49] See Anderson, P. W. "More Is Different" in *Science*, Vol. 177, No. 4047 (1972): "The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe. … Instead, at each level of complexity, entirely new properties appear, and the understanding of the new behaviors requires research which…is as fundamental in its nature as any other" (393).
[50] See also Van Dijk, J. B. J., "Process Physics: Toward an Organismic, Neo-Whiteheadian Physics" in Davis, Andrew M., Teixeira, Maria-Teresa, and Schwartz, Wm. Andrew (eds), *Process Cosmology: New Integrations in Science and Philosophy* (Palgrave: 2022). In addition to reinterpreting physical laws as cosmic habits, Van Dijk argues that "these 'laws' should better be seen as *measurement phenomenologies*—data-compliant algorithms capable of closely following the changing states of measurement instruments, *not* the changes in nature itself" (28).
[51] Carl Woese, "A New Biology for a New Century" in *Microbiology and Molecular Biology Reviews*, Vol. 68, No. 2 (June 2004), 185.
[52] See Arran Gare, "Approaches to the Question 'What Is Life?': Reconciling Theoretical Biology with Philosophical Biology" in *Cosmos and History: The Journal of Natural and Social Philosophy*, Vol. 4, Nos. 1-2 (2008), 59.

mechanistic terms (that is, solely in terms of efficient causal relations between external parts). It also leaves a good deal of evident facts entirely unaccounted for (e.g., that as organisms we are ourselves "*directly* conscious of our purposes as *directive* of our actions"[53]). Modern science's inability to find aims, feelings, or creativity in Nature follows from its adoption of Descartes' methodologically clarifying but, when ontologically reified, ultimately disastrous dualism separating mind from body. With "mind" thus neatly tucked away outside of the physical world, natural science was free to ignore half the evidence provided by human experience by describing the interaction of mindless bodies according to deterministic rules of succession.[54]

> "Scientific reasoning is completely dominated by the presupposition that mental functionings are not properly part of nature. … As a method this procedure is entirely justifiable, provided that we recognize the [obvious but undefined] limitations involved. The gradual eliciting of their definition is the hope of philosophy."[55]

The hope of origin of life science, including the Hot Spring Hypothesis, is that a rational account of life's emergence is possible, and that it could be achieved through precisely modeling and experimentally verifying one or more viable chemical pathways leading from molecular motion to biological function, including metabolism[56], replication, adaptation, anticipation, and ultimately conscious human agency. The process philosophical response to this revolutionary scientific proposal is twofold:

1) to affirm that an evolutionary continuum bridges any apparent ontological gaps between physical, biological, and mental processes such that "the ultimate natures of things lie together in a harmony which excludes mere arbitrariness,"[57] and

2) to question whether the "matter" life is said to have emerged from could be anything like what classical materialism had been imagining.[58]

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[53] Whitehead, *Modes of Thought* (The Free Press, 1938), 156.
[54] Whitehead, *Modes of* Thought, 154.
[55] Whitehead, *Modes of Thought*, 156.
[56] The Hot Spring Hypothesis may help overcome the division between proponents of "genetics-first" and "metabolism-first" scenarios for life's origin (see A. Eschenmoser, "The Search for the Chemistry of Life's Origin" in *Tetrahedron*, Vol. 63, No. 52 [2007], 12830), as the "progenitor" environment discussed in Part 1 leaves ample room for nucleic and amino acids to complexify in parallel.
[57] Whitehead, *Science and the Modern World*, 18. The affirmation of a cosmic evolutionary continuum aligns with astronomer Eric Chaisson's argument that a philosophically informed "inclusive scientific worldview can rationally explain the origin, evolution, and complexity of all structured systems in the known Universe…[as] more than a subjective, qualitative narrative" ("Energy Rate Density. II. Probing Further a New Complexity Metric" in *Complexity*, Vol. 17, No. 1 [2011], 60).
[58] See physicist and philosopher Timothy Eastman's *Untying the Gordian Knot: Process, Reality, and Context* (Lexington Books, 2020). Eastman criticizes materialism for upholding the dogma of "actualism" by denying any role for "*potentiae*" in Nature, a denial that he argues makes the findings of quantum physics (not to mention human agency) unintelligible. See also Ruth Kastner, Stuart Kauffman, and Michael Epperson, "Taking Heisenberg's Potentia Seriously" in *International Journal of Quantum Foundations*, Vol. 4 (2018), wherein they define

The first step in any integration of origins of life science with process philosophy must be to overcome the mechanistic-materialistic substance ontology that continues to inform many biologists' interpretations of the physics and chemistry to which biology is thought to be reducible.[59] Appeals to mechanism may have been justified during the reign of the classical paradigm, when physics was still rooted in well-attested self-consistent physical concepts regarding externally related material particles with simple location in absolute space and time. But following the quantum and relativistic revolutions, no such system of concepts exists.[60] A century later, while complexity theorists have made important progress toward integrating the special sciences, and while technological applications continue to dramatically reshape human society, the metaphysical foundations of physical knowledge remain in disarray, with dozens of theoretical interpretations of quantum phenomena vying for explanatory priority.[61] Process philosophers are eager to join the growing chorus of quantum physicists and systems biologists to contribute to the development of a post-materialist ontology that may shed more light on otherwise confounding scientific findings.[62]

Whitehead predicted in the mid-1920s that the next great advance in physics would be made in the realm of biology.[63] From Whitehead's perspective, the advance would involve the recognition that "organism" rather than "matter" is key to understanding the regularity of Nature; that mechanism is an abstraction from creative activity; and that enduring entities at every scale from electrons to cells to galaxies are best understood as organisms engaged in the evolution of environments favorable to their persistence and enhancement.[64] Whitehead offered the first systematic sketch of a more generic process-relational ontology that resituates

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"actualism" as "the doctrine that only actual things exist" despite the fact that a coherent quantum ontology requires making reference to potentialities (5-6).

[59] See John Dupré and Daniel J. Nicholson, *Everything Flows: Toward a Processual Philosophy of Biology*: "Although physics emancipated itself from the mechanicist worldview at the turn of the twentieth century (which is partly what led Whitehead to embrace process metaphysics…), mechanicism never really lost its grip on biology" (28).

[60] Whitehead, *Science in the Modern World*, 97. While classical mechanistic models may still offer predictive value when deployed within narrowly defined conditions, they have been obsolete as ontology for over a century.

[61] In *Philosophy of Physics: Quantum Theory* (Princeton University Press, 2019), philosopher of science Tim Maudlin puts it starkly: "No consensus at all exists among physicists about how to understand quantum theory. … Instead, there is raging controversy" (2). He adds that there really cannot even be said to be a "quantum theory" at all; rather, there is "a recipe or prescription…for making predictions about data" (5). See also the quantum physicist Carlo Rovelli, who goes so far as to say that "a lot of current work in theoretical physics is a map without a territory" ("Carlo Rovelli on Consciousness, the Illusion of Time, and Philosophy of Relational Quantum Mechanics" on the "Theories of Everything" YouTube Channel hosted by Curt Jaimungal, December 17, 2021 [timestamp: 37:55]; https://www.youtube.com/watch?v=r_fUPbBNmBw).

[62] See Segall's *Physics of the World-Soul: Whitehead's Adventure in Cosmology* (SacraSage, 2021) for a detailed explication of Whitehead's contributions to contemporary new paradigm natural sciences, including quantum, relativity, evolutionary, and complexity theories.

[63] Whitehead, *Harvard Lectures of ANW: Philosophical Presuppositions of Science*, 12.

[64] Whitehead, *Harvard Lectures of ANW: Philosophical Presuppositions of Science*, 141, 156. See also Whitehead, *Process and Reality*, Part II, Chapter III: "Organism and Environment."

physics and biology in a broader cosmic ecology.[65] His scheme allows us to envision a universe of nested self-organizing processes of varying degrees of complexity, with "no absolute gap between 'living' and 'non-living'" systems.[66] His organic realism thus makes good on biochemist Addy Pross' call for an "integration of animate and inanimate matter within a single conceptual framework."[67] In such a context, biology becomes the study of the more complex organisms while physics becomes the study of the simpler organisms.[68] Rather than construing the universe as a structural hierarchy of things, with all causal arrows pointing downward to a base layer of substantial particles, process metaphysics re-imagines the cosmos as a dynamic hierarchy of processes, with activities at every level being constrained by their internal relations to one another and to the wholes in which they are enveloped.[69] Process philosophy thus rejects reductive mechanistic accounts of life and joins systems biology in welcoming formal and final causation back into our scientific understanding of Nature.[70]

To be fair, it is undeniable that mechanistic accounts and computer models can provide insights for guiding further research in some limited domains of application, particularly when the kinetic components being investigated are sufficiently stable in the timeframes considered.[71] The metaphysical challenge presented by process philosophy does not forbid the machine metaphor as a heuristic device for drawing causal maps of isolated or idealized systems. Computer modeling is obviously an essential instrument in the tool kit of contemporary physics, chemistry, and biology. The process intervention is meant only to check claims to total explanation. As the biologist and creator of General Systems Theory, Ludwig von Bertalanffy, put it:

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[65] As Jesse Bettinger and Timothy Eastman put it, physics and biology thus become "two pillars of an even more general discipline: complex systems" ("Foundations of Anticipatory Logic in Biology and Physics" in *Progress in Biophysics and Molecular Biology 131* [December 2017], 118).

[66] Whitehead, *Process and Reality*, 102.

[67] Addy Pross, "Toward a general theory of evolution: Extending Darwinian theory to inanimate matter" in *Journal of Systems Chemistry*, Vol. 2, No. 1 (2011), 2. While Pross notes the remarkable prescience of Whitehead's ontological shift from process to substance for bridging the gap between chemistry and biology (12), it remains to be seen whether he is willing to replace classical conceptions of "matter" with Whitehead's generalized concept of organism.

[68] Whitehead, *Science and the Modern World*, 129.

[69] Dupré and Nicholson, *Everything Flows*: "The complex web of causal dependencies between the various levels means that we cannot fully specify the nature of an entity merely by listing the properties of its constituents and their spatial relations. It also means that we cannot pick out any level in the hierarchy as ontologically or causally primary" (27).

[70] See Mariusz Tabaczek's article "The Metaphysics of Downward Causation: Rediscovering the Formal Cause" in *Zygon*, Vol. 48, No. 2 (June 2013) for a helpful conceptual history of emergence and an insightful analysis of downward causation in terms of formal causation. Tabaczek ultimately defends a substantialist Aristotelean formal cause, distancing himself from processual accounts because of their panpsychist implications. For further helpful discussions of the place of formal and final causality in the biological world, see: Evan Thompson's *Mind in Life*, 129-133; Alicia Juarrero's *Dynamics in Action: Intentional Behavior as a Complex System* (Bradford Books: 1999), 46-48, 126-128; and Terrence Deacon's *Incomplete Nature: How Mind Emerged from Matter* (W. W. Norton, 2011).

[71] Dupré and Nicholson, *Everything Flows*, 29.

> "We cannot speak of a machine 'theory' of the organism, but at most of a machine fiction. … We could at most say that organisms can be regarded 'as if' they were machines. We do not at all wish to underestimate the value of picturable fictions in science, but we cannot remain satisfied with the one offered in the present case."[72]

Bertalanffy here accepts the machine fiction as a methodological shortcut for aiding research, even though he thoroughly rejects it as a metaphysical explanation of biological organization. His rejection of a machine ontology follows from the fact that the machine metaphor remains "crypto-teleological," i.e., that every machine implies an external engineer whose purposes the machine was designed to fulfill.[73] If modern science rejects the idea of a divine designer imposing purposes on its creation, then it should also reject the mechanistic ontology implying such a picture. It is important to note that such divinely imposed teleology differs in kind from the sort of *immanent* or *intrinsic* teleology first described by Aristotle[74] and later refined by Kant, whose account of "natural purposes" is discussed in subsection b below. In the case of the "as if" heuristic deployment of mechanistic or computational models, it is essential to remember that that the "designer" in question is the human researcher whose purposes are defined by the parameters of the hypothesis under consideration. Such models at best offer partial descriptions of abstractly demarcated conditions and subcomponents. When it comes to ontology, mechanistic models remain observer dependent in the above sense and are simply too abstract to adequately account for the complex sympoietic[75] dynamism of living organization. This is not because organisms are too *complicated* to accurately model. Regardless of future increases in computational power, Robert Rosen has argued that in principle "organisms cannot be completely formalized" because the *complex* (not merely complicated) "closed causal loops" they instantiate "have nonalgorithmic, noncomputable" self-referential semantic elements that are irreducible to any computational syntax.[76] Further, as Dupré and Nicholson point out, mechanical explanations "are accurate only on the particular timescales of the phenomena they are called upon to explain."[77] When the entire lifecycle of an

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[72] Bertalanffy, *Modern Theories of Development: An Introduction to Theoretical Biology* (Oxford University Press, 1933), 38.
[73] Bertalanffy, *Modern Theories of Development: An Introduction to Theoretical Biology* (Oxford University Press, 1933), 37.
[74] See Christopher Shields, *Aristotle* [Routledge, 2007], 84).
[75] In *Staying with the Trouble: Making Kin in the Chthulucene* (New York: Duke University Press, 2016), Whiteheadian philosopher of science and technology Donna Haraway defines "sympoiesis": "Sympoiesis is a simple word; it means 'making-with.' Nothing makes itself; nothing is really autopoietic or self-organizing. … Sympoiesis is a word proper to complex, dynamic, responsive, situated, historical systems. It is a word for worlding-with, in company. Sympoiesis enfolds autopoiesis and generatively unfurls and extends it" (58). See also Anne Sophie Meincke, "Autopoiesis, biological autonomy and the process view of life" in *The European Journal for Philosophy of Science* Vol, 9, No. 5 (2019) for an argument that the autopoietic view of life implies a process ontology.
[76] Rosen, *Essays on Life Itself* (New York: Columbia University Press, 2000), 54, 136. See also Gare, "Approaches to the Question 'What Is Life?': Reconciling Theoretical Biology with Philosophical Biology" in *Cosmos and History: The Journal of Natural and Social Philosophy*, Vol. 4, Nos. 1-2 (2008), 61-67: "As Kepler and Newton freed science from the assumption of earlier astronomers that all planetary motion is in circles, Rosen has freed science, and biology in particular, from assumptions about mathematical modeling which effectively made life itself unintelligible" (66).
[77] Dupré and Nicholson, *Everything Flows*, 30.

organism is considered, the seemingly solid components referenced in mechanical accounts (whether genes, proteins, organelles, or organs) dissolve into the continuous stream of activity constituting the organism as an energetically open, ecologically entangled complex dynamic system. While shocking to our substantialist habits of thought, the fact is that "in general, none of the parts of an organism is as old as the organism itself."[78]

It may be argued that the genetic code constitutes a set of instructions older than the organism itself. But this betrays too abstract and decontextualized an idea of genetic "information," particularly in the context of an ontology claiming to be materialistic.[79] As Woese suggested, it is "wrong to consider the codon assignments in cryptographic isolation" since they are just a surface manifestation of something deeper and more fundamental to biological phenomena, i.e., the evolution of the "phenotype-genotype relationship."[80] In some sense, it is true that the *form* of living organisms remains unchanged as its material parts are constantly turned over and replaced. In the case of DNA molecules, the nucleic acid sequences remain largely unchanged during the lifespan of an individual organism thanks to the remarkable fidelity of cellular copying and error correction processes, even if the individual molecules themselves are scattered and replaced during cell division.[81] The popular idea that organisms can be entirely specified by instructions coded in genes is dubious for several reasons. It is here—in what Woese called "the real problem of the gene" and perhaps of biology itself (i.e., how the process of gene translation evolved[82])—that the machine metaphor for life shows itself to be spectacularly inadequate. *Growing an organism is not like booting up a computer*.[83] First of all, the abstraction "gene" (as in a particle-like unit of heritable information for specifying proteins and thus phenotypes) no longer has a single clear biochemical definition.[84] Furthermore, the

[78] Dupré and Nicholson, *Everything Flows*, 17.
[79] See Sarah Imari Walker and Paul C. W. Davies, "The algorithmic origins of life" in *Journal of the Royal Society Interface*, Vol. 10 (2012). Walker and Davies understand genetic information and functionality is context dependent, distributed throughout the environment and emergent from the whole history of the organism, rather than being "a local property of a molecule" (2). Their critique of digital-first conceptions of biological information, which neglect the analog format of the proteome, is well taken (3). Yet by defining life in terms of "information control" ("information manipulates the matter it is instantiated in" [6]) and insisting its emergence represents a fundamental shift in the causal structure of Nature, they beg many metaphysical questions about physical ontology, which they hint at but do not directly address at least in the cited paper. It is not at all clear that the "top-down" informational causality they point to is compatible with materialism.
[80] Carl Woese, "A New Biology for a New Century" in *Microbiology and Molecular Biology Reviews*, Vol. 68, No. 2 (June 2004), 176.
[81] Dupré and Nicholson, *Everything Flows*, 17.
[82] Woese, "A New Biology for a New Century" in *Microbiology and Molecular Biology Reviews*, Vol. 68, No. 2 (June 2004), 176. Woese adds that while the complex process of gene expression known as translation "is describable in reductionist terms," it is nonetheless "neither predictable nor fully explainable therein" (180).
[83] For a comprehensive critique of the literalization of computational metaphors in molecular biology, see Evan Thompson, *Mind in Life*, 179-187: "whereas software and hardware are independent in a computer—the hardware has to be there before the program can be run, and hardware and software do not produce each other autopoietically—DNA replication and gene activation are entirely dependent on the autopoiesis of the cell. They contribute enormously to this process, but they also owe their existence to it" (180).
[84] For a helpful discussion of the dissolution of the classical conception of the gene, see Peter Godfrey-Smith, *Philosophy of Biology* (Princeton University Press, 2014), 81-85. See also Francesca Bellazzi, (2022) "The Emergence of the Postgenomic Gene" in *European Journal for Philosophy of Science*, Vol. 12, No. 17.

information required for making an organism cannot be simply located in genetic material but must be distributed throughout the stochastically self-organizing molecular interactions composing the intracellular matrix and indeed the whole historical sequence of environments that organisms have evolved and developed within.[85]

Besides these theoretical limitations to the mechanical method of explanation, further practical and ethical concerns can be raised. Woese, who was well aware of the import of complexity theory for deepening the ontological reach of biology, warned that the tremendous instrumental success of reductionistic molecular biology had now run its course, and that without a new vision of life biology was threatening to become an engineering discipline "that solely does society's bidding" rather than being "society's teacher":

> "A society that permits biology to become an engineering discipline, that allows that science to slip into the role of changing the living world without trying to understand it, is a danger to itself. … Society cannot tolerate a biology whose metaphysical base is outmoded and misleading: the society desperately needs to live in harmony with the rest of the living world, not with a biology that is a distorted and incomplete reflection of that world."[86]

b. The Kantian Connection and the Extent of Self-Organization in Nature

While much progress has been made in physics and biology by means of mechanistic modeling, the modern machine paradigm's overstressing of efficient causes is no less distorting than the medieval Scholastic period's overemphasis on final causes. It remains the task of a sound metaphysics to explain the proper relation between efficient and final causes.[87] Sometimes to move forward, it can be helpful to look back by examining the history of natural philosophy in search of wrong turns and alternative pathways for thinking Nature. The complex causality and intrinsic purposiveness evident in even the simplest organisms was given its earliest modern philosophical articulation by Kant in his *Critique of Judgment* (1790). Kant's claim that there would never be another Newton who might explain how even a mere blade of grass was produced by mechanical causes alone is frequently recounted in histories of scientific progress.[88] Darwin is then introduced as precisely the Newton of the grass blade that Kant had philosophically forbidden, with his theory of evolution by natural selection offered as an explanation for how apparently purposive behavior and functional structure are really just products of blind mechanical forces passively amplified by Natural Selection.[89] Unfortunately, this story fundamentally misunderstands the philosophical context of Kant's argument and dramatically overplays Darwin's scientific hand. Darwin's *On the Origin of Species* (1859)

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[85] For another thorough treatment of the inadequacy of the computer metaphor, and the role of environmental context (including intracellular context) in specifying phenotypic development, see Richard Lewontin, *The Triple Helix: Gene, Organism, and Environment* (Harvard University Press, 2000), 17-18.
[86] Carl Woese, "A New Biology for a New Century" in *Microbiology and Molecular Biology Reviews*, Vol. 68, No. 2 (June 2004), 173, 185.
[87] Whitehead, *Process and Reality*, 84.
[88] Kant, *Critique of Judgment*, Sec. 75.
[89] Peter Godfrey-Smith, *The Philosophy of Biology* (Princeton, 2014), 60.

offered a theory of speciation, not an account of self-organization and certainly not of biological origination. In fact, his theory must presuppose self-organizing biological individuals that can reproduce before it can do any explanatory work at the level of phylogenesis.[90] When it comes to ontogenesis, or the development of individual organisms, Kant's skepticism of mechanism remains as valid as ever.

In order to provide the philosophical context missing from most scientific accounts of biological phenomena, this subsection begins with a brief review of Kant's transcendental method.[91] This is followed by a more detailed treatment of his definition of self-organization. The hope is that Kant's critical framing of the biological problem-space brings into sharper relief the important metaphysical advances contributed by Whitehead's organic realism.

In his first critique, the *Critique of Pure Reason* (1781/1787), Kant inaugurated a Copernican Revolution in philosophy by reversing the until then taken for granted relationship between cognition and its objects. Rather than assuming, as dogmatic metaphysicians had, that cognition must conform to objects, Kant argued the reverse, that objects must conform to our cognition:

> "This would be just like the first thoughts of Copernicus, who, when he did not make good progress in the explanation of the celestial motions if he assumed that the entire celestial host revolves around the observer, tried to see if he might not have greater success if he made the observer revolve and left the stars at rest."[92]

Kant thus analogically extends into epistemology what Copernicus' had accomplished in astronomy. The upshot of Kant's transcendental maneuver is that it secures the synthetic *a priori* knowledge claimed by physical science. From Kant's point of view, Reason cannot be passively instructed by empirical Nature like a pupil, since (per Hume[93]) accidental observations of particulars provide no inductive basis for the establishment of necessary and universal laws or causal principles. As Kant has it, for scientific knowledge of physical laws to be possible, the scientist must play the role of judge, putting Nature on trial and compelling Her to answer questions as Reason frames them. This is because, according to Kant, "Reason has insight only into what it itself produces according to its own design."[94] Kant would later put it even more starkly: "He who would know the world must first manufacture it."[95] As is evidenced by the

[90] See Thompson, *Mind in Life*, 131.
[91] As Steven J. Dick has pointed out, Kant's relevance to astrobiology was established well before his development of transcendental philosophy in the final two decades of his life. His first major work, "Universal Natural History and Theory of the Heavens" (1755) explored the possibility of alien life. Dick wonders if this imaginative exercise "affected Kant's unusually generalized yet deeply critical philosophy" (see "History and Philosophy of Astrobiology" in *Astrobiology*, Vol. 12, No. 10 [2012], 917-918).
[92] Kant, *Critique of Pure Reason* (New York: Cambridge University Press, 1998), 110/Bxvi.
[93] See David Hume, *An Enquiry Concerning Human Understanding*, in Steven M. Cahn (ed.), *Classics in Western Philosophy* (Indianapolis: Hackett Publishing Company, 2012), 843, 856, 899.
[94] Kant, *Critique of Pure Reason* (New York: Cambridge University Press, 1998), 109/Bxiii.
[95] Kant, *Opus Postumum* (Cambridge: Cambridge University Press, 1993), 240.

mechanistic model-centrism characteristic of so much contemporary scientific materialism[96], Kant's influence is pervasive even among those with no explicit allegiance to his transcendental project. Consider, for example, the words the famous physicist Richard Feynman had written on his blackboard at the time of his death: "What I cannot create, I do not understand."[97]

While Kant's revolution had provided philosophical justification for the knowledge produced by physical science, it came at the cost of forgoing scientific realism. In order to secure the rational necessity and universality of its laws, Kant had to limit our knowledge of physics to the sensory domain of phenomena. From his transcendental point of view, "nature is nothing in itself but a sum of appearances…merely a multitude of representations of the mind."[98] He construed the phenomenal domain as a kind of cognitive construct, the synthetic product resulting from the application of our innate categories of understanding (e.g., quantity and quality, substance and accident, cause and effect, etc.) to the spatiotemporal display produced *a priori* by the geometric and arithmetic organization of our sensory intuitions (i.e., geometry is said to be rooted in our pure intuitions of spatial simultaneity, while arithmetic derives number from our pure intuitions of temporal succession[99]). Natural science's synthetic *a priori* knowledge of the mathematical order and lawfulness of phenomenal Nature is thus grounded in the unity of Reason, rather than in a mind-independent universe,[100] with the nature of the latter remaining hidden behind the dense fog obscuring the noumenal ground of our sensory intuitions.[101]

While Kant resisted Berkeleyan idealism by insisting that *something* exists beyond the rationally organized formal order of the sensory screen, he marked this noumenal realm as a mere "X" of which nothing further can be known. As Whitehead quipped, "According to Kant we never know the real things, but only an *édition de luxe* which has been expurgated into rationality."[102] Kantian quietism as regards ontology resurfaced later in Niels Bohr's "Copenhagen interpretation" of quantum phenomena.[103] Bohr is reported to have responded to a question about whether the quantum theory somehow mirrored an underlying quantum world:

[96] See Randall Auxier and Gary Herstein, *The Quantum of Explanation: Whitehead's Radical Empiricism* (Routledge, 2017), 199, 233.
[97] See the CalTech Archives (February 1988). https://archives.caltech.edu/pictures/1.10-29.jpg
[98] Kant, *Critique of Pure Reason* (New York: Cambridge University Press, 1998), 236/A114.
[99] Kant, *Kant's Prolegomena to any Future Metaphysics* (Chicago: Open Court, 1912), 36/Sec. 10.
[100] Kant's transcendental framework could thus be understood to provide a rational answer to the question raised by Eugene Wigner in his famous paper "The Unreasonable Effectiveness of Mathematics in the Natural Sciences" in *Communications in Pure and Applied Mathematics*, Vol. 13, No. 1 (New York: John Wiley and Sons, 1960).
[101] Kant, *Critique of Pure Reason* (New York: Cambridge University Press, 1998), 354/B295.
[102] Whitehead, "First Lecture, 1924" in *Whitehead at Harvard*, 46.
[103] For more on this connection, see Michel Bitbol and Stefano Osnaghi, "Bohr's Complementarity and Kant's Epistemology" in *Bohr, 1913-2013, Séminaire Poincaré XVII* edited by Olivier Darrigol, Jean-Michel Raimond, Vincent Rivasseau, Bertrand Duplantier (Springer: 2013), 145-166. See also Jason Bell and Seshu Iyengar, "Whitehead and Kant at Copenhagen" in Brian Henning and Joseph Petek (eds.), *Whitehead at Harvard, 1924-1925* (Edinburgh University Press, 2021), 197-225.

> "There is no quantum world. There is only an abstract quantum physical description. It is wrong to think that the task of physics is to find out how nature *is*. Physics concerns what we can *say* about nature."[104]

It is important to note that while Kant's transcendental idealism limited scientific knowledge of Nature to appearances, he nonetheless fiercely upheld the objectivity of this knowledge. All rational knowers share the same set of categories and forms of intuition, thus securing the universality and necessity of the known laws of Nature. But in his final *Critique of Judgment*, focused on the status of teleological judgment in both aesthetics and biology, Kant unwittingly discovered a further limitation to his transcendental approach. While the motion of matter throughout the inorganic world from falling apples to orbiting planets had succumbed to the explanatory power of the new scientific method, Kant realized that living organisms exhibited a form of causality entirely foreign to physical science. Newton's law of gravitation perfectly described the ripened apple's downward trajectory from tree branch to soil, but neither his laws of gravitation nor of motion said anything about the metamorphic process of growth from seed through flower that put the apple up there to begin with.[105] Organic processes of development evidently unfold for the sake of an end, as though the apple were the purpose of the seed (or vice versa). As we've seen, Kant found it absurd even to try to imagine how another Newton, through mechanical causes alone, might explain how even a mere blade of grass could be produced:

> "The internal form of a mere blade of grass is sufficient to show that for our human faculty of judgment its origin is possible only according to the rule of purposes."[106]

While he rejected traditional theological explanations, Kant realized that organisms, in that they exemplify "natural purposes," cannot be comprehended rationally without the aid of formal and final causation. Unlike the inorganic or unorganized matter presupposed in mechanistic models of physics, organized beings are *both cause and effect of themselves*, such that *their parts reciprocally produce one another for the sake of the whole to which they belong*.[107] Kant's *Critique of Judgment* thus inaugurates the study of "self-organization" in at least the *living* world if not the whole of Nature.[108] While the causal nexus of the inorganic

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[104] Aage Petersen, "The Philosophy of Niels Bohr" in *Bulletin of the Atomic Scientists*, September 1963, Vol. XIX, No. 7 (Chicago: Educational Foundation for Nuclear Physics, 1963), 12.

[105] While Newton conceived of his laws of motion in terms of a direct exchange of forces between impenetrable bodies (i.e., efficient causes), his law of gravitation could not be so construed, as it implied action at a distance with no known medium to propagate efficient causal forces. This led Newton to theologically speculate that the space between masses is divinely occupied, i.e., is the *sensorium of God* (see Henry, J. "Newton, the sensorium of God, and the cause of gravity" in *Science in* Context, Vol. 33, No. 3 (2020), 329-351. doi:10.1017/S0269889721000077).

[106] Kant, *Critique of Judgment* (Dover, 2005), 167/Sec.67. Whitehead would add that there is nothing in the materialistic doctrine of evolution that might explain how a man like Newton could come to be (see Price, Lucien. Dialogues of Alfred North Whitehead: As Recorded by Lucien Price [Westport, CT: Greenwood Press, 1977], 283).

[107] Kant, *Critique of Judgment* (Dover, 2005), 162-163/Sec. 64-65.

[108] Evan Thompson argues that Kant's conception of self-organization is a precursor to the contemporary concept of "autopoiesis" (Thompson, *Mind in Life*, 138).

physical world appeared to be exhaustively determined in mathematico-mechanical terms, the whole-to-part causality of the biological world confounded the Cartesian-Newtonian categories of classical scientific materialism.

But rather than displacing the reign of the mechanical *nexus effectivus* in physics by integrating the formal and final causes evident in living organization, the transcendental strictures of Kant's critical method forced him to confine the explanatory reach of natural purposiveness, not only to the realm of appearances (as was also the case for physical explanations), but also to playing the role of nothing more than a heuristic device regulating our reflective judgments concerning organized beings. While he argued forcefully that even the simplest of organisms is irreducible to mechanism, he was not willing to grant our judgments of their natural purposiveness the status of genuine scientific knowledge. When we think or feel purposes expressed in Nature, whether of a providential or simply individual sort, we are merely analogizing Nature as a whole or in its parts to ourselves, to our own rational faculty. Kant admitted that such analogies are highly suggestive of supersensible possibilities through which our own rational freedom might somehow be brought into harmony with the apparent determinism of inorganic Nature. But he insisted that the analogy remains merely an aesthetic feeling or moral intuition, not a scientific finding. *Aims* are but useful fictions that cannot feature in scientific explanations. As a result, given that Kant defined the domain of life by its purposive self-organization, he insisted that there could be no properly scientific study of living phenomena.

Fortunately, since Kant's day dramatic advances in our scientific understanding of a time-developmental universe have made it easier to understand how self-organization can be physically grounded.[109] But these advances have also dramatically upended the classical scientific understanding of "matter." In the wake of Kant's *Critique of Judgment*, Friedrich Schelling closed the eighteenth century with a series of groundbreaking treatises on natural philosophy that began the double task of resituating mind in Nature and reimagining matter in self-organizing terms.[110] Schelling sought a third way beyond both the Kantian idealistic approach, which begins with the rational subject and explains how an apparently objective Nature is constructed, as well as the materialistic approach, which begins with physical mechanism and tries to explain how apparent subjectivity might become appended to it. He sought instead for a more primordial creative ground from out of which both subjects and objects coemerge. Schelling's procedure was to distill human self-consciousness down to its minimal conceivable experiential potencies, and then to reconstruct the dynamic evolutionary

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[109] Thompson, *Mind in Life*: "Our conception of matter as essentially equivalent to energy and as having the potential for self-organization at numerous spatiotemporal scales is far from the classical Newtonian worldview" (140). See also Brian Swimme and Mary Evelyn Tucker, Ch. 10: "Rethinking Matter and Time" *in Journey of the Universe* (Yale University Press, 2011).

[110] These treatises include: in 1797, *Ideas for a Philosophy of Nature* (Cambridge: Cambridge University Press, 1988); in 1798, *On the world soul, a hypothesis of the higher physics for the clarification of universal organicity*, selections of which have been translated by Iain Hamilton Grant in *Collapse: Philosophical Research and Development*, Vol. VI (Falmouth: Urbanomic, 2010), 58-95; and in 1799, *First Outline of a System of the Philosophy of Nature* (New York: State University of New York, 2004). See also Arran Gare, "Approaches to the Question 'What Is Life?': Reconciling Theoretical Biology with Philosophical Biology" in *Cosmos and History: The Journal of Natural and Social Philosophy*, Vol. 4, Nos. 1-2 (2008), 68-72.

path of Nature upward from these simple experiential beginnings through a series of organizational stages back to mind.[111] Whitehead's organic realism continued this project in the twentieth century greatly aided not only by developments in mathematical logic but by the quantum and relativistic revolutions as well as the progress of physiology and evolutionary theory.[112] He was inspired by these advances to make self-organization constitutive beyond just the biological scale spanning from bacteria to Gaia*, but at every scale* from electrons to galaxies and (as we wait for more empirical data concerning earliest phases of cosmogenesis from the James Webb space telescope) perhaps beyond.

Whitehead credits Kant with initiating a turning point in the progress of metaphysics through his realization that "our trust in science demands a metaphysic which equally supports [the] belief in the coherent rationality of things."[113] Kant attempted to arrive at rational coherence along the Cartesian route by making the measuring, calculating mind the sovereign legislator of a merely phenomenal and entirely mechanical Nature. While Descartes believed that his geometric idea of matter described real things, for Kant the Cartesian method was really only the way the *res cogitans* or thinking substance—itself dreamed up—began to *imagine* matter, reducing Nature to the pure "knowability" of *res extensa*.[114] Thus, for Kant, an apparently objective world was said to emerge from the constructive activity of the subject (including the activity of the imagination, though always held in check by fidelity to sensory data and to the categorical logic of the understanding). But as we've seen, when confronted with the purposive whole-to-part causality of organisms, which Kant felt was suggestive of analogies to Reason's self-legislating power, he retreated from scientific explanation and inspired a generation of Romantic poets by conjecturing a mysterious noumenal substratum unifying the rational subject with all things from behind the scenes.[115] Whitehead seeks a deeper coherence for

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[111] See Esposito, Joseph, L. *Schelling's Idealism and Philosophy of Nature* (Bucknell University Press, 1977), 80ff. See also Gare, "Approaches to the Question 'What Is Life?': Reconciling Theoretical Biology with Philosophical Biology" in *Cosmos and History: The Journal of Natural and Social Philosophy*, Vol. 4, Nos. 1-2 (2008), 68-69.

[112] In *Science and the Modern World*, Whitehead mistakenly suggests that "the whole of the German idealistic movement [remained] out of touch with its contemporary science so far as reciprocal modification of concepts is concerned" (139). Schelling in particular had an important influence on the leading-edge scientists of his day (see Esposito, Joseph, L. *Schelling's Idealism and Philosophy of Nature* (Bucknell University Press, 1977), 125ff; see also Gare, "Approaches to the Question 'What Is Life?': Reconciling Theoretical Biology with Philosophical Biology" in *Cosmos and History: The Journal of Natural and Social Philosophy*, Vol. 4, Nos. 1-2 [2008], 70). Robert Richards characterizes Schelling's natural philosophical works as "[groaning] with the weight of citations of the most recent, up-to-date experimental work in the sciences" (*The Romantic Conception of Life: Science and Philosophy in the Age of Goethe* [Chicago University Press, 2002], 128). What can be said is that Whitehead philosophically amplified twentieth century advances in physics and biology to breathe new life into Schelling's non-mechanistic naturalism, which had languished for over a century following the rise of materialistic positivism. For more on the Schellingian resonances in Whitehead's philosophy, see Otávio S. R. D. Maciel, "Outlines of a Speculative Cosmology: Whitehead's Philosophy of Organism Meets Descola's Four Anthropological Dispositions Toward Nature" in Davis, Andrew M., Teixeira, Maria-Teresa, and Schwartz, Wm. Andrew (eds), *Process Cosmology: New Integrations in Science and Philosophy* (Palgrave: 2022), 100-102.

[113] Whitehead, "First Lecture, 1924" in *Whitehead at Harvard*, 46.

[114] See Bruno Latour, *An Inquiry Into Modes of Existence: An Anthropology of the Moderns* (Harvard, 2013), 110, 112, 121.

[115] Kant, *Critique of Judgment*, 188-193/Sec. 77.

scientific explanation across physical and biological domains by further generalizing Kant's transcendental mode of inquiry beyond just the special conditions of human cognition. Rather than a merely apparent world emergent from a transcendental subject, his philosophy of organism "stand[s] Kant on his head"[116] by inverting the process, such that occasional subjects are understood to emerge from the objective conditions of their environments: "the subject emerges from the world—a '*superject*' rather than a subject."[117] In other words, like every organic creature in Nature, we create and come to know ourselves as subject-superjects by actively organizing a real togetherness of formerly alien things.[118] Whitehead's organic realism thus allows for the reintegration of what Kant had torn asunder, "ending the divorce of science from the affirmations of our aesthetic and ethical experiences"[119] by planting the self-conscious power of Reason back into the cosmic context from which it originates:

> "The process of cognition is merely one type of relationship between things which occurs in the general becoming of reality. … [Kant] asked, How is cognizance possible? I suggest to you the more general question, How is any particular entity possible having regard for the relationships which it presupposes?"[120]

Every entity that emerges in cosmic history places on the rest of the cosmos the obligation of being patient of it. For example, apart from the patience of the systematic coherence of the electromagnetic field required by its electrons, there can be no living organism even for a billion billionth of a second.[121] Every entity must be studied in the context of an environment providing some systematic character essential to the very nature of the entity in question. The idea of an organism independent of spatiotemporal relations, or independent of electromagnetic and gravitational fields, is meaningless. Any attempt to classify organisms by means of their supposedly isolated properties obscures the fluid togetherness of things, which is to say that the essence of life is inseparable from its cosmic history and habitat. In addition to their systematic or highly ordered character, there are also accidental aspects of any given environment, aspects which are determinate but which cannot be determined by consideration of the environment or the organism in isolation. A particular bacterium could be chemotaxing in a laboratory petri dish, digesting cellulose in a termite's gut, or stowing away on the next SpaceX launch capsule. It is here, in the tension between the givenness of a systematic environment and the constructive activity of individual organisms that Whitehead introduces his controversial panexperientialist postulate: "the togetherness of an entity with the accidental items of its determinate environment is what we mean by the *experience* of the entity," to which he adds the qualification that he does not mean cognitive (i.e., self-conscious) experience.[122] In other words, rather than assuming in advance that all subjectivity is

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[116] Whitehead, *Harvard Lectures of Alfred North Whitehead: Philosophical Presuppositions of Science*, 113.
[117] Whitehead, *Process and Reality*, 88.
[118] Whitehead, *Science and the Modern World*, 151.
[119] Whitehead, *Science and the Modern World*, 157.
[120] Whitehead, "First Lecture, 1924" in *Whitehead at Harvard*, 46-47.
[121] Whitehead, "First Lecture, 1924" in *Whitehead at Harvard*, 49.
[122] Whitehead, "First Lecture, 1924" in *Whitehead at Harvard*, 50 (italics added). See also *Process and Reality*: "The principle that I am adopting is that consciousness presupposes experience, and not experience consciousness. It is

sequestered inside human heads, or at most reserved for highly cephalized animals, Whitehead grants some modicum of experiential potency—some subjective *form*[123] and subjective *aim*[124]—to every self-organizing process in the universe. While the brain and outward facing sense organs are clearly particularly well-organized systems for sensing and responding to accidental features of their environment, it is becoming increasingly well-accepted among biologists that even the simplest forms of cellular life exhibit experiential agency (e.g., decision-making and learning capacities[125]). Some (e.g., Michael Levin[126]) are even prepared to entertain Whitehead's adventure in generalization by affirming that *every self-organizing system in Nature enjoys experience to some degree.*

Physical science requires that living organisms be interpreted according to the same principles applying elsewhere in the universe. But this relation of dependence runs in both directions, as it entails that interpretations of other parts of the physical universe must be brought into accord with what we know of living organisms—including both our own first person embodied phenomenological acquaintance with feelings and aims, as well as our third person physiological knowledge of self-organization and auto-/sympoiesis.[127] As Thompson puts it:

> "Life is not physical in the standard materialist sense of purely external structure and function. Life realizes a kind of interiority, the interiority of selfhood and sensemaking. We accordingly need an expanded notion of the physical to account for the organism or living being."[128]

In the eyes of Whiteheadian philosopher Bruno Latour, further progress in science requires that researchers come to understand that the "matter" of materialism first conjured into existence

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a special element in the subjective forms of some feelings. Thus an actual entity may, or may not, be conscious of some part of its experience" (53).

[123] In *Process and Reality*, Whitehead defines "subjective forms" as "private matters of fact" (22), including "emotions, valuations, purposes, adversions, aversions, consciousness, etc." (24). "[A]n actual entity, on its subjective side, is nothing else than what the universe is for it, including its own reactions. The reactions are the subjective forms of the feelings" (154).

[124] "In its self-creation the actual entity is guided by its ideal of itself as individual satisfaction and as transcendent creator. The enjoyment of this ideal is the 'subjective aim,' by reason of which the actual entity is a determinate process. This subjective aim is not primarily intellectual; it is the lure for feeling. This lure for feeling is the germ of mind" (*Process and Reality*, 85).

[125] See Catherine Offord, "Can Single Cells Learn?" in *The Scientist* (May 2021). https://www.the-scientist.com/features/can-single-cells-learn-68694 [accessed December 21, 2021].

[126] While Whitehead uses the term "cognition" as a near synonym for human thought, Levin defines it more broadly in cybernetic informational feedback terms as part of an empirically grounded effort to establish an electrically mediated experiential continuum from chemical networks to human minds. Levin suggests his "scale-free" conception of cognitive agency "can perhaps be seen as a form of panpsychism" (Levin, "The Computational Boundary of a 'Self': Developmental Bioelectricity Drives Multicellularity and Scale-Free Cognition" in *Frontiers in Psychology*, Vol. 10, Article 2688 (2019), 18.

[127] Whitehead, *Process and Reality*, 119. As Haraway notes, in the living world, nothing really makes itself: sympoietic relationships enfold and extend autopoiesis (*Staying With the Trouble*, 58).

[128] Thompson, *Mind in Life*, 238.

by Descartes is really "the most idealist of the products of mind."[129] Even the simpler, supposedly inert processes of the inorganic world forcefully express themselves (e.g., the vibratory reiteration of electromagnetic waves, the supernova explosions of dying stars, etc.), even if their lack of mental originality severely restricts their expression to what the causal past allows them to be.[130] The very concept of "force"—which has proven so irreplaceable to physicists in their study of everything from particles to galaxies—emerges from and gains its meaning only by continual reference to *experience*, to our *feelings* of attraction or repulsion, of being pushed or pulled by the insistent presence of others. As Schelling, speaking to Newtonian scientists, wrote in his *Ideas for a Philosophy of Nature* (1797):

> "you can in no way make intelligible what a force might be independent of you. For force as such makes itself known only to your *feeling*. Yet feeling alone gives you no objective concepts. At the same time you make objective use of those forces. For you explain the movement of celestial bodies—*universal gravitation*—by forces of attraction and maintain that in this…you have [a physical ground of explanation for] these phenomena."[131]

In point of fact, experience can grant us no such physical ground of explanation, if by "physical" is meant the Cartesian idea of *res extensa*, i.e., a "barren extensive universe" of mute matter in motion set ontologically apart from the organismal experience of our living bodies.[132] As Whitehead put it, echoing Schelling:

> "There is nothing in the real world which is merely an inert fact. Every reality is there for feeling: it promotes feeling; and it is felt. Also there is nothing which belongs merely to the privacy of feeling of one individual actuality. All origination is private. But what has been thus originated, publicly pervades the world."[133]

All our scientific knowledge of distant quasars and black holes hits its mark, not because a disembodied mind has correctly represented the formal essences of Nature, but because our organism (equipped with its world-wide network of geometrical notations, telescopes, satellites, computers, and rigorous peer reviewers) has succeeded in translating the *lines of force* at work in the wider universe into the *feelings of life* at work within ourselves. All our knowledge, no matter how abstract or formal, must make its final appeal in the courtroom of experience, since the court of Cartesian-Kantian Reason, having disavowed the facts of feeling involved in all its acts of knowing, has as a result been cut off from its only means of concrete relation to reality. If everything were actually submerged in abstract geometric spacetime, science could never follow the threads of experience, could never arrive at the immanence of a truly de-idealized and naturalistic conception of physicality.[134] Whitehead's

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[129] Latour, *An Inquiry Into Modes of Existence*, 106.
[130] Whitehead, *Process and Reality*, 177.
[131] Schelling, *Ideas for a Philosophy of Nature*, 18.
[132] Whitehead, *Process and Reality*, 122.
[133] Whitehead, *Process and Reality*, 310.
[134] Latour, *Modes of Existence*, 106.

organic realism re-embodies and concretizes scientific knowledge by attributing unconscious vector feelings to energetic transmission throughout the actual world.[135]

In summary, the emergence and evolution of biological organisms is not a fugitive offshoot from otherwise mechanically determined laws of motion, but evidence of the excessive abstraction of these laws. While mechanical accounts can clearly function as powerful heuristics, closing the explanatory gap between matter, life, and mind requires overcoming the restrictions Kant placed on scientific knowledge by expanding classical conceptions of physical ontology to make room for the formal and final causes (feelings and aims, in Whitehead's terms) characteristic of self-organizing processes at whatever scale they occur, from electrons to E. coli and beyond.

c. Towards a General Theory of Evolution

Doing justice to the phenomenon of life as we observe it on this planet and as we directly experience it within ourselves requires acknowledging an aim or potency intrinsic to prebiotic cosmogenesis that already suggested life even if it did not yet fully achieve it. Far from requiring some sort of extra-physical vital force to explain how life could emerge from dead matter, Whitehead insisted that "there be no jump whatever in principle as between living and inanimate."[136] Accomplishing this explanatory feat not only involves recognizing the self-organizing dynamics constitutive of enduring order across all scales of Nature, but also entails a generalization of evolutionary principles beyond the artificial limits of biology. Such a generalization is a great aid to origin of life research, as it strengthens the analogies between physical vibration, combinatorial chemical selection, and biological self-organization.

Another short historical interlude is in order, both to introduce Whitehead's important influences and to reconsider the road not traveled by twentieth century biology, despite the appreciation for the limitations of reductionistic methods in the study of emergent complexity in Nature that was evident in the early part of the century. This interlude is also important to correct mistaken assumptions about the influence of evolutionary theory on Whitehead's thought.[137] Upon arriving at Harvard in 1924, Whitehead became acquainted with the work of several philosophically inclined biologists, including the physiologist Lawrence J. Henderson and the entomologist William Morton Wheeler. Whitehead mentions Henderson's work in a section titled "The Order of Nature" in *Process and Reality* as "fundamental for any discussion of this subject."[138] One of the works cited is *The Fitness of the Environment* (1913), the last sentences of which read:

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[135] Whitehead, *Process and Reality*, 177.
[136] Whitehead, *Harvard Lectures of Alfred North Whitehead: Philosophical Presuppositions of Science, 172.*
[137] See George R. Lucas, "Evolutionist Theories and Whitehead's Philosophy" in *Process Studies*, Vol. 14 (1985), wherein Lucas argued that evolution played no significant role in Whitehead's cosmology. Newly published lecture notes from Whitehead's students at Harvard have shown, on the contrary, that Whitehead had much to say about Darwin and evolutionary theory more generally. Lucas has since recanted his earlier position, which was based on a partial reading of Whitehead's published works (see "Uncovering a 'New' Whitehead" in *Whitehead at Harvard, 1924-1925*, 330).
[138] *Process and Reality*, 89.

> "The properties of matter and the course of cosmic evolution are now seen to be intimately related to the structure of the living being and to its activities; they become, therefore, far more important in biology than has previously been suspected. For the whole evolutionary process, both cosmic and organic, is one, and the biologist may now rightly regard the Universe in its very essence as biocentric."[139]

As for Wheeler, Dennis Sölch has shown that his books on emergent evolution "show a more than general commonality with Whitehead's thought."[140] In his book, aptly titled *Emergent Evolution* (1928), Wheeler writes:

> "If the naturalist is to accept both genetic continuity and novelty in evolution, the viable novelty at each emergence must be very small indeed. … Novelties such as life and mind, conceived in wholesale fashion, are of such magnitude that we can regard them only as representing the final accumulative stages of a very long series of minimal emergences."[141]

Wheeler builds on Whitehead's new organic conception of physics as laid out in *Science and the Modern World*, characterizing emergent organisms as "intensively manifold spatiotemporal events" rather than static externally related particles.[142] He further suggests that the organic view "resolve[s] the opposition between historicism and naturalism"[143] in biology, a bifurcation that survives today in the form of the two broad approaches to origin of life science, the historical and the universal.[144] Organic realism resolves the bifurcation precisely by interpreting the cosmic evolutionary process as the necessary and sufficient condition for the emergence of life, whether on Earth or elsewhere. Whitehead's general theory of evolution entails the extension of self-optimizing selection processes beyond just the biological domain. It may be that many possible chemical pathways to life exist, leaving room for historical contingency; but the general conditions of evolution remain the same everywhere, meaning that given the right environmental conditions, the emergence of biological organisms is all but inevitable. As is unpacked below, Whitehead's generalization of evolutionary theory entails that all order in Nature, including physical particle-fields and laws as much as biological species and instincts, is historically emergent.

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[139] Henderson, *The Fitness of the Environment: An Inquiry Into the Biological Significance of the Properties of Matter* (New York: Macmillan, 1913), 312.
[140] Sölch, "Wheeler and Whitehead: Process Biology and Process Philosophy in the Early Twentieth Century" in *Journal of the History of Idea*s, Vol. 77, No. 3 (July 2016), 491.
[141] Wheeler, *Emergent Evolution and the Development of Societies* (London: Kegan Paul, Trench, Trubner and Co., Ltd., 1927), 18.
[142] Wheeler, *Emergent Evolution*, 17.
[143] Wheeler, "Present Tendencies in Biological Theory," *Scientific Monthly* Vol. 28, No. 2 (1929), 108.
[144] See Scharf, Caleb et al., "A Strategy for Origins of Life Research" in *Astrobiology*, Vol. 15, No. 12, 2015, 1033. Scharf et al. add a third approach, the synthetic, but for our purposes it can be folded into the other two.

Long before much empirical data was available to confirm it, Whitehead mused about earlier cosmic epochs in which "the dominant trend was the formation of protons, electrons, molecules, the stars."[145] How did an entity as stable as the electron arise? Primordial electrons emerging from a magnetic seed field were at first mere flashes in the pan, fitful stretches of enduring organization.[146] At this early stage of the evolutionary process, "reproduction" comes in the simple form of vibratory reiteration. Electrons and other "primate organisms" gradually gained the capacity for reiterative self-propagation by evolving a more favorable environment and by forming stabilizing sympoietic associations among themselves as well as with primates of different species.[147] "Evolution for countless ages stood still until something happened to produce an environment"[148]: evolution thus advanced as organisms produced and transformed their environments for their own purposes (and were themselves transformed in turn).[149] Whitehead offers the example of the associative formation of atomic elements, wherein a positive nucleus merges with negative electrons to produce a neutral atom:

> "The neutral atom is thereby shielded from any electric field which would otherwise produce [destructive] changes in the space-time system of the atom."[150]

Just as the theories of niche construction[151] and symbiogenesis[152] have revealed in the biological context, the primate organisms engaged in physical evolution are not isolated systems adapting to a fixed environment, but coevolving agents actively constituting their environments. In Whitehead's terms, primate organisms are vibratory "stream-systems" inseparable from the underlying energy fields from which they emerge.[153] And since the environmental field is largely composed of other organisms, adaptation always means co-evolution. Each seemingly independent organism is a distinctive enfoldment of its environment, co-implicated with the entire cosmic ecology of other organisms. In this sense, the problem of evolution is essentially that of procuring a favorable environment, such that organism itself becomes an environmental concept.[154]

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[145] Whitehead, *The Function of Reason*, 24.
[146] Whitehead, *Harvard Lectures of Alfred North Whitehead: Philosophical Presuppositions of Science*, 135. See also more recent research on this early phase in cosmic evolution by Subramanian K., "The origin, evolution and signatures of primordial magnetic fields" in *Reports on Progress in Physics* (July 2016), 79(7):076901 and Ichiki K, Takahashi K, Ohno H, Hanayama H, Sugiyama N., "Cosmological magnetic field: a fossil of density perturbations in the early universe" in *Science* (February 2006), 10;311(5762):827-829.
[147] Whitehead, *Science and the Modern World*, 112, 133.
[148] Whitehead, *Harvard Lectures of Alfred North Whitehead: Philosophical Presuppositions of Science*, 141.
[149] Whitehead, *The Function of Reason*, 7. See also Richard Levins and Richard Lewontin, *The Dialectical Biologist* (Harvard University Press, 1985): "It is impossible to avoid the conclusion that organisms construct every aspect of their environment themselves. They are not passive objects of external forces, but the creators and modulators of these forces" (104).
[150] Whitehead, *Science and the Modern World*, 134.
[151] See F. John Odling-Smee, Kevin N. Laland, and Marcus W. Feldman, *Niche Construction: The Neglected Process in Evolution* (Princeton University Press, 2000).
[152] See Duur K. Aanen and Paul Eggleton, "Symbiogenesis: Beyond the Endosymbiosis Theory?," in *Journal of Theoretical Biology*, Vol. 434 (2017), 99-103.
[153] Whitehead, *Science and the Modern World*, 37.
[154] Whitehead, *Harvard Lectures of Alfred North Whitehead: Philosophical Presuppositions of Science*, 155.

> "We habitually speak of stones, and planets, and animals as though each individual thing could exist, even for a passing moment, in separation from an environment which is in truth a necessary factor in its own nature. …The individual thing is necessarily a modification of its environment, and cannot be understood in disjunction."[155]

Whitehead adds that while thought about discrete "things" is to some degree inescapable, such abstraction always presupposes the systematic background of the environment required for such "things" to exist. Rather than things, Whitehead emphasizes the creative activity of organisms, which are not isolated substances but "[emerge] by reason of the niche which is there for [them] in the Universe" as a potential which they participate in actualizing.[156] The abstractions of science fall into error when they are haphazardly applied across inconsistent backgrounds: environmental context cannot be ignored if we hope to penetrate to the final nature of reality. For example, the internal organization of a living cell shelters greater complexity than the surrounding environment, allowing molecules to engage in activities that would be highly improbable outside such a context.

Whitehead's extension of evolution to the physical world offers a coherent, bottom-up account of the emergent stability of organism-environments from particle-fields to biospheres, thus allowing science to reinterpret the order of Nature as a plastic hierarchy of historically achieved stabilities, harmoniously requiring each other.[157] Physical laws can then be understood as enduring habits left in the wake of organismal aims. Whitehead conceived of these stable habits as historically canalized layers of social order. Enveloping physical habits continue to genetically condition without unduly restraining the evolution of organic novelty.

> "Thus a society is, for each of its members, an environment with some element of order in it, persisting by reason of the genetic relations between its own members."[158]

Whitehead thus invites us to draw an analogy between the self-organizing molecular societies constitutive of biological organisms and the many examples of physical self-organization across spatiotemporal scales.[159] More recently, the astronomer Eric Chaisson has developed a quantitative model for measuring the "energy rate density" of self-organizing systems across various scales of cosmic evolution, going so far as to attribute simple metabolism to galaxies[160] and primitive forms of variation, adaptation, selection, and even crude replication to stellar societies:

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[155] Whitehead, *Adventures of Ideas* (New York: The Free Press, 1933), 154.
[156] Whitehead, *Harvard Lectures of Alfred North Whitehead: Philosophical Presuppositions of Science*, 356.
[157] Whitehead, *Process and Reality*, 93.
[158] Whitehead, *Process and Reality*, 90. See also p. 92: "This doctrine, that order is a social product, appears in modern science as the statistical theory of the laws of nature, and in the emphasis on genetic relation."
[159] Whitehead, *The Function of Reason*, 24.
[160] Eric Chaisson, "Energy Rate Density. II. Probing Further a New Complexity Metric" in *Complexity*, Vol. 17, No. 1 (2011), 59.

"Much as for biological evolution among living species, the process of selection, generally considered, also seems operative in the physical evolution of nonliving systems (although selective pressures for the latter are likely partly internal and autocatalytic). At least as regards energy flow and structural complexity while undergoing stellar evolution, stars have much in common with life—provided that stars are examined broadly, dynamically, and over extremely long periods of time."[161]

Chaisson's proposal for quantifying the evolution of complexity across scales via energy flows through open, nonequilibrium systems is a promising advance lending further credence to Whitehead's speculative generalization of evolution. Stars may not be "alive" in the sense relevant to origin of life scientists, but given the continuity of cosmic evolution they can be placed along the same ascending gradient of self-organization as biological organisms and complex human societies. In Whitehead's terms, such processes of social evolution—from electrons to stars to bacterial and human cultures—constitute "the orderliness whereby a cosmic epoch shelters in itself intensity of satisfaction."[162]

For Whitehead the "electromagnetic society" is among the most dominant environments forming the general background for our cosmic epoch.[163] A bewildering array of more specialized subordinate societies find themselves precipitating out of this wider electromagnetic society, subject to its influence but functioning as vehicles of further evolutionary novelty and more intense experiential satisfaction as they explore the edges of established niches.[164] Whitehead enumerates examples of such societies, beginning with waves of electromagnetic energy and increasing in complexity through atoms, molecules, stars, galaxies, and planets, to living cells, and societies of cells like plants and animals.[165] Each builds on the achievements of the last and is sheltered by the order reproduced by its environing communities, even as variant organisms scour the instabilities along the edges of established environments in search of new potential niches.[166]

At the base of all this organized activity is the first stirring of life-like motion in the universe, which Whitehead calls "Rhythm":

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[161] Eric Chaisson, "Energy Rate Density as a Complexity Metric and Evolutionary Driver" in *Complexity*, Vol. 16, 37-38.
[162] Whitehead, *Process and Reality*, 119.
[163] Whitehead, *Process and Reality*, 98.
[164] Whitehead, *Harvard Lectures of Alfred North Whitehead: Philosophical Presuppositions of Science*, 141.
[165] Whitehead, *Process and Reality*, 98.
[166] See George Allan, "Diagrams and Myths" in *Whitehead at Harvard, 1924-1925*: "The relationship of two different kinds of stable environment with their differing kinds of stable entities creates a minor instability along their adjacent edges, a niche chipped away from the continuity of their shared boundary, a slight breach creating an openness that is neither one environment nor the other. A crack of some sort in the established order of things can offer an opportunity to escape the repression of unsuitable possibilities, to be free to achieve something different, to create a novel variant that until then had been impossible or even inconceivable" (294).

> "The Way of Rhythm pervades all life, and indeed all physical existence. This common principle of Rhythm is one of the reasons for believing that the root principles of life are, in some lowly form, exemplified in all types of physical existence."[167]

Rhythm begins in the vibratory patterns exhibited by physical fields. Gradually these vibrations develop enduring harmonies, experientially valued for their own sake, which then merge into ever higher achievements of harmony.[168] The origination and further evolution of life on Earth is a result of a complexifying series of internal amplifications of the rhythmic energy pervading the cosmic environment.

In *The Function of Reason* (1929), Whitehead expands on his conception of cosmic evolution driven by primitive rhythms into the self-amplifying complexity of the biosphere by developing the general concept of the "cycle," which contemporary biochemists have scientifically elaborated into concepts including *thermodynamic work cycles*[169]*, autocatalytic hypercycles*[170]*, hypercyclic cooperative networks*[171]*,* and *dehydration/rehydration cycles* (as highlighted in the Hot Spring Hypothesis introduced in Part 1 of this chapter). In Whitehead's words:

> "In the Way of Rhythm a round of experiences, forming a determinate sequence of contrasts attainable within a definite method, are codified so that the end of one such cycle is the proper antecedent stage for the beginning of another such cycle. The cycle is such that its own completion provides the conditions for its own mere repetition."[172]

Despite his commitment to a methodologically reductionist interpretation, Pross' theory of "dynamic kinetic stability" in molecular replicating systems (specifically, in RNA oligonucleotides) provides an example of the empirical payoff of a general theory of evolution for origin of life research. Such systems behave analogously to biological systems in that (given the right environmental conditions) they undergo cyclical processes of replication, mutation, and selection. Some molecular systems compete for ecological niches, while still others form cooperative cross-catalytic networks that not only maintain holistic replicative capabilities but accelerate their complexification.[173] While Whitehead and Pross share the goal of integrating the special sciences of physics, chemistry, and biology into a universal science of evolution, Pross' allegiance to the reductionistic method leads him to attempt an explanation of the more complex feelings and aims of life and mind in terms of the simpler kinetic forces of "inanimate" molecules. But Pross' methodological reductionism evidently does not commit him to

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[167] *Function of Reason*, 21.
[168] Whitehead, *Science and the Modern World*, 96.
[169] Stuart Kauffman, *A World Beyond Physics: The Emergence and Evolution of Life* (Oxford University Press, 2019), xi.
[170] Alicia Juerraro, *Dynamics in Action*, 121.
[171] Pross, "Toward a general theory of evolution: Extending Darwinian theory to inanimate matter" in *Journal of Systems Chemistry*, Vol. 2, No. 1 (2011), 3.
[172] Whitehead, *Function of Reason*, 21.
[173] Pross, "Toward a general theory of evolution: Extending Darwinian theory to inanimate matter" in *Journal of Systems Chemistry*, Vol. 2, No. 1 (2011), 3-4.

metaphysical reductionism. He refers to his dynamically stable replicators as "molecular fountains," acknowledging Woese's rejection of the machine metaphor in favor of a philosophy of the organism as "patterns in an energy flow."[174] That said, Pross pulls up short of affirming any role for natural purposes in evolution beyond the biological sphere. Purpose (or "teleonomy") only emerges for Pross when thermodynamically constrained chemical replicators cross the threshold into cellular animacy by gaining the metabolic means of freeing themselves, at least locally and temporarily, from entropy.[175]

Whitehead's organic realism is not premised upon ignorance of the laws of thermodynamics. While the rhythmic vibrations pervading the physical world appear highly repetitive—e.g., a proton will endure for countless billions of years—even in these simpler forms probabilistically mapped with mathematical precision, the reiteration of pattern is never perfect. In the background of our highly organized biosphere, ancient layers of social order give us every indication that they have entered a period of prolonged decay. As physicist Brian Greene puts it, "*the current order is a cosmological relic*."[176] Grandfather galaxies cease to spiral, slowing new star birth as senescent stars burn out, swallowing the planetary spheres probably essential to the sheltering of life. But in earlier cosmic epochs, while still in their creative prime, these astrophysical organisms were expressions of "primordial appetitions," mysterious impulses that under the right conditions cause energy to run upwards.[177] The upward impulse evident in the evolutionary expansiveness of our cosmos is only privatively accounted for by a still materialistic science in terms of a postulated extraordinarily "negentropic" or "low entropy" cosmic origin state. While we cannot obtain direct knowledge of the selective striving at work in the early universe, Whitehead's organic realism implies that what appears entropic at present was agentic in the past. Atoms, stars, and galaxies are historically emergent, self-organizing, complex systems—*organisms* nested in a cosmic hierarchy of evolving processes. The primordial appetitions active in the early formation of the universe could account for the apparent "fine tuning" of physical laws, constants, and other conditions for the emergence of life.[178] It is not that quarks, protons, and electrons somehow conspired with the intention of producing life, but rather that the co-evolutionary dynamics of these and other primate organisms assured the universe would unfold in an internally related, organization enhancing way.[179]

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[174] Pross, "Toward a general theory of evolution: Extending Darwinian theory to inanimate matter" in *Journal of Systems Chemistry*, Vol. 2, No. 1 (2011), 6, 8.

[175] Pross, "Toward a general theory of evolution: Extending Darwinian theory to inanimate matter" in *Journal of Systems Chemistry*, Vol. 2, No. 1 (2011), 11.

[176] Brian Greene, *The Fabric of the Cosmos: Space, Time, and the Texture of Reality*. Knopf Doubleday: 2007, 171, 173-174.

[177] *Whitehead, Function of Reason*, 24; *Process and Reality*, 105.

[178] See Friederich, Simon, "Fine-Tuning", *The Stanford Encyclopedia of Philosophy* (Winter 2021 Edition), Edward N. Zalta (ed.), (https://plato.stanford.edu/archives/win2021/entries/fine-tuning/).

[179] See Grandpierre, Attila. "Extending Whiteheadian Organic Cosmology to a Comprehensive Science of Nature" in Davis, Andrew M., Teixeira, Maria-Teresa, and Schwartz, Wm. Andrew (eds), *Process Cosmology: New Integrations in Science and Philosophy* (Palgrave: 2022), 70ff.

As living organisms, we feel selective impulses directly in the form of our own aims and emotions. The biosphere is full of evidence of activities directed by purposes. Indeed, as Kant so convincingly argued, purposiveness *defines* the biological domain. The reductive dismissal of final causes in Nature explains away biological phenomena, thus making the scientific search for an origin of life redundant. There simply is nothing to explain: the biosphere is just a rare chemical reaction at the extreme end of physical improbability. Worse, since scientists, too, are organic beings, the elimination of aims as real features of the universe pulls the epistemic rug out from under the entire scientific enterprise. As Whitehead quipped, "Scientists animated by the purpose of proving they are purposeless constitute an interesting subject for study."[180] Purpose may be all but veiled from view in our observations of the present state of the large-scale physical universe, but the challenge of accounting for biological creativity, not to mention our own intellectual capacity to examine the evidence, suggests something more is at play.

While the originating energies that rhythmically coalesced into atoms, stars, and galaxies are now in gradual decay, the more complex progeny of these processes have leaned on the enhanced order and relative stability already achieved to continue their emergent evolution at other scales. As recurrent cycles canalize into enveloping social environments, subordinate societies issue in creative cycles more sensitive to novelty, producing variations which are further elaborated into cycles of cycles as locally evolved complexity ramps up.[181] As in Darwinian evolution, imperfect replication of inherited patterns functions creatively when new patterns are selectively amplified by changing environmental conditions. It follows that a living organism is only "the more highly organized and immediate part of the general environment."[182] But in addition to the chance process of selection described by Darwin, Whiteheadian selection includes the subjective aims of organismal agents seeking deeper intensities of experiential satisfaction. Thereby a gradual transition to more complex types of order is achieved.[183]

While simple enduring physical objects like rocks fail to secure the delicacy of social organization required to favor much intensity of experience, what they lose in subjectivity they gain in survivability. Highly complex animals, on the other hand, have an extremely refined physiological organization capable of sheltering a rich inner life and affording the realization of elaborate goals. But they are also in constant need of food and are susceptible in the extreme to small changes in their usual environment. Increase the temperature a few dozen degrees, alter the chemical composition of the atmosphere just slightly, or withhold water for several days and an animal body will cease to function. Even under the best of conditions, animals age and die. These facts lead Whitehead to deny Herbert Spencer's theory of evolutionary selection based on "survival of the fittest"[184]:

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[180] Whitehead, *Function of Reason*, 16.
[181] Whitehead, *Function of Reason*, 22.
[182] Whitehead, *Process and Reality*, 119.
[183] Whitehead, *Process and Reality*, 91.
[184] See *Principles of Biology* (1864).

> "The fallacy does not consist in believing that in the struggle for existence the fittest to survive eliminate the less fit. The fact is obvious and stares us in the face. The fallacy is the belief that fitness for survival is identical with the best exemplification of the Art of Life. In fact life itself is comparatively deficient in survival value. The art of persistence is to be dead. … The problem set by the doctrine of evolution is to explain how complex organisms with such deficient survival power ever evolved. They certainly did not appear because they were better at it than the rocks around them. It may be possible to explain 'the origin of species' by the doctrine of the struggle for existence among such organisms. But certainly this struggle throws no light whatever upon the emergence of such a general type of complex organism, with faint survival value."[185]

Thus the problem for evolution is the production of organic societies which achieve greater complexity without at the same time becoming overly specialized.[186] The selective factor in the evolution of complexity is not mere survivability, but the subjective aims of organisms themselves.[187] What we recognize as full-blown *mind* in ourselves and in the higher animals—the conceptual initiative not only to experience but to *think* about and so anticipate novel experience—is an evolutionarily enhanced expression of thoughtless aesthetic adjustments toward an ideal of harmony swarming already at the subatomic scale (e.g., in the form of the Principle of Least Action).[188] In Whitehead's view, the evolutionary telos of the universe is toward an increase in experiential satisfaction in service to the Art of Life.[189]

The truncated view of evolution implied by scientific materialism ultimately recognizes only the random variation and mindless selection of changes in the external relationships of unchanging material particles. In such a universe, there really is nothing to evolve, there is only purposeless change in the relative position of inert particles. In contrast, in Whitehead's general theory of evolution, everything is thrown into process, such that the only endurances are historically evolved organic structures of activity, each one a unit of emergent value. For Whitehead, the whole point of evolutionary theory is to shed scientific light on the process whereby the more complex organisms arise from simpler antecedents. To deny the evident tendency to increasing complexity and intensity of experience is to deny evolution.[190]

d. The Place of Feeling and Aim in Nature

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[185] Whitehead, *The Function of Reason*, 4.
[186] Whitehead, *Process and Reality*, 100.
[187] Whitehead's approach to evolutionary selection can thus be fruitfully compared with James Mark Baldwin's theory of "Organic Selection." See Adam C. Scarfe, "James Mark Baldwin with Alfred North Whitehead on Organic Selectivity: The 'Novel' Factor in Evolution" in *Cosmos and History: The Journal of Natural and Social Philosophy*, Vol. 5, No. 2 (2009).
[188] Whitehead, *Process and Reality*, 102.
[189] Whitehead, *The Function of Reason*, 8.
[190] Whitehead, *Science and the Modern World*, 109-110. See also Pross, "Toward a general theory of evolution: Extending Darwinian theory to inanimate matter" in *Journal of Systems Chemistry*, Vol. 2, No. 1 (2011): "Within the biological world there is no doubting that a definite process of complexification over the extended evolutionary time frame has taken place… [T]hat evolutionary drive toward greater complexity cannot be denied" (3).

Grasping Whitehead's panexperientialist proposal requires the wholesale reformulation of classical conceptions of space, time, matter, and mind. The entrenched nature of these abstractions makes it difficult to follow the Whiteheadian proposal, as opponents are apt to import old meanings into Whitehead's novel phraseology. This subsection thus introduces and defines some of the key concepts of Whitehead's process-relational ontology in the hopes of avoiding misunderstanding.

In *Process and Reality*, Whitehead describes two species of process, *macrocosmic transition* and *microcosmic concrescence*, and articulates distinct methods for addressing each. These processes are the systole and diastole of cosmic creativity, the metaphysical heartbeat driving emergent evolution from bosons to bacteria to Bach. The macrocosmic process consists in "the transition from attained actuality to actuality in attainment," thus effecting the shift from the actualized past to the real potentiality of an unactualized future. The microcosmic process converts mere potentiality into actual attainment, generating novel experiential value from the materials of the perished past. The macrocosmic process of transition operates as an efficient cause providing the environmental conditions constraining what can be attained in the future, while the microcosmic process of concrescence expresses a final cause by means of which aims can be achieved in the present: "The present is the immediacy of teleological process whereby reality becomes actual."[191]

The process of concrescence is ontologically primary, as it constitutes the concreteness of each present moment as it arises and perishes to contribute itself to cosmic evolution. Its phases of growth can be examined using the method of "genetic analysis," which in his Harvard lectures Whitehead also refers to as the "functional point of view" that is essential to higher order sciences like biology and psychology.[192] This mode of analysis looks at what transpires within each concrescing actual occasion of experience, abstractly dividing occasions into their component "prehensions" (i.e., either physical feelings of perished occasions in their environing past or conceptual feelings of as yet unactualized possibilities), while never forgetting that "the whole function is one fact," with parts and whole in undivided relationship.[193] Genetic analysis provides a "view from within," an *endocosmic* account of the production of novel togetherness in each bud or drop of experience. Whitehead's re-imagined account of subject-object relations helps convey the concept of concrescence:

> "The word object means an entity which is a potentiality for being a component in feeling; and the word subject means the entity constituted by the process of feeling, and including this process. The feeler is the unity emergent from its own feelings; and feelings are the details of the process intermediary between this unity and its many data."[194]

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[191] Whitehead, *Process and Reality*, 214-215.
[192] Whitehead, *The Harvard Lectures of Alfred North Whitehead, 1925-1927: General Metaphysical Problems of Science* (2021), 77.
[193] Whitehead, *The Harvard Lectures of Alfred North Whitehead, 1925-1927: General Metaphysical Problems of Science* (2021), 77.
[194] Whitehead, *Process and Reality*, 88.

The other method aimed at the examination of macrocosmic process Whitehead calls "coordinate" or "morphological" analysis, which seeks the metrical relations among entities of the already actualized external world. This latter mode of analysis focuses on extensive relations in spacetime, the "geometrical strains" binding our bodies together into the prehensive unity of the surrounding universe. This method of analysis tempts science to adopt a mechanistic framework in that it foregrounds objectively measurable motion while backgrounding the subjectively motivating feelings and functional aims responsible for driving the evolutionary expansiveness of the world-process. Coordinate analysis of the morphology of extension is another way of describing what natural science is doing in all its measurements and modeling of mechanical parts, which are always measurements of *what has already become.* In contrast, the functional, genetic mode of analysis re-contextualizes the objective beings of the past by involving them in the eternally recurrent process of concrescence: perished objective beings are prehensively unified into novel subjective becomings. Though it is often modeled as such by physicists, the cosmos is not simply a collection of inert simply located particles: it is a community of creative participants hurdling themselves beyond the settled past. The universe expands like an embryo grows, as though through cellular division[195], with each concrescent experiential occasion inheriting from its predecessors (=efficient cause) and contributing the novelty it achieves to the process of evolutionary selection (=final cause). In this sense, "the concept of function demands a fusion of efficient and final causes."[196] In all its sophisticated modeling, science must remain cognizant of both finished facts *and* concrescent actualizations of novel facts. No scientific scheme can ever possess the complete set of facts for the simple reason that Nature itself is perpetually perishing, "an incompletion in process of production" that is forever passing beyond itself, caught in creative advance.[197] The incompleteness of Nature must be understood to supervene upon morphological extensiveness.[198] Both genetic/functional and coordinate/morphological modes of analysis contribute to the pursuit of a cosmological scheme adequate for explaining the emergence of life, but Whitehead privileges the former, insisting that "you cannot express a world whose most concrete aspect is function in [merely] morphological terms."[199]

Whitehead uses the phrase "intensity of satisfaction" to describe the subjective aims and feelings constitutive of each process of concrescence, with the relative intensity dependent upon the ordered complexity provided by the environing society from out of which the concrescence arises.[200] Concrescence is the creative process whereby "the many become one

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[195] See Van Dijk, J. B. J., "Process Physics: Toward an Organismic, Neo-Whiteheadian Physics" in Davis, Andrew M., Teixeira, Maria-Teresa, and Schwartz, Wm. Andrew (eds), *Process Cosmology: New Integrations in Science and Philosophy* (Palgrave: 2022), 44-45.

[196] Whitehead, The Harvard *Lectures of Alfred North Whitehead, 1925-1927: General Metaphysical Problems of Science* (2021), 56.

[197] Whitehead, *Process and Reality*, 215.

[198] Whitehead, *Lectures of Alfred North Whitehead, 1925-1927: General Metaphysical Problems of Science* (2021), 301.

[199] Whitehead, *The Harvard Lectures of Alfred North Whitehead, 1925-1927: General Metaphysical Problems of Science* (2021), 77.

[200] Whitehead, *Process and Reality*, 100.

and are increased by one,"[201] or the process whereby the perished past is remembered and transitions into to the future with renewed evaluation accruing. The concrescent growth of such complex societies "exemplifies the general purpose pervading nature."[202] The past can pass into the future *only through the concrete duration of the present*: experience is always a function of what William James called the "specious present," which is not a solipsistically frozen instant cut off from its origins and destiny, but the living tension between an inherited past and an anticipated future. For Whitehead, our perception of metrical space and material bodies arises in an abstract present. He calls it "presentational immediacy." It is Descartes' *res extensa*, granting us clear and distinct perspectival perception through the eyes and other sense organs of the colored surfaces and other relevant features of our immediate surroundings. Though clear and distinct, the sense perceptions afforded by this mode are also prone to error. Time perception, on the other hand, is a function of what Whitehead calls "causal efficacy," which is the feeling of efficient-to-final causal transition from one occasion of experience to the next. We experience causal efficacy in the functioning of our living bodies, not so much via what we see *through* the eyes or hear *through* the ears, but in the blink of the eyes due to a bright flash, or the wince of the ears due to a loud noise, phenomena which clue us into the fact that these organs are themselves immersed within the causal nexus of the universe and not simply neutral windows through which a disembodied mind gazes at a separate reality. Causal efficacy grants us vague but insistent feelings of energetic vectors and physical purposes inherited from the enveloping environment. Concrete experience is a complex hybrid of the two modes of perception, including elements of presentational immediacy and causal efficacy: we distinguish them only for the purposes of intellectual analysis. The two modes are related not through deductive logic or deterministic causality but through analogy and symbolic imagination.[203] Forgetting this epistemic situation leads to the fallacy of misplaced concreteness.

In Whitehead's cosmological scheme, scientific objects abstracted from the "coordinate" or "morphological" domain are mathematizable and Turing-simulable. They belong to what Eastman calls the Boolean domain of geometric extension that can be measured and modeled in bits, rendered exhaustively in binary code as 1's and 0's or yes/no/and/or logical gates.[204] In the "genetic" or "functional" realm of concrescence, in contrast, the classical logical rules of non-contradiction and the excluded middle do not yet apply. The experiential satisfaction of concrescence cannot be measured or digitally modeled, since the prehensions composing it co-exist in organic harmony on their way to final satisfaction as a novel unit of emergent value contributing itself to universe evolution. Concrescence is the process of realization allowing past actualities to grow together and be brought into contrast with "pre-space *potentiae*"[205] hovering in a "poised realm"[206] between quantum coherence and classicality. It is the process

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[201] Whitehead, *Process and Reality*, 21.
[202] Whitehead, *Process and Reality*, 100.
[203] See Whitehead, *Process and Reality*, 121ff.
[204] See Eastman, *Untying the Gordian Knot* (2020).
[205] Eastman, *Untying the Gordian Knot*, 46-47.
[206] Vattay G, Kauffman S, Niiranen S. "Quantum Biology on the Edge of Quantum Chaos" in *PLOS ONE*, Vol. 9. No. 3 (2014): e89017.

whereby the given past environment constrains pure potentiality so as to find a probable pathway to the achievement of final satisfaction in a novel occasion of experience. Before a concrescence is completed, an occasion can be said to be composed of data including many prehensions of its past, some initially in conflict with one another. The process of concrescence integrates contradictory feelings into complex contrasts, sometimes (in more evolutionarily advanced organisms) drawing upon prehensions of novel possibilities not found in its past, transforming clashes into some modicum of aesthetic harmony. These conflicts in the initial data are why the principle of non-contradiction cannot be applied in the genetic analysis of concrescence, since a definite actuality has not yet been achieved. Only once a concrescing subject has achieved its aesthetic aim and perished into objectivity can standard logic and measurements in spacetime be applied.

While abiotic physics may appear reducible to symmetrical dyadic relations of mechanical cause and effect, this is true only of isolated ideal *models* of the physical world. In the real world, dyadic input-output relations inevitably involve *context* and are thus asymmetrical triadic relations in the sense articulated by Eastman.[207] In Whitehead's terms, each concrescent pulse in the vibratory reiteration characterizing the life-history of an electron or other primate organism alters the environmental situation from out of which it emerged. Each novel concrescence inherits and integrates the feelings of the past which it finds before adding itself, a new pulse of emotion and unit of value, to this past: "The many become one, and are increased by one." "It is unnecessary to labor the point," Whitehead says, "that in broad outline certain general states of nature recur, and that our very natures have adapted themselves to such repetitions." Because of Nature's tendency to conform to such repetitive habits, statistical "laws" can be formulated with a good deal of precision, particularly for describing the behavior of the prebiotic world. "But there is a complimentary fact," Whitehead continues, "which is equally true and equally obvious: nothing ever really recurs in exact detail."[208] It follows that even the simplest of physical vibrations contributes itself to the irreversibly cumulative character of evolutionary time and thus to the creative advance of Nature.[209]

The intensity of satisfaction of a concrescent actual occasion of experience—its *feelings* and *aims*—cannot be spread out on a coordinate grid to be measured because neither are part of extended spacetime. The realm of intensity or of prehensive feeling is not in extended space and time and has no mass or momentum; rather, measurable spacetime relations are a secondary expression of or emergence from enduring networks (or "societies," in Whitehead's terms) of occasional feelings. Spacetime and other physical fields shaping our cosmic epoch are thus emergent out of the collective decisions of primate organisms, a result of what these experiential occasions have found satisfying, rather than pre-existent containers of some kind to which organisms are passively subjected and forced to conform. The extent of conformity to a measurable and predictable spacetime manifold is a function of the stubborn habits accumulated by past environments inherited in the present. The cosmic habits forming the

[207] See Eastman, *Untying the Gordian Knot*, 27, 49.
[208] Whitehead, *Science and the Modern World*, 5.
[209] Whitehead, *Process and Realty*, 237.

spacetime manifold, the electromagnetic and gravitational societies, etc., set the base notes for further evolution, leaving open the possibility that in the distant future our universe will continue expanding into more dimensions than what at present are detected.

Thus, the very gravitational gradient of spacetime and the energetic dynamics of light are functions of feeling, of *enjoyment*, such that the measurable shapes that the cosmos takes in the extensive domain must be understood to be precipitated products achieved by concrescent activities always *inwardly* underway and so never appearing in the measurable domain. In Whitehead's words: "the creature is extensive, but…its act of becoming is not extensive."[210] The concrescent activity of experiential realization does not appear outwardly because it is what does the peering. It is the subjective side of the equation governing cosmogenesis. When Whitehead refers to "intensity of satisfaction," what he means to say is that there is an aesthetic achievement whereby the perished objects of the past are brought together under contrast with one another, "prehensively unified." These processes of unification through contrast find exemplification at all scales in Nature, from the vibratory formation of the first atoms to the cycling of pre-living protocells as described in the Hot Spring Hypothesis (see Part 1 and subsection e below). The many objects of the perished past grow together into a new unity, a new whole of some kind, which has an associated experiential vector launching it out of the past, through the present, and into the future. Organismic concrescence is telic, expressing an aim, generating a purposeful unfolding that feels its way toward greater intensity of experience, thus contributing greater organizational complexity to the societies in which it is situated. In thermodynamic terms, we could link these vectors to the many examples of emergent complexity wherein self-organizing systems "fall up" into local minima free energy states.[211] In the case of the Hot Spring Hypothesis, the exploitation of free energy minimization (what Kauffman calls "order for free" emergent throughout the evolutionary process that complements the work of natural selection[212]) is evident in the self-assembly of spherical liposomes and other complex polymers. Such self-assembly and self-organization would be an example of a society of molecules feeling their way to higher-order unities and functions. Talk of affective aims is not meant to conflict with the known laws of thermodynamics or chemistry, but rather is offered as a more generic metaphysical interpretation of increasingly well understood but non-mechanical processes of integrated cell and organismal physiology.[213] The creative advance into what from a mechanistic point of view appear to be more and more improbably complex patterns of activity at every scale of cosmic organization are not unexplained anomalies but expected consequences of Whitehead's organic cosmology. His Philosophy of Organism offers an account of the *why* as a speculative interpretation of the *how*—the latter being a matter of detailed scientific investigation of the efficient causes

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[210] Whitehead, *Process and Reality*, 69.
[211] See Eastman, *Untying the Gordian Knot*, 134. See also Marc Kirschner, John Gerhart, and Tim Mitchison, "Molecular 'Vitalism,'" in *Cell*, Vol. 100 (2000), 79-88.
[212] Stuart Kauffman, *The Origins of Order: Self-Organization and Selection in Evolution* (Oxford University Press, 1993), 30.
[213] See Kirschner et al., "Molecular 'Vitalism,'" in *Cell*, Vol. 100 (2000) for more on the chemical principles at play in biological self-assembly, as well as the limitations of machine analogies in biology: "biological systems, which might seem machine-like, on closer examination operate on very different principles" (79).

operating in the morphological domain. The role of metaphysics here is not to propose new testable hypotheses (scientists hardly need the help of philosophers for this), but to interpret the existing findings of the special sciences in light of more generic categories with the ultimate aim of integrating these findings within a broader cosmological context which includes our role as conscious inquirers.

> "The useful function of philosophy is to promote the most general systematization of civilized thought. There is a constant reaction between specialism and common sense. It is the part of the special sciences to modify common sense. Philosophy is the welding of imagination and common sense into a restraint upon specialists, and also into an enlargement of their imaginations. By providing the generic notions philosophy should make it easier to conceive the infinite variety of specific instances which rest unrealized in the womb of nature."[214]

The search for a scientific account of *how* life emerged takes on an entirely new philosophical tenor once the metaphysical significance of Whitehead's genetic analysis of concrescence is taken on board. Life is then understood as the realization of experiential purposes, a heightening of mental originality present in germ since the beginning of the universe, and not just an improbable rearrangement of pre-determined material parts.

While material bodies thought to be fully present at an instant remain confined to the abstract morphological domain, energetic activity implies a "time-depth" and thus comes closer to the functional descriptions required in biology.[215] Further, energy can, in Whitehead's terms, be translated into the intensive or functional domain as *experience* or *emotion*—not conscious deliberation, imagination, or self-reflective thought of the sort that human beings enjoy—but a more basic form of feeling, a "vector feeling," in Whitehead's terms. At the most primitive level of physical process, these vector feelings are just gravitational gradients, or the inheritance of the vibratory frequency of a helium atom from moment to moment of its life-history, the repetition and enjoyment of the feeling of that particular frequency, that particular mode of togetherness of protons, neutrons, and electrons. What begin as extremely simple and relatively habitual feeling vectors self-amplify as they cycle and grow together in increasingly organized cosmic environments. After billions of years of accreting value-experience through various stages of expansion and contraction, the already self-organizing order achieved by the physiochemical world sheltered the further cycling of molecular products in suitable planetary environments. No miracles or ontological ruptures are required for hot spring cycling of appropriate ingredients to give birth to auto-/sympoietic metabolism and reliable molecular replication. Life springs naturally from cosmic creativity.

Still, it might be asked, How can molecules within not yet quite living protocells be said to realize aims or achieve experiential satisfaction? These subjective qualities are essential

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[214] Whitehead, *Process and Reality*, 17.
[215] Whitehead, *The Harvard Lectures of Alfred North Whitehead, 1925-1927: General Metaphysical Problems of Science* (2021), 76-77.

elements in Whitehead's organic realism, which is why a translation is here being attempted. In the case of molecular societies, the embodiment of experiential satisfaction would be expressed by the harmonic resonance of each molecule's vibratory frequency. In Whitehead's process-relational scheme, particles are no longer to be conceived of as solid substances fully present at an instant and requiring nothing but themselves in order to exist. Instead, their being consists in their becoming, such that the classical notion of inert or "dead" matter is replaced with the notion of a nexus of cycling vibratory patterns. The vibratory resonances among the atoms composing a molecule signifies a primitive feeling of "sympathy," i.e., "feeling the feeling in another and feeling conformally with another."[216] What is the source of enduring order in the universe? Whitehead's wager is that material morphologies originally spring from vibratory resonance, and that evolution selects for more intense aesthetic harmonies. Biological organization dramatically enhances the selection process, allowing extremely complex molecular patterns to emerge which would be highly improbable in abiotic environments.[217] Whitehead elsewhere refers to the sympathetic resonance among molecular components as a form of "experiential togetherness," denying that anything can be said to be "together" without presupposing the experiential meaning.[218] Thus, what appear as wave-lengths and vibrations to spectrometers, for the molecular occasion in question is felt as "pulses of emotion."[219] In conscious human experience, emotion is always "interpreted, integrated, and transformed into higher categories of feeling" far more complex than primitive molecular emotions. "But even so," Whitehead continues, "the emotional appetitive elements in our conscious experience are those which most closely resemble the basic elements of all physical experience."[220]

To sum up, there is a creative lure toward more intense relationship operative at every scale of cosmic evolution, but which becomes richer as physical organization complexifies and new means of sheltering otherwise improbable energetic pathways are found (e.g., cooperative chemical networks and genetic memory, symbolic language, digital information technology, etc.). This tendency is an aim toward order that is driven or goaded by the lure of deeper aesthetic satisfaction. It is the great cosmic "counter-agency" to entropy that Whitehead discusses in *The Function of Reason*. His organic realism is an attempt to give physics *animacy* again, not despite the scientific facts, but because these facts themselves (e.g., the causal continuity between physics, chemistry, and biology) cry aloud for such a metaphysical interpretation.[221] This language is not meant to discount the details of physics in the realm of extension. It's just an attempt at reintegrating the for too long neglected domains of creativity and intensity back into the modern scientific understanding of the universe. Whitehead prioritized the realm of intensity as the concrete reality, with the realm of extension being its secondary expression. But you could not have one without the other, an inside without an

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[216] Whitehead, *Process and Reality*, 162.
[217] See Marshall, S.M., Mathis, C., Carrick, E. *et al.* "Identifying molecules as biosignatures with assembly theory and mass spectrometry" in *Nature Communications*, Vol. 12, No. 3033 (2021). Marshall et al. have devised a means of experimentally identifying biosignatures by measuring molecular complexity using mass spectrometry.
[218] Whitehead, *Process and Reality*, 189.
[219] Whitehead, *Process and Reality*, 163.
[220] Whitehead, *Process and Reality*, 163
[221] Whitehead, *Science and the Modern World*, 110.

outside. Both are required for the cosmic engine of evolution to creatively advance. Whitehead's organic realism is a protest against the sort of scientific materialism that tries to explain away subjective interiority by reduction to collisions of externally related objects. Science cannot rationally explain the shapes taken in space by living organisms without giving intensity its due. Intensity is *Natura naturans* (Nature naturing), and without this creative process springing from intensity of satisfaction, then the finished products of *Natura naturata* (Nature natured or already sprung) would not make any sense.

e. Whiteheadian Resonances in the Hot Spring Hypothesis

Whitehead's speculative method involves utilizing specific notions developed for application to a restricted set of facts for the divination of more generic notions applying to all facts.[222] Following his lead, the environmental rhythms and causal dynamics driving chemical selection at play in the Hot Spring Hypothesis[223] can be interpreted as a special example of Whitehead's more generic account of the production of novelty via the process of concrescence. Following the empirically detailed account of the hot spring progenitor offered in Part 1, this final subsection of Part 2 draws preliminary connections to Whitehead's metaphysical scheme.

One empirical implication of Whitehead's metaphysical speculations is that the search for the origin of life is really the search for an *environment* suitable for the origin of life. Which early Earth environments provide the rhythms required for something like Pross' dynamic kinetic stability and cooperative cross-catalytic networks to emerge? The burgeoning Hot Spring Hypothesis makes plausible the idea that the wet-dry cycling of geyser-fed thermal ponds would have provided an ideal context for chemical replication-variation-selection cycles to catch fire.

In such a dynamic environment, the chemical selection process can get underway even before genetic templating has been invented. Empirical study has shown that the natural rhythms of the hot spring environment could easily shelter the complex chemistry necessary to initiate and sustain the thermodynamic instability, metabolic stability, and experiential intensity characteristic of even the simplest living organisms. Deamer and Damer's research into life's origins is making clear that "the transition [from physics and chemistry] to [biological] life is a continuum,"[224] supporting the process philosophical intuition that there is no ontological gap between physics and biology, nor between matter and mind, thus alleviating the need for the miraculous emergence of something from nothing.

The geological and astrophysical conditions must be just right for an "urable"[225] planet to ripen into life. Various reliable rhythms in the environment can facilitate the emergence of otherwise

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[222] Whitehead, *Process and Reality*, 5.
[223] Bruce Damer and David Deamer, "The Hot Spring Hypothesis for an Origin of Life" in *Astrobiology* Vol. 20, No. 4 (2020), 432.
[224] "A Field Trip to the Archean in Search of Darwin's Warm Little Pond" by Bruce Damer in *Life* (Issue 6, 2016), 6.
[225] "Urability" is a new concept Damer is developing with Deamer to refer to the thermodynamic and chemical conditions necessary for life to emerge on a planet. We are used to thinking of the "habitability" of planets, but

improbable kinetic sinks by sheltering and concentrating organic chemicals from a background of relative chaos. The progenitor environment hypothesis shows how sustained cyclical processes of chemical combinatorial selection can generate the complexity required for cellular emergence.

As Damer and Deamer describe it, continued cycling through drying and rewetting phases drives a series of natural experiments that undergo combinatorial selection through three distinct phases:

1) A multilamellar phase characterized by reduced water activity;
2) A hydrated phase in which encapsulated polymer mixtures bud off into protocell compartments whose stability is then tested in the open water; and
3) An intermediate hydrogel phase in which surviving protocells and concentrated solutes form a moist aggregate before drying and fusing into longer polymer chains.[226]

> "Each drying cycle…cause[s] lipid membranes of the vesicles to open, allowing polymers and nutrients to mix. On rewetting, the lipid membranes … reencapsulate different mixtures of polymers, each mixture representing a kind of natural experiment… [P]rotocells would then survive to pass on [their] polymer sets to the next generation, climbing an evolutionary ladder."[227]

If Damer and Deamer are correct, then it was not a single heroic autopoietic cell, but a heroic sympoietic community that gave birth to life. Damer's progenitor hypothesis describes the formation of networks of polymers at the edges of warm little ponds that would be drying out and refilling, drying out and refilling, with a crucial "gel-like" phase in between where complex cities of lipid sheaths would allow for the first gift economy on Earth to emerge as the protocellular survivors of the wet budding phase return to the community during the gel phase to share their battle tested chemical wares. Along the edges of these ponds, continued dehydration cycles would catalyze the synthesis of longer polymers, including nucleic acids and peptides, forming complex chains and molecular worms that gradually begin to manifest the first biological functions on the planet, and perhaps in the universe. In Whiteheadian terms, each wet-dry cycle initiates another throb of experience making its contribution to the evolutionary advance into novelty.

A fruitful application of Whitehead's metaphysically generic account of concrescence to the production of novelty achieved via the chemical selection of polymer-filled protocells is thus

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"urability" has to do with establishing not just habitability for existing life but the conditions for the origin (ur-) of life. For more on urability, see Part 1.

[226] Bruce Damer and David Deamer, "The Hot Spring Hypothesis for an Origin of Life" in *Astrobiology* Vol. 20, No. 4 (2020), 436-437. See also See "Coupled Phases and Combinatorial Selection in Fluctuating Hydrothermal Pools: A Scenario to Guide Experimental Approaches to the Origin of Cellular Life" by Bruce Damer and David Deamer in *Life* (Issue 5, 2015).

[227] "Life Springs" by Martin J. Van Kranendonk, David W. Deamer, and Tara Djokic in *Scientific American*, August 2017.

possible. Concrescence is Whitehead's description of the iterative, cumulative process whereby novelty emerges over the course of cosmic evolution. Each cycle of concrescence commences as objective beings in the past environment grow together into a new subjective becoming or occasion of experience. The objects of the perished past are felt by the concrescing occasion and brought into harmony with its subjective aim at intensity of satisfaction. Depending on the complexity of the surrounding environment, a given occasion's subjective aim achieves varying grades of experiential intensity. In this way, the formal and final causation operative in concrescence is limited by the environing material providing the efficient causes out of which it arises.[228] Once subjective satisfaction has been achieved, the concrescent entity perishes into a "superjective" phase, thereby adding whatever novelty it has achieved back to the environment for subsequent cycles of concrescence to inherit.[229] Shifting from Whitehead's generic metaphysical account back to the special case of the progenitor scenario, we can see how as a new wet phase commences, each liposome encased protocell that buds off from the layers formed during the dry phase amounts to a chemical experiment, incorporating whatever polymer chains were achieved in the last cycle for further testing. These buds are like Whitehead's "drops of experience, complex and interdependent,"[230] with each cycle of concrescence achieving greater chemical stability and driving the accumulation of further functionality. While Whitehead insists that some degree of "subjective aim" is expressed in these processes, it is important to note that in the case of protocells or even the first biological cells, the experiential purposes in question are far from intellectual or conscious, but merely "lures for feeling" provocative of the synthesis required for emergent novelty to be generated.[231] While *life* is a matter of degree, Whitehead hints that "an organism [can be considered in the usual sense to be] 'alive' when in some measure its reactions are inexplicable by any tradition of pure physical inheritance."[232] In this sense, while the initial emergence of biological organisms was entirely dependent on suitable environmental conditions, "[biological] life is a bid for freedom" achieving a new level of self-creation relative to its physiochemical components.

Damer likes to say that the universe before the emergence of the biosphere—the atomic, astrophysical, galactic environments—gets a "D" for creativity, in the sense that at these scales relatively few stable forms of organization were found, and for billions of years they have been fixed in place and at present find themselves running down or wasting away. No further evolution can transpire. The abiotic cosmos is thus *ergodic*. It wasn't until the biological realm invented template copying and self-repairing complex adaptive and anticipatory cellular organization that the creativity of the cosmos ratcheted up again to find new, more complex energy cycles to flow into. While it may be true that that the universe before biological life emerged gets a "D" in creativity, the important point here is that it is not an "F." It did just *enough* to pass, expressing enough creativity to achieve the atomic and stellar processes necessary for generating the heavier elements that would later become essential for cellular

228 Whitehead, *Process and Reality*, 87.
229 Whitehead, *Process and Reality*, 84.
230 Whitehead, *Process and Reality*, 18.
231 Whitehead, *Process and Reality*, 85.
232 Whitehead, *Process and Reality*, 104.

life. Prebiotic cosmogenesis unfolded at a much slower rate than biological evolution can, with its more potent novelty producing engines, but at least some degree of aim and affective satisfaction was present from the beginning, otherwise atoms, stars, and galaxies could never have formed. These sidereal processes are tremendous organizational achievements in their own right, considering the relative chaos from out of which they came. "Such a change of thought," in Whitehead's terms, "is the shift from materialism to organism, as the basic idea of physical science."[233]

3. Conclusion

As was affirmed in our Introduction, natural science must be granted autonomy to pursue hypotheses concerning the modes of operation of the empirical world independent of the speculative postulates of philosophers and the sacred doctrines of theologians. And yet, in a time of paradigmatic upheaval, if the special sciences are to avoid degenerating into a medley of *ad hoc* hypotheses then they must themselves become philosophical by engaging in a thorough examination of their metaphysical presuppositions.[234] Without a ground-up re-imagination of entrenched materialistic assumptions, progress on questions like the origin of life (not to mention the origin of matter and mind) will remain stunted. Further, amidst an intensifying planetary emergency, philosophy and religion have an essential role to play in the translation of scientific findings into a meaningful and motivating worldview for an increasingly precarious civilization. In large part due to the truly unprecedented scope of our scientific knowledge and the technological power it affords, our species now finds itself on the verge of initiating a major evolutionary transition. The Anthropocene[235] is not the work of a god, but merely that of a conscious animal. Indeed, as we have seen, perhaps humanity's vast endogenous and even vaster technologically augmented information processing capacities are dramatic amplifications of the social networks established by our progenitor ancestors. Whether the present anthropogenic metamorphosis in the Gaian system brings near-term extinction or creative advance for human beings remains to be seen.[236] The coauthors of this paper hope that their transdisciplinary collaboration has contributed some theoretical insight into the origin of life on Earth. As for the destiny of human life on this planet, there remains an urgent practical need to integrate science with philosophy and religion in pursuit of a viable pathway for our species through the great transformation in Earth history that is already underway.

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[233] Whitehead, *Process and Reality*, 309.
[234] Whitehead, *Science and the Modern World*, 18.
[235] See Meera Subramanian, "Humans versus Earth: the quest to define the Anthropocene" in *Nature* 572 (2019), 168-170. https://www.nature.com/articles/d41586-019-02381-2
[236] See Kelly, Sean. *Becoming Gaia: On the Threshold of Planetary Initiation*. (Revelore Press, 2020).

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