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DOI: https://doi.org/10.56315/PSCF3-24McFarland

The Irreducible Novelty of Chemistry in Natural History

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The central metaphor of nature as a watch has colored the debate about natural theology since Paley and Darwin. However, a chemical interpretation of natural history will differ because chemical systems do not work like watches. Here, a natural history of chemical constraints proposed by R.J.P. Williams is interpreted through Joseph Earley's two modes of "chemical becoming" with classical realism and the philosophy of emergence. This interpretation shifts attention from a system's irreducible complexity to its irreducible novelty, focusing on its novel existence and its transcendental truth, goodness, and beauty. A view of natural history in which irreducible novelty evolves through chemistry has several advantages: it accommodates continuous change (giving direction to a gradual mechanism of evolution) and irreversible change (providing an important yet limited role for chance rather than denying its existence or overemphasizing its power). A chemical perspective perceives the inherent "makeability" and manifest order of the universe.

Keywords: natural history, natural theology, science and faith, emergent evolution, biochemistry, antecedent order, chance

Questioning the Watchmaker

Darwin described his intellectual journey with a sort of conversion narrative. Once, Darwin was delighted by William Paley's argument that nature was complex like a watch, and therefore, nature required a maker as does a watch. But in his autobiography, Darwin wrote,

> The old argument of design in nature, as given by Paley, which formerly seemed to me so conclusive, fails, now that the law of natural selection has been discovered. We can no longer argue that, for instance, the beautiful hinge of a bivalve shell must have been made by an intelligent being, like the hinge of a door by man.[1]

Darwin found a mechanism of variation and natural selection that could make functional biological structures ranging from bivalve shells to complex eyes. Both Darwin and Paley assumed that the universe is like a watch and that God is fundamentally a watchmaker. They disagreed only on whether this God is blind.

Darwin and his followers have imported most of Paley's theological assumptions. According to Michael Hanby:

> Paley's conflation of nature and artifice "sets the agenda" for Darwinian biology, supplying the latter's defining problem, its view of the organism, the concept of creation which it seeks to overcome, and the "God" it refuses to believe in. … Darwin brings Paley's natural theology and his conflation of nature and art to their logical conclusions.[2]

This article was written in response to an invitation essay written for *PSCF* by Stephen Contakes, who has also guided the peer-review evaluation and development.

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Hanby offers an alternative to these nineteenth-century theological analogies of nature as a watch by looking to the classical realism of Augustine and Aquinas, focusing on being and essence rather than mechanism, asking "what is life?" rather than "how did life come to be?" Hanby writes,

> There can only be mechanism because there are first things, *beings*, which are irreducible to mechanism, and no mechanical description of, say, a bird in flight, ever suffices as a complete account of *how* a bird flies.[3]

The mechanism itself may be reduced to its parts and its history, but that does not completely account for the existence of that mechanism, which still displays an emergent, irreducible novelty. The mechanism of natural selection may, or may not, be sufficient to account for the many novelties of life, but when Paley, Darwin, and their followers ask only that question, they neglect others more fundamental: what life is, and what it means.

The theories of intelligent design and "irreducible complexity" argue that known evolutionary mechanisms are insufficient to account for the most complex biological structures, such as the flagella, or periods of evolutionary change, such as the Cambrian explosion.[4] These arguments tend to focus on the most complex phenomena, which inherently require complex mechanisms and detailed arguments, so that the dialogue becomes a sort of "numbers game" with dueling probabilities and parameters, an exercise in which the novelty and purpose of the change itself is decentered.[5]

We can reframe the dialogue by asking instead, "What is irreducible about these new things?" which can include their complexity, but also other aspects. To use Paley's metaphor, if we ask only how the watch was made, we neglect the question of what the watch is for in the first place, or what it is doing in a grassy field. If nature is more than an intricate watch, then God is more than a distant watchmaker.

Theologies from before the invention of the watch, communicating ancient and medieval views of God, can refresh our twenty-first-century understanding of creation. In many of these older views, God is not seen as a hands-on artisan who makes the world like a watch. According to theologian Katherine Sonderegger:

> The act of creation is in truth not like an artist who realizes her concept or plan in a painting, emerging in dazzling color from bare canvas and board. Though Christians are surely right to speak of Personal Agency in the doctrine of creation, we are warned against assimilating such Agency to the artistry and design of creatures. Scripture's silence on this analogy is eloquent … its preoccupation in the opening chapters of Genesis is goodness, moral reality, not material objects as such.[6]

In ancient and classical creation theology, novelty is a more fundamental category than complexity. In scripture, God's creativity is literally a "new creation" (2 Cor. 5:17; Gal. 6:15) or presented in conjunction with the idea of things beginning, when all was new (Mark 10:6; 13:19). Colossians 1:15–20 is a psalm of praise to the irreducible novelty of the incarnation and resurrection of Jesus, firstborn of creation. History culminates in God creating a new heaven and a new earth in continuity and discontinuity with the old (Isa. 65:17; Rev. 21:1). God is not creating all things complex, but has created things as *good* and is creating all things *new* (Rev. 21:5). When Genesis 1 repeatedly calls creation "good," the text is asking us many questions, not first and foremost "how did God make this?" but rather, "what does God mean when he calls all this 'good'?" As Jesus said, "No one is good but God" (Mark 10:18), so we look to God's unchanging nature to define goodness. Classical theologies discussed these matters in terms of transcendentals such as truth, beauty, and goodness, in which created things can participate.

At the end of an essay about the relationship of science to the theology of creation, Hanby defines "irreducible novelty" in terms of these transcendentals, not in terms of complexity:

> Creation, in other words, is the condition of possibility for anything being genuinely *new*, and this irreducible novelty is visible in, and indeed is, the irreducible goodness, beauty, and truth of every concrete act of existence. This power of making new, as Paul says in Romans, is already visible in and as the world, had we only the eyes to see and the ears to hear it, and yet since we cannot help but see and hear it, we are "without excuse."[7]

In this definition, irreducible novelty is a theological gift to be received with wonder, not a quantitative measure or gap in understanding. What is irreducible is the unique way in which the created system participates in goodness, beauty, and truth.

The metaphor of nature as a watch has limited our discussion of creation to mere complexity and bracketed out its goodness and beauty. As a chemist who makes proteins (not watches), I nevertheless see in nature many chemicals bright and beautiful, which are irreducibly novel even if reducibly complex. In *A World from Dust: How the Periodic Table Shaped Life,* I described how chemicals in natural history have dissolved, mixed, melted, and precipitated throughout the narrative of evolution.[8] Here I give a theological interpretation to that story by identifying its moments of irreducible novelty, looking at creation not as a watch in a field of grass but as chemical structures and systems, on a planet in a field of stars.[9]

Chemical Perspectives on Emergence and Irreducible Novelty

In *A System of Logic,* one of the first texts defining emergence of novelty,[10] John Stuart Mill described emergent behavior as coming from chemistry, not watch-like mechanics. He explains that, in chemistry, two substances combine to make a third

> with properties entirely different … Unlike mechanics, chemistry is not a deductive but an *experimental science* … Once the new property has emerged, however, it presents itself as an entirely independent value, even though it has been discovered to be the complex result of the combination of simpler parts.[11]

Mill's new properties exhibit irreducible novelty despite their reducible complexity.

Later, the philosopher Chauncey Wright, a friend of both Darwin and Charles S. Peirce, "was able to transfer the idea of emergent novelty from the static conceptual framework of associationism to the much more dynamic Darwinian evolutionary thought."[12] Both Wright and Peirce were pragmatist philosophers who emphasized thinking about novel effects ("last things, fruits, consequences, facts" in William James's words) rather than the origins of those effects.

Wright discussed the biological emergence of the novel effects of flight and consciousness. Of these, the emergence of flight is more obviously related to chemical causation. The gradual variation and selection of limb structures resulting in a wing is like the variation and selection of biochemical structures within the wing. Once a wing evolves, the new flying creature can inhabit an expanded space, allowing greater chances for survival. Evolution of novel chemical structures and reactions likewise allows the organism to survive in more places and under more conditions.

The pragmatists' emphasis on future effects requires teleological, goal-driven "final causation" that is not obviously compatible with the undirected, "efficient causation" of Darwinian natural selection. Peirce addressed this conflict by proposing that "final causes are basically habits … not static 'entities,'"[13] and according to Menno Hulswit, they complement efficient causes "inasmuch as each act of causation has both an efficient and a teleological component."[14] Each act of causation incorporates "an aspect of irreducible novelty, which coincides with objective chance" and which is also irreversible. Emergence of new forms of self-organization, including new chemical structures, reactions, and processes in natural history, "may be seen as a teleological or quasi-teleological concept in the Peircean sense."[15]

Some prominent chemists agree: "Irreversible processes are the source of order"[16] in nature, according to Ilya Prigogine, who won the 1977 Nobel Prize in Chemistry, writing with Isabelle Stengers. They give examples such as the physical-chemical "transition from laminar flow to turbulence [which] is a process of self-organization,"[17] clock reactions, and a biochemical "catalytic loop."[18] Order emerges from chance, as when "a random fluctuation in the external flux, often termed 'noise,' far from being a nuisance, produces new types of behavior … [including] more complex reaction schemes."[19] Prigogine and Stengers approvingly cite Peirce's statement that "Force is in the long run dissipative; chance is in the long run concentrative"[20] as a source of novel chemical forms of self-organization.

Self-organization is also a major theme of Jacob Klapwijk's philosophical definition of emergent evolution across "five ontological or explanatory levels: the physical, the chemical, the biotic, the mental, and the social level."[21] Klapwijk relates the earlier of these levels to the later:

> Then we may discover in the baffling world of minerals and microbes, of plants and animals,

> a pathway of meaning: a development that may be considered meaningful because it is not devoid of ends and purposes and appears to be a precursor to the human search for meaning."[22]

The chemist John Satherley applies Klapwijk's definition of emergent evolution especially at the first two of the five levels of natural history. Satherley describes the inner structural layers of the earth, the unusual boiling point of water, and the self-organizing lipid bilayers as

> *vital* ingredients that make this planet a *habitat* for living creatures … The evolution of the inanimate things of the universe must be considered alongside of, and integrally connected with, any type of biological evolutionary hypothesis.[23]

If something like Klapwijk's "pathway of meaning" can be discovered in geochemical and biochemical structures and processes, this path implies a common goal and therefore a unity.[24] This chemical perspective on natural history breaks down dualisms and unites concepts. Peirce insisted on continuity of all things over dualism, so that "all phenomena are of one character … present[ing] that mixture of freedom and constraint, which allows them to be, nay, makes them to be teleological, or purposive."[25] Rather than extending purposelessness "upward" from the physical and chemical levels to the biotic, mental, and social levels, we can interpret the world in such a way that we perceive purposefulness "downward" when we find the natural laws, habits, and tendencies toward particular ends at the so-called "lower" levels. Our unity with nature can elevate its purpose, rather than reducing our purpose.

We can also extend our search for transcendentals downwards, asking the question "how does this new physical, chemical, or biological thing manifest and participate in the true, beautiful, and good?" rather than merely "how could this complexity have come about?"[26] A focus on irreducible novelty unites efficient, formal, and final cause; chance and constraint; chemistry, physics, and biology; and even natural being and becoming.[27]

There is no necessary conflict between appreciating something's irreducible novelty and reducing its complexity into understandable steps of development or evolution. A created thing can be caused by other, secondary, agents, but all of them remain created by God as the primary Agent. Understanding the components or causes of a novel object or system, or the mechanism that created novelty, in no way diminishes its irreducible novelty. However it came about, the genuinely new thing still makes the world better, truer, and more beautiful, even after its path into the world is traced. The human task is to experience, understand, and describe it, and the chemist's task is to do all this at the elemental and molecular level.

R. J. P. Williams and the Recognition of Chemotypes

Both Paley and Darwin began with a moment of recognition at the level of the organism, with Darwin especially focusing his thought on the evolution of species, which are groups of organisms. Eventually this led to a problem: how exactly should a species be defined? For Thomas Pfau, this "species problem" comes from assumptions made prior to scientific investigation, involving how to perceive the "form" of the species:

> Darwin had struggled to articulate what exactly he meant by "species," since at every step of his far-flung empirical research the reality of species appeared to have been already presupposed. … [S]cientific cognition [remains] haunted by the ontological commitments associated above all with classical Aristotelian-Thomist realism and its origins in Plato's doctrine of ideas.[28]

Recognizing a species or "kind" of animal is not as simple as recognizing a watch in a field, yet it is essential to understanding how species transmute. Irreducible novelty, with its emphasis on the Platonic transcendentals of the true, beautiful, and good, grounds the scientific act of classification by supposing that the mind's ability to recognize the form of the species and its fitness to its environment (which is part of the goodness of creation) reflects truth, not accidents.[29]

Hanby argues that recognition of form played an implicit but unacknowledged role in Richard Dawkins's characterization of genes as "survival machines" driving evolution. When Dawkins states that a "DNA molecule could theoretically live on in the *form* of copies of itself for a hundred million years," he "performs the covert work of granting to DNA an 'essence,' denied to organisms themselves, transcending its particular material instances."[30] By vitalizing the "form" of replicating DNA, Dawkins endorses a kind of formal causation, which Peirce says also imports final causation and goal-directed behavior.

A focus on classical realism and transcendentals, rather than on complexity, accounts for Darwin's and Dawkins's moments of recognition. These ancient and medieval traditions say we can recognize species and genes because

> If we reflect on our grasp of any being, we perceive *that* we grasp it, and so each being is true (*verum*), intelligible, capable of being cognitively grasped. We also grasp that it is good (*bonum*), valuable or worthwhile, capable of being desired or loved, at least at an end for acts of knowing. At this point, we reach the experience of divine beauty.[31]

Robert Joseph Paton Williams was a renowned chemist who classified living organisms by chemistry, rather than by biological homology.[32] His "chemotypes" are groups of species based on chemical processes of their cells, which he defined as "controlled energized chemistry essentially in physically confined and organized flow systems."[33]

In *The Chemistry of Evolution,* Williams and João José Rodiles Fraústo da Silva state,

> The complexity of flow systems does not allow us to treat each and every observed case, species, individually, but we can describe in general terms the classes of species, "chemotypes," and their evolution which, as we shall explain, are systematic, causative, and not random in their relationships.[34]

In particular, three "thermodynamic characteristics of chemotypes … have evolved systematically and inevitably following the equally inevitable changes of the environment."[35] These chemical definitions give Williams a different view of evolution:

> Evolution may be blind in its diversification of similar organisms (species) but it expands within a directed time cone of physical and chemical opportunity in an ecosystem, increasing and improving the retention and use of elements and energy.[36]

The adverbs "systematically" and "inevitably" are not often found in descriptions of Darwinian evolution but come directly from Williams's chemical perspective and classification of species into chemotypes.

Williams himself speaks without reference to transcendence, but others interpret his work in this light. Notably, Alister McGrath cites Williams's work as a narrative that "resonates with the core themes of the Christian vision of reality"[37] in *The Open Secret: A New Vision for Natural Theology,* of which part of the renewal is "discerning the transcendent in nature"[38] in terms of "abduction to the best explanation" (McGrath quoting Peirce's common phrase).[39] McGrath could cite Williams as an example of "natural theology's capacity to make sense of things"[40] because Williams did not argue for irreducible complexity, but rather gave examples of a good and even beautiful chemistry sequence leading to complex life, which McGrath could interpret in the transcendental framework of irreducible novelty.

At a crucial point in *The Chemistry of Evolution,* Williams and Fraústo da Silva followed a Peircean path of abductive reasoning by juxtaposing the shapes (forms) of two graphs and linking levels together. In this book, figure 4.3 (p. 135) shows the concentrations of the free metallome and the caption states, "Note how closely the sequence follows the inverse of the Irving-Williams binding constant sequence," which is shown in figure 2.8 (p. 67). Formal recognition of the similarities between the two graphs led the authors to state, "Note how we have linked biochemical and geochemical features together."[41] In addition, they made accurate predictions: the chemical sequence predicted by Williams and Fraústo da Silva was later supported by genetic analysis.[42] This led the authors to propose that both biological and geological evolution followed a chemical sequence "systematically and inevitably"; their proposal is a statement of final causation and goal-directed behavior. More than efficient cause is at play here!

Joseph Earley's Two Modes of Chemical Becoming

What exactly is novelty to a chemist? Joseph E. Earley, a philosopher of chemistry, described two distinct ways in which new things come to be in chemistry, in an essay titled "Modes of Chemical Becoming."[43] Earley's examples of the generation of new chemical structures and systems can be considered "irreducible" in their goodness, truth, and beauty, and therefore in their novelty.

First Earley described how scientists determined the structure of a molecule of argon dichloride. This molecule does not form naturally, but small quantities can be made fleetingly in a laboratory, with a lifetime around 10^{-12} s. Scientists observed the spectrum predicted by theory for a molecule of argon dichloride in a particular shape. Earley writes, "Not only can we say that a new chemical entity has come into existence, but we can also tell what the shape of that entity is!"[44]

Earley's exclamation point shows his excitement at this new thing. The argon and chlorine existed before, but the arrangement of the components is novel. (This is similar to Mill's associative conception of novelty.) This molecule has a particular shape and lifetime. If it relates to other molecules in useful ways, we can say it has gained a particular function. Even if it does not, it still truly exists. As for whether it is beautiful and good, Earley thinks it is. Irreducible novelty can be thought of as the exclamation point we put on our observations of the surprising new things we observe.[45]

Earley's second example is that of a new, dynamic chemical system. In a continuously stirred tank reactor, chemicals are put in and out at different rates, often producing chaotic readings on the sensors that monitor the reactions. Sometimes the rates of input and output can be changed carefully to simplify the chaotic readings into a simple oscillation. (This is similar to Wright's evolutionary conception of novelty.) This gradual simplification produces a well-defined and stable system that cannot be ascribed to any single component. Out of chaos, from a location that cannot be precisely predicted in advance, comes predictable recurrence, distributed throughout the system. Earley wrote,

> The networks of chemical changes that give rise to this kind of organization can be regarded as composed of several parts—several sets of processes, each of which partially controls the others. When these diverse parts of a reaction-network achieve a kind of balance, harmonious oscillation results, and the system *as a whole* serves as a center of agency.[46]

In Klapwijk's terms, an intelligible, dynamic form would self-organize and affect other levels of existence, including the mental perception of the system's observers.[47]

These novel coherent centers of agency have complexity that can be reduced to components and understood using the rules and laws of chemistry. However, the precise atomic location and moment of self-organization is driven by chance, so it is irreducible in Prigogine's and Peirce's terminology. When the molecule or system is broken or decomposed, so is its present elegance, harmony, and agency, and its irreducible novelty is lost.

The Antecedent Order of Natural History

Earley's definitions of "chemical becoming" can be expanded to chemistry in other contexts. We are people in the act of becoming, alive in a universe that is itself in the act of becoming. When new things occur in nature as part of this becoming, brought about by atoms reacting, they can be understood through the discipline of chemistry. The arc of natural history can be told as a story of chemical becoming, composed of a sequence of chemical reactions from the Big Bang to the present day.

In another essay, Earley argued that chemistry should itself be taught with this narrative arc, which he called (somewhat grandly) the "Evolutionary Epic":

> Logically, perhaps one should start with the vacuum—an excitable medium. New classes of entities—quarks, atoms, molecules, stars, organisms, societies—could then be introduced as arising in evolutionary (historical, in Collingwood's sense) transitions from prior entities.[48]

All true elements of the triumvirate of irreducible novelty are found in Earley's argument for this "new philosophical basis" of teaching chemistry: certainly the story contains *truth*, and he also states that it is "*good* preparation for professional work" and motivates students with the "*beauties* of nature."[49]

But the classical realist tradition would add that Earley's scientific story, however epic, is insufficient in itself, because it is founded on a pre-existent order, or *Logos.* Hanby writes:

> Nature is more than simply whatever happens and is irreducible to a dynamic historical process, however "creative." It will have to apprehend and articulate an "all-at-once" unity and completeness in things that precedes their

> temporal development and the realization of historical possibilities and thus an antecedent order, that is true and good prior to our activity upon it, a givenness that precedes our activity as its condition of possibility. All this, in turn, will require the rediscovery of a truth that is irreducible to function, that is more than mere possibility, a truth that is not of our own making though we may be its midwife.[50]

This "antecedent order" is summed up for chemists by the periodic table of the elements, which represents the limits and laws of our discipline. Universal physical laws led to a universal periodic table of relationships among the elements that hold true for the stars, for the earth's core, for evolution, for natural history, and for our human flesh.

Hanby suggests that scientists should assess the beauty of nature as a gift to be appreciated, not a puzzle to solve. He wrote, "Were biologists to approach their subjects as one approaches a painting, it would no doubt transform the very meaning of science, restoring it to *theoria* in the traditional sense."[51] Chemists can approach natural subjects as one approaches a painting as well.

The beauty of nature revealed by chemistry includes the order of the periodic table's rows and columns. All matter on this planet has been ordered into fewer than one hundred natural elements at the atomic level, themselves ordered by the chemical patterns captured by the periodic table of the elements. As those atoms reacted over billions of years, more-reactive chemicals reacted before less-reactive chemicals, and more-stable compounds persisted longer than less-stable compounds. Chemistry allows us to understand why natural geochemical or biochemical events happened in a certain order, and it can place those events in the context of the central symbol of chemistry: the periodic table.[52]

Irreducible Novelty in *A World from Dust*

The editor of a group of essays responding to Klapwijk's *Purpose in the Living World?* wrote, "Why should the task of critically immersing oneself in evolutionary thought and thinking it through, step by step, not be received as a divinely mandated creaturely task with its own integrity *coram Deo*?"[53] Under this same mandate, we can think through Williams's view of the chemical constraints of natural history, step by step, in terms of Earley's two modes of becoming, looking for the moments of irreducible novelty.[54]

In 2016, I wrote an overview of natural history based on Williams's chemical sequence, titled *A World from Dust: How the Periodic Table Shaped Life*.[55] A theology of creation is implicit in this book, as it is in every natural history, although I translated theological into philosophical terms for a general audience, as is customary for popular science books. Here I attempt to bring new things out from the old, by revealing the original theology that motivated the writing of the book and delineating the events where something irreducibly novel came about, step by step. The major events in this chemical narrative of natural history are acts of order, goodness, and beauty, which made genuinely new systems or structures, each demonstrating irreducible novelty even in the presence of reducible complexity.

1. Stellar Nucleogenesis

In the beginning, the periodic table was (mostly) void.[56] The Big Bang, the premier event of irreducible novelty, was an event of physics rather than chemistry. The initial expansion of the universe produced hydrogen and helium, with only traces of heavier elements. The force of gravity gathered hydrogen and helium into stars so massive that atoms in the center were crushed together. This overcame atomic repulsion so that nuclei joined and fused into new elements. This process drove forward to bigger nuclei with larger atomic numbers, which are more stable (with iron the most stable). Even today, more than ten billion years later, the lighter elements predominate in the universe, and the heavier an element is, in general, the harder it is to find.[57] The new, heavier elements provided new structures and reactions, like carbon's four bonds, oxygen's powerful electronegativity, and metals' unusually shaped electronic orbitals, all of which can serve as recognizable chemical forms and centers of agency. The existence of each new element allowed new chemical movements of electrons and new structural forms of molecules, so that each is irreducibly novel. These new atomic structures are like Earley's example of the new structure of argon dichloride, applied at the atomic, rather than at the molecular, level.

2. From Atoms to Molecules and Liquids

As heavier elements formed, they were spread across the universe by supernovae; then some were collected again into objects smaller and more dense than stars: planets.[58] This was the birth of geology. One consequence of electronic energy levels established by the periodic table's trends was that metals lost electrons while non-metals gained them. Bonds formed, allowing the binary combination of metals with abundant oxygen, and then with less-abundant sulfur; then more complex chemical combinations followed. Solid rocks formed from these, rocks that included much of the oxygen available due to its potential to form strong bonds. Meanwhile, oxygen and hydrogen formed water that, with its combination of small atoms and strong hydrogen bonds, formed a liquid phase.[59] Most places in the universe were either too cold or too hot for large liquid oceans to form, but the earth was located in the right place on the phase diagram of pressure versus temperature, close to water's triple point.[60] The liquid phase and water cycle provided by oceans is essential to chemistry because it allows molecules to move while in constant contact, facilitating the formation of complex assemblies more easily than could occur in solid or gas (or plasma) phases. It is no accident that the continuously stirred tank reactor in Earley's second example is in the liquid phase. A liquid phase allowed irreducibly novel systems, similar to Earley's reactor, to form in nature.

3. Mineral Evolution

At some point, life began to multiply and evolve. But the first kind of "evolution" facilitated by the liquid phases on and inside young Earth may have been mineral. After planetary accretion 4.5 billion years ago, mere hundreds of different minerals existed on the earth—today there are more than four thousand.[61] Robert Hazen and colleagues list ten stages of mineral evolution, including igneous rock formation, granite formation, and plate tectonics driven by the liquid phase of the earth's mantle allowing minerals to mix, flow, and (in their term) evolve. This is evolution in a chemical, rather than a biological, sense of the word. The authors wrote,

> Mineral evolution is not analogous to biological evolution through Darwinian natural selection … Minimization of Gibbs free energy simply leads to nucleation and growth of quartz, but not olivine. The driving force for mineral evolution, rather, is the evolving diversity of prebiotic and biologically mediated temperature-pressure-composition environments.[62]

The generation of mineral diversity is another example of irreducible novelty. Most of these new minerals contain novel crystalline structures that may be unique to our planet, each with new chemical properties, perhaps even serving as templates for the origin of life.[63] Each new mineral serves as an example of irreducible novelty, extending to the new colors of gems hidden in the depths to be revealed to human miners billions of years later.

4. From Solubility to Three Biochemical Roles

Chemical cycles of dissolution and precipitation connected the crust to the ocean. Both dissolving and precipitating are chemical actions described by chemical equilibrium constants and kinetic rate constants, themselves set by the strength of bonds and stabilities of chemicals in the solid phase versus dissolved in water, themselves rooted in the trends of the periodic table. These chemical solubilities affect biology and determine the biochemical roles each chemical can adopt:[64]

1. Concentrations below nanomolar (gold, tin, and lead) = not abundant enough to be used;
2. Concentrations below micromolar (manganese, iron, and zinc) = trace amounts for biochemical catalysis;
3. Concentrations below millimolar (carbon, nitrogen, and oxygen) = build novel covalent structures;[65] and
4. Concentrations above millimolar (sodium, potassium, and chloride ions) = adjust osmotic and electrochemical ionic balance.

In each of these categories, life selected some elements with the proper solubility but, for chemical reasons, not others: for example, the lighter element may have been selected because it was more abundant. Williams wrote extensively about these biogeochemical rules and selections, making predictions of the chemical sequence over time from classifications such as these four chemical categories.[66] Williams predicted that redox-sensitive ions would change categories according to their redox potentials as the earth oxidized over billions of years, and later we observed these trends in new genomic analyses around the turn of the century.[67] Each of the three active biochemical roles (catalysis/metabolism, structure, and ionic balance) can be considered an instance of irreducible novelty, in which each element fulfills a new role for life in a particular way specific to that element's chemistry.

The novel structures made by life from carbon, nitrogen, oxygen, etc., are similar to Earley's novel argon dichloride structure, while the novel dynamic processes of dynamic catalysis, metabolism, and ionic balance are similar to Earley's dynamic flow reactor example. The dynamic stability of the flow reactor is similar to biological homeostasis. Both the novel structures and the novel systems work together to produce the living organism, or they are produced by the living organism in its process of living. Each new chemotype is an example of irreducible novelty.[68]

5. Photosynthesis

Another category of novelty came about when life harnessed light for making and maintaining chemical structures and systems. Like mineral evolution, biological evolution can also make colored molecules that interact with the visible wavelengths of light from the sun, absorbing solar energy from far beyond the earth. This energy would often dissipate, heating the environment, but over time, life directed some of that energy productively, moving electrons to form new bonds in photosynthesis. At first, sunlight helped move less-stable, more-mobile electrons from iron ions and hydrogen sulfide, but a combination of manganese and calcium in a rock-like crystalline structure eventually cracked the toughest molecule open, prying electrons off stable, but abundant, water molecules.[69] Thus sunlight was made into new bonds among carbon atoms, building up sugars that the living microbe stored until their energy was needed. The chemical reaction of water-oxidizing photosynthesis produced a byproduct that at first was more dangerous than useful: diatomic O_2, which is oxygen gas. But as photosynthetic organisms multiplied, this gas would cover the world and lead to new things never seen before on this planet. The sugars, as fuel for rapidly reproducing life, were the firstfruits of the irreducible novelty of photosynthesis, but in a billion years or so, the oxygen that was rejected became the cornerstone of animal life.

6. The First Great Oxidation Event and the Ordered Sequence of Prehistorical Metals

The chemical composition of the atmosphere changed as life carried out photosynthesis and produced oxygen. Oxygen in the atmospheric gas phase increased and came into contact with the liquid ocean and solid land, reacting with the entire surface of the planet. A bit more than two billion years ago, this atmospheric change created new banded-iron formations in oceans across the globe as iron (II) oxidized to iron (III) and immediately precipitated due to iron (III)'s low solubility.[70] This new solid material was just the most obvious consequence of the shifting of the planetary redox potential toward increased oxidation. A more oxidized atmosphere shifts redox-sensitive metals to a higher oxidation state, making some metal ions more soluble and some less, and therefore shifting the metals that could fulfill the biochemical roles of metabolism and catalysis. Binding sites for metals such as nickel and cobalt were removed from genomes, while those for metals such as molybdenum and copper appeared more.[71] Metabolisms shifted from using reduced molecules such as hydrogen sulfide and ammonia to sulfate and nitrate. Combined, these trends mean that biochemistry itself developed new reactions, new structures, and new biological species (or, better yet, Williams's new "chemotypes"), each an example of irreducible novelty that can be traced back to the chemical properties of oxygen.

7. The Second Great Oxidation Event and the Cambrian Explosion

The most important chemical novelty happened later, when enough oxygen accumulated in the atmosphere that it could be reliably used as a reactant rather than a product for biochemical re-actions.[72] Oxygen levels rose as geological processes such as glaciation eroded the planet's surface, leaving behind a global geological gap called the "Great Unconformity." Chemically, the eroded rocks dissolved in the oceans, increasing calcium, molybdenum, and phosphate levels, all of which are important ingredients for life.[73] In fact, calcium and phosphorus are two of the three dual-role elements (in terms of the four roles listed in section 4),[74] which can support multiple kinds of novel reactions at once.

Then, around 600 million years ago, new life forms appeared relatively suddenly in the fossil record, in an event called the "Cambrian explosion." The dramatic numbers and forms of these Cambrian fossils have sparked debate about whether this event is irreducibly complex.[75] Yet the "Great Unconformity" shows that geology was changing dramatically before the Cambrian explosion, which would have provided crucial chemicals used by life. In addition, the rate of speciation is estimated to be about 5–10 times faster than normal—a significant increase that is still continuous with typical, if accelerated, mechanisms of evolutionary chance.[76] If chemistry did cause the Cambrian explosion, irreducible novelty is supported and enhanced for those who find a beauty in chemistry and in the connections it can make across disciplines. If chemistry's role was less important, then the irreducible novelty would be attributed to the other source.

8. The Ordered Sequence of Historical Metals

The order provided by chemistry extended to human history, because the sequence in which metals could be mined from the earth and used by civilizations was ordered by the chemical parameter of redox potential. Gold has a high, positive redox potential, meaning that it accepts electrons readily and can be easily reduced to a neutral state, so it is commonly found in the neutral, metallic state in the earth. Silver and copper also have high positive redox potentials, meaning they could be mined and used for coinage by early humans. The other metals known to the ancients (mercury, lead, and tin) likewise have positive or near-neutral redox potentials, but nickel, cobalt, chromium, zinc, and aluminum have more negative potentials, meaning they bind oxygen and other elements more tightly (i.e., are oxidized) so are not found naturally in the metallic state.[77] For these metals, civilizations must discover more powerful chemical methods such as electrochemistry to reduce the metals to a neutral state. We spend huge amounts of energy to do this to make aluminum's irreducible novelty.

Once the irreducible novelty of chromium in the form of chromate was unlocked by chemistry, it was combined with lead in a laboratory to make a bright yellow, insoluble pigment named chrome yellow. The beautiful brightness of chrome yellow is an irreducibly novel color. It was a favorite of nineteenth-century artists such as Vincent van Gogh, and it allowed him to create his paintings of sunflowers, which are themselves artistic examples of irreducible novelty. Even if we can analyze Van Gogh's chrome yellow and determine which laboratory it came from and exactly how it was made, it remains a unique and beautiful part of creation, no less irreducibly novel for our understanding of its mechanism of origin.[78] In fact, our participation in its mechanism of origin and increased understanding of it may allow us to appreciate its beauty and novelty that much more.

Implications for Meaning, "Makeability," and Chance

The visual motif of *A World from Dust* is an arrow. Arrows are predominant in most of the figures referenced in this article, and time or redox potential (which increased with time) is commonly on the x-axis of graphs. In these figures, chemistry ordered the arrows, but the arrows point beyond chemistry.

Klapwijk wrote, "The deepest mystery of evolution is not the emergence of new realities; it is time."[79] A watch tells time, but its mechanism is solid and cyclical: a watch never grows or evolves. A chemical system that unfolds over time, and a geobiochemical system that evolves, is integrated more deeply with time. The irreversible changes of increasing entropy cannot be turned back, as Prigogine noted, so that the physical world experiences directional change, like the mental world of experience rather than the cyclical, mechanical change of a watch.

The question is whether these arrows of becoming, both within and without, are truly aligned with each other, and whether together they point toward something specific, which would be some final cause such as Peirce posited. C. Stephen Evans makes a case that sequences of becoming, which can include Williams's chemical sequence, are signs pointing to God's activity as Creator: "God has instituted the signs so as to make it possible for people to become aware of his reality. And there is a 'hard-wired' natural tendency to 'read' the sign in this way, to see it as pointing to God."[80] Yet these signs can always be discounted or denied. Irreducible novelty is not irresistible.

If there is more than efficient cause, then thinking about formal and final causes reveals the truth about the world. As David Bentley Hart wrote, "[Goal-directed behavior] is an intrinsic rational determination in a complex system, not … intrinsically imposed by some detached designing intelligence."[81] If so, truth is integral to the system and these arrows point to

> an ultimate reality where existence and perfect intelligibility are convertible with one another because both subsist in a single unrestricted act of spiritual intelligence. This, in theological terms, is one of the paths of the mind's journey into God.[82]

Hart, Pfau, Peirce, McGrath, Hanby, and others, coming from their own philosophical perspectives, align and point to the conclusion that the mind, through the sciences, reveals truth because God made it to do so. The scientific goal-directed behavior and emergence described by Williams, Earley, and Prigogine seem to me to point in the same direction. These irreducible novelties are truly good and beautiful.

If chemistry brought these about in nature, then we can repeat and isolate those chemical reactions in the laboratory for our own purposes, using them to make new things for our own purposes: knowing through making.[83] When our artificial laboratories and workshops first copied, then expanded, the chemical structures and systems that could be made, we produced irreducible novelty. The novel chrome yellow pigment led to Van Gogh's novel *Sunflowers*. Even an artist as great as Van Gogh depended on others and on nature itself, so that his creative achievement was an act of co-creation within the larger gift of Creation.

Learning about these overlapping and integrated processes demonstrates the "makeability" of knowledge itself. The act of retracing the events, chemical and otherwise, that led to the creation of *Sunflowers* is itself an act of comprehending irreducible novelty. Unlike irreducible complexity, one can trace this path without reducing the novelty of Van Gogh's creation.

A chemist's work is as important as that of a watchmaker, and both types of makers operate underneath the transcendent act of original and ongoing creation that is from God alone. Klapwijk wrote, "To create out of nothing is one thing. To cause something to originate out of existing material is another."[84] But these acts of subcreation, within their limits, can clearly be good, beautiful, and truly novel. Hanby wrote, "The advent of meaning in the world and the realization of these various possibilities are surely *ex nihilo* events; they mark the appearance of genuine novelties, irreducible to their antecedents."[85]

Theologian John Milbank writes that this "makeability" of the universe is so important that it can be elevated to the status of a new transcendental![86] One need not go that far to emphasize it as important, and to correlate it with acts within the discipline of chemistry could also align with Milbank's transcendental "makeability." Given chemistry's emphasis on synthesizing and making new structures, "makeability" seems particularly apt.

A chemist who makes a new tool for separating phases or molecules is like Nicholas of Cusa's toolmaking spoonmaker, whom Milbank cites in his writing on the theological significance of making and therefore of "makeability." Nicholas of Cusa wrote that the spoon is formed and named by the spoonmaker, and yet is a reflection of divine creativity, because "all human arts are 'images' of the Infinite Divine Art."[87] But the spoonmaker insists he is no mere mimic: "So my artistry involves the perfecting, rather than the imitating, of created visible forms, and in this respect it is more similar to the Infinite Art."[88]

According to Milbank, Nicholas "regards 'makeability' as the criterion for theoretical understanding, thereby reversing, as we also saw, the inherited assumption that the only criterion for the possibility of making something was previously to have understood it with theoretical adequacy."[89] This combinatorial, empirical approach is common in chemistry, and is also an effective way to teach, as when students in a multi-institutional effort mix chemicals, each student trying a different combination, to test for catalytic efficiency in the "Solar Army" effort.[90] These chemists do not know how effective their combination of chemicals will be until they run the experiment; they know by making.

In the book *Making Good,* Trevor Hart seeks "to reckon with the nature of God's creative action vis-à-vis the world … in his capacity as 'Maker of the heavens and earth.'"[91] Hart describes "God's determination 'to create creators'"[92] using the analogy of the artist as creator, showing that artistry at both the divine and human levels leads to "the establishment of a world in which God and the creature dwell together 'at one' in peace and mutual enjoyment."[93] In Hart's account, creative acts in the past reveal that God is near: "Faith in God as Creator also discerns God's dynamic presence in history's midst, 'opening it up for the possible and the new in unexpected and unforeseeable ways.'"[94]

As every chemist knows, making new molecules or systems is difficult, and experiments are not always (or often) successful.[95] Chance may favor the prepared mind, but it is always at work in the lab. Any view of nature that emphasizes "makeability" must also accommodate a significant role for chance events. The chemical perspective has been shown to do this, in Prigogine's and Peirce's emphasis on irreversible events (which are driven by chance) being a source of irreducible novelty. In this, they align with medieval thinkers like Boethius and Dante, and recent thinkers published in this journal,[96] who also found a place for chance or fortune in their philosophies. This is in contrast to proponents of irreducible complexity, who insist that nature happened "Not by Chance."[97]

Williams, speaking from the perspective of chemistry, incorporates chance mutations as causative agents in his chemical sequence to explain how destructive chemicals can produce a sequence of responses from an organism: first protective, then opportunistic:

> The suggested principle to explain "directed" evolution is then that mutation is not random over the whole genome but that its intensity is related to the harmful effect of a new environmental energy source or any new damaging substance. Several such substances were released in turn in time due to the oxygen increase in the atmosphere and so new chemotypes of organisms evolved in a sequence as new groups of genotypes were better able to handle the damaging environment.[98]

Klapwijk also finds a place for chance in his view of emergent evolution:

> Random events have unchained orderings that are anything but random. Contingency catalyzes functionality and purpose; it has elicited, again and again, higher and more complex levels of meaning. Thus believing people have good reason to say that God called the physical nature into being and that He, at the same time, incorporated all higher levels of ordering into His creation as potentials from the beginning. Thus they are also justified in saying that humans are, at the same time, a product of evolution and created according to God's image.[99]

If irreducible novelty has a place for meaning, for making, and for chance, it also has a place for us. Klapwijk remarks on the way nature seems to have anticipated life:

> Can we say: Evolution takes advantage of emergence? No matter how incomprehensible this may be, it appears at times—I express myself carefully—that the process of becoming on Earth, despite its capricious and unpredictable course, did indeed anticipate the biological forms that were forth-coming.[100]

The Periodic Table of the Elements was an antecedent, rational structure imprinted in the laws of nature at the beginning of time, and it provided every *thing* life needed (with emphasis on the word "thing"). It established chemical rules and trends that unfolded through an interplay of necessity and chance. Most of these unfolding events were continuous with what went before and can be understood by analogy to things we can make ourselves, but we are far from understanding it all.

All events do not occur by clockwork necessity, but neither do all occur by unformed and unguided chance. I understand the events creating chemotypes as emphasizing predictable necessity, while, on the other hand, those creating species as emphasizing unpredictable chance. However we understand this interplay, we can copy these events and make new things with this confidence: God made us, from the world, to understand and participate in the world through our disciplinary foci, including through chemistry.

Notes

[1]Quoted in George Johnson, "Raw Data: A Creationist's Influence on Darwin," *New York Times*, May 23, 2014, https://www.nytimes.com/2014/05/23/science/a-creationists-influence-on-darwin.html.

[2]Michael Hanby, *No God, No Science: Theology, Cosmology, Biology* (Hoboken, NJ: Wiley-Blackwell, 2013), 188.

[3]Ibid., 204.

[4]My specific responses to intelligent design arguments can be found in Benjamin J. McFarland, "Mixed Metaphors: Intelligent Design and Michael Polanyi in *From Darwin to Eden*," *Perspectives on Science and Christian Faith* 73, no. 4 (2021): 228–32, https://www.asa3.org/ASA/PSCF/2021/PSCF12-21McFarland.pdf.

[5]An example of this is the dialogue between Michael Behe and Kenneth R. Miller regarding the blood clotting cascade and the bacterial flagellum. Both authors wrote chapters in *Debating Design: From Darwin to DNA*, ed. William A. Dembski and Michael Ruse (Cambridge, UK: Cambridge University Press, 2004).

Michael Hanby wrote that the questions of intelligent design when debated do not resolve because they become focused on minutiae: "Accounting for novelty, then, becomes, quite literally, a matter of accounting, not of explaining what makes a thing or its states genuinely and irreducibly *new*" (Hanby, *No God, No Science,* 221).
Irreducible novelty represents a response to the incomprehensible diversity of creation that is more than arguments about accounting and probabilities.

[6]Katherine Sonderegger, *Systematic Theology: The Doctrine of God, Volume 1* (Minneapolis, MN: Fortress Press, 2015), 369. Exceptions may include times when God is described as a potter, but even then, the clay being molded tends to be metaphorical rather than material, resulting in the creation of something spiritual or social, rather than a natural object in the universe.

[7]Michael Hanby, "Saving the Appearances: Creation's Gift to the Sciences," *Pro Ecclesia* 22, no. 1 (2013): 29–54, https://doi.org/10.1177/106385121302200102.

[8]Benjamin J. McFarland, *A World from Dust: How the Periodic Table Shaped Life* (Oxford, UK: Oxford University Press, 2016).

[9]Asking "how did God act through chemistry?" may be no less limited of a perspective than asking "how did God act like a watchmaker?" Regardless, it is a novel perspective that God might accommodate and illuminate like the others.

[10]Elly Vintiadis, "Emergence," in *Internet Encyclopedia of Philosophy* (2012), https://iep.utm.edu/emergence/.

[11]Andrea Parravicini, "Pragmatism and Emergentism. In Chauncey Wright's Evolutionary Philosophy," *European Journal of Pragmatism and American Philosophy* 11, no. XI-2 (2019), https://doi.org/10.4000/ejpap.1623.

[12]Ibid.

[13]Charles S. Peirce, quoted in Menno Hulswit, "Teleology," in *The Commens Encyclopedia: The Digital Encyclopedia of Peirce Studies. New Edition*, ed. Mats Bergman and João Queiroz (2014): 120320-1519a, http://www.commens.org/encyclopedia/article/hulswit-menno-teleology.

[14]Ibid.

[15]Ibid.

[16]Ilya Prigogine and Isabelle Stengers, *Order Out of Chaos: Man's New Dialogue with Nature* (New York: Bantam Books, 1984), xxi.

[17]Ibid., 141–42.

[18]Ibid., 145.

[19]Ibid., 166.

[20]Ibid., 302.

[21]Jacob Klapwijk, *Purpose in the Living World? Creation and Emergent Evolution* (Cambridge, UK: Cambridge University Press, 2008), 99. For example, "Idionomy and self-organization thus understood are two sides of the same coin. They are an unmistakable indication of emergence" (p. 121).

[22]Ibid., 6. Elsewhere Klapwijk defines the bonding of oxygen and hydrogen to make water as non-supervenient because "they can be explained by the structural traits of the underlying atoms. The supervenient properties of emergent life forms, on the contrary, are characteristics that cannot be completely explained from the structural properties of more elementary constellations and that are, therefore, to be recognized as non-reductive in nature" (p. 120). Klapwijk's distinction is difficult to maintain (what about viruses or lipid bilayers?), and in my opinion, unnecessary. If we define irreducibility in terms of goodness, truth, and beauty, then the emergent structure of the H_2O molecule with the advantages described by Satherley can be considered an example of irreducible novelty, even though the molecule can be reduced to atoms. Even the water molecule is not "completely explained" to us by its structure, and it may never be.

[23]John Satherley, "Emergence in the Inorganic World," *Philosophia Reformata* 76, no. 1 (2011): 47, https://doi.org/10.1163/22116117-90000501.

[24]Robert Spaemann remarked that an "authentic teleology" is "an emerging property, non-reducible to its conditions of origin," distinguished as a "fundamental 'tending-towards,' as tendency and fulfilling." Robert Spaemann, "The Unrelinquishability of Teleology," in *Contemporary Perspectives on Natural Law*, ed. Ana Marta González (Abingdon, UK: Routledge, 2016) 281–96. Spaemann connects physical-chemical tendencies with the "unity of the person over time [that] presupposes that being, existing, has a vectorial meaning," stating "There is only teleology in human action because and insofar as there is a direction in natural tendency" (p. 293).

[25]Hulswit, "Teleology," quoting Peirce, CP 7.570 (1892). I take Peirce's application of his synechism (anti-dualism) to apply to all "things" literally; since God is not a "thing," Peirce's reasoning may not apply to all areas of theology.

[26]The latter question should be seen as a subset of the former.

[27]Prigogine and Stengers, *Order Out of Chaos,* 256: "We are now entering a new era in the history of time, an era in which both being and becoming can be incorporated into a single noncontradictory vision." This scientific unity refers to the lack of a natural distinction, and it is different from Klapwijk's distinction between creation and becoming, in that Klapwijk's is a theological distinction consistent with classical realism. Prigogine's lack of distinction is valid for nature and objects, while Klapwijk's is valid for God and nature.

[28]Thomas Pfau, *Incomprehensible Certainty: Metaphysics and Hermeneutics of the Image* (South Bend, IN: University of Notre Dame Press, 2022), 511. Later, Pfau continues this thought:

> For where (scientific) knowledge should eventuate, the event of seeing must have already taken place; and what allows a phenomenon to stand out against a background of visual miscellany and sheer "noise" of disjointed optical data is its very reality and specificity, that is, its conspicuously textured and distinctive *form* (p. 520).

[29]Other thoughts on the theology of naming and classification can be found in Beth Stovell and Matthew Morris, "Taxonomic Theology: An Interdisciplinary Approach to a Biblical and Biological Theology of Naming," *Perspectives on Science and Christian Faith* 74, no. 4 (2022): 194–211, https://www.asa3.org/ASA/PSCF/2022/PSCF12-22Stovell.pdf.

[30]Hanby, *No God, No Science*, 222, first sentence quoting Richard Dawkins, *The Selfish Gene* (Oxford, UK: Oxford University Press, 1976), 35.

[31]Mark K. Spencer, "Classical Theism, Divine Beauty, and the Doctrine of the Trinity," chapter 15 of *Classical Theism: New Essays on the Metaphysics of God*, ed. Jonathan Fuqua and Robert C. Koons (New York: Routledge, 2023), 288.

[32]Andrew J. Thomson, "The Science of RJP Williams," *Journal of Biological Inorganic Chemistry* 21, no. 1 (2016): 1–3, https://doi.org/10.1007/s00775-015-1328-5.

[33]Robert Joseph Paton Williams and João José Rodiles Fraústo da Silva, *The Chemistry of Evolution: The Develop-*

ment of Our Ecosystem (Amsterdam, The Netherlands: Elsevier, 2005), 127. The authors define chemotypes as "broad groups of organisms that have major distinctive chemical, energetic, spatial or organizational features" (p. 443).

[34]Ibid., 119–20.

[35]Ibid., 442.

[36]Ibid., 442.

[37]Alister E. McGrath, *The Open Secret: A New Vision for Natural Theology* (Hoboken, NJ: John Wiley & Sons, 2011), 243. Williams is cited on p. 242.

[38]Ibid., 73.

[39]Ibid., 244.

[40]Ibid.

[41]Williams and Fraústo da Silva, *The Chemistry of Evolution*, 134–35.

[42]McFarland, *A World from Dust,* 170–73.

[43]Joseph E. Earley, "Modes of Chemical Becoming," *Hyle* 4, no. 2 (1998): 105–15, https://hyle.org/journal/issues/4/earley.pdf.

[44]Ibid., 108.

[45]In one sense, an exclamation point does not change the content of the sentence, but in another sense, it changes everything. We relate to the novelty with gratitude for its creation, and our understanding of the world is made new.

[46]Earley, "Modes of Chemical Becoming," 111.

[47]If the structural novelty of argon dichloride is elegant, the systemic novelty of a continuously stirred tank reactor is musical, "harmonious" like an instrument in tune. Both of these cases of irreducible novelty are not only beautiful, but they may also be functional and could be "good" for something; as Earley wrote, "Since both of these cases generate coherences that are centers of agency, they should be considered to produce new chemical entities."

[48]Joseph E. Earley, "Would Introductory Chemistry Courses Work Better with a New Philosophical Basis?," *Foundations of Chemistry* 6, no. 2 (2004): 137–60, https://doi.org/10.1023/B:FOCH.0000034992.42777.95.

[49]Ibid., 139.

[50]Michael Hanby, "Questioning the Science and Religion Question," in *After Science and Religion: Fresh Perspectives from Philosophy and Theology*, ed. Peter Harrison and John Milbank (Cambridge, UK: Cambridge University Press, 2022), 170.

[51]Hanby, "Saving the Appearances," 42.

[52]The periodic table is not only an exemplar of order: in most chemists' opinion, it is beautiful as well, although that may be in the eye of the beholder. Order and beauty have often been associated in theology and philosophy. For example, John Haught described Alfred North Whitehead's definition of beauty as "the 'harmony of contrasts' or the 'ordering of novelty' … Beauty arouses our appreciation by turning what would otherwise be contradictions or clashes into aesthetic patterns that preserve both nuance and coherence." (John Haught, "What Is the Purpose of Existence?," *Engelsberg Ideas*, August 11, 2020, https://engelsbergideas.com/essays/what-is-the-purpose-of-existence/.) So, if the story of natural history is told as an ordered sequence of chemical reactions producing new things, then that telling will emphasize its beauty, and therefore its irreducible novelty.

[53]Bruce C. Wearne, "Jacob Klapwijk's Invitation: Come to the Party!," with Introduction by Guest Editor," *Philosophia Reformata* 76, no. 1 (2011): 1–10, https://doi.org/10.1163/22116117-90000499.

[54]Klapwijk wrote that in cases of emergence, "a scientific explanation is excluded" (*Purpose in the Living World?,* 94), which seems to contradict my assertion that irreducible novelty can be scientifically reducible; however, throughout the book, Klapwijk accommodates scientific explanation (i.e., efficient causation) with other levels of causation and with theological meaning, so that the truth, goodness, and beauty of an organism do not compete with its natural history. Throughout the book, Klapwijk depends on the recognition of these different levels through formal reasoning, while referring to efficient explanations for the separation or definition of the levels. For example, on p. 96, plants are recognized as a novel form of life in the same way as Williams's chemotypes, using the language of "nested bowls" which echoes Williams's cone illustration on the cover of *The Chemistry of Evolution*; on p. 105, Klapwijk states that "we *recognize* that there are various kinds of reality" [emphasis mine]; on p. 104, he wrote that "continuity and discontinuity are intertwined" and therefore compatible; and on p. 136, he specifically argues against irreducible complexity in terms appropriate to irreducible novelty.

[55]McFarland, *A World from Dust.* I identified as a Christian in the introductory Author's Note, although the book was written for an audience without a theological background.

[56]Ibid., 46–50.

[57]Ibid., figure 3.3, 47.

[58]Ibid., 60–61.

[59]For more on the special properties of water for life, see Ruth M. Lynden-Bell et al., eds., *Water and Life: The Unique Properties of H_2O* (Boca Raton, FL: CRC Press, 2010).

[60]McFarland, *A World from Dust,* figure 4.4, 75.

[61]Robert M. Hazen et al., "Mineral Evolution," *American Mineralogist* 93, no. 11-12 (2008): 1693–720, https://doi.org/10.2138/am.2008.2955.

[62]Ibid., 1712.

[63]The origin of life is not included in this article, although it is addressed in *A World from Dust,* chapter 5, as "hints." This event may be continuous with geochemistry if a proper mineral template interacts with dissolved solutes, or it may have been a discontinuous, emergent miracle as Klapwijk allows for. Either way, the life produced is irreducibly novel. Helpful discussion of this topic can be found in the "Rethinking Abiogenesis" series published in this journal: see Emily Boring, J. B. Stump, and Stephen Freeland, "Rethinking Abiogenesis: Part 1, Continuity of Life through Time," *Perspectives on Science and Christian Faith* 72, no. 1 (2020): 25–35, https://www.asa3.org/ASA/PSCF/2020/PSCF3-20BoringStumpFreeland.pdf; and Sy Garte, "Continuity, Simplification, and Paradigm Shifting in Biological Evolution," *Perspectives on Science and Christian Faith* 74, no. 3 (2022): 149–55, https://www.asa3.org/ASA/PSCF/2022/PSCF9-22Garte.pdf.

[64]McFarland, *A World from Dust,* figure 4.5, 84.

[65]Phosphate, with a solubility between millimolar and micromolar, adopts both metabolic and limited structural roles.

[66]For an overview, see Robert Joseph Paton Williams, "The Bakerian Lecture, 1981. Natural Selection of the Chemical Elements," *Proceedings of the Royal Society of London. Series B. Biological Sciences* 213, no. 1193 (1981): 361–97.

[67]McFarland, *A World from Dust,* 32 and 129–31.

[68]Several types of cells, ordered by their redox potentials like the chemical sequence, can be seen in ibid., figure 6.3, 125.

[69]Ibid., figure 7.2, 152. Much of this power is located in the element: magnesium-containing materials can catalyze photosynthetic-adjacent reactions in inorganic laboratory environments.

[70]Ibid., figure 8.1, 161.

[71]Ibid., figure 4.5, 84 and figure 8.4, 172.

[72]One interesting puzzle is that oxygen levels were very high for brief periods before and during the first great oxidation event, so oxygen is not the only factor, but other factors such as genetic complexity and multicellularity/specialization must be present in life to take advantage of oxygen's chemical power.

[73]McFarland, *A World from Dust,* 186–89.

[74]Calcium can both build and balance, while phosphate can both build and participate in metabolism/catalysis. The third dual-role element is sulfur.

[75]McFarland, *A World from Dust,* chap. 9, especially 184–90, addresses these claims in more detail, as well as in McFarland, "Mixed Metaphors."

[76]McFarland, *A World from Dust,* 185.

[77]Ibid., figure 11.2, 251. There are exceptions to the historical trend of decreasing redox potentials in the mining of metals—iron is a notable one—but as an overarching explanation, it serves well to put the historical events in good order. The irreducible novelty of gold was accessible without chemical methods, but the irreducible novelty of aluminum requires chemical methods to access. The novelty of the properties produced by these metals is still "irreducible" even if metals themselves must literally be "reduced" by the addition of electrons to be experienced by human senses.

[78]For example, see Muriel Geldof, Inez Dorothé van der Werf, and Ralph Haswell, "The Examination of Van Gogh's Chrome Yellow Pigments in 'Field with Irises near Arles' Using Quantitative SEM–WDX," *Heritage Science* 7 (2019): 1–11, https://doi.org/10.1186/s40494-019-0341-3.

[79]Klapwijk, *Purpose in the Living World?,* 209.

[80]C. Stephen Evans, *Natural Signs and Knowledge of God: A New Look at Theistic Arguments* (Oxford, UK: Oxford University Press, 2010), 154.

[81]David Bentley Hart, "Science and Theology: Where the Consonance Really Lies" in *After Science and Religion: Fresh Perspectives from Philosophy and Theology*, ed. Peter Harrison and John Milbank (Cambridge, UK: Cambridge University Press, 2022), 70.

[82]Ibid., 74.

[83]This approach means that chemical experiments in the laboratory are an act of subcreation, while the theological origin of creation itself remains with God. Consistent with Hanby's argument, nature is not an artifact, but we can isolate and make artifacts mimicking nature because of natural integrity and chemical laws.

[84]Klapwijk, *Purpose in the Living World?,* 192. See also Pfau, *Incomprehensible Certainty,* where he states that for Ruskin, truth is "not a correlate of finite 'making' (*facere*) but, instead, manifests an anterior, transcendent 'creating' (*creare*). An intrinsic property of being that can never be secured in propositional form, truth is attainable only qua participation" (p. 527).

[85]Hanby, "Questioning the Science and Religion Question," 168.

[86]Ibid. Hanby writes:

> Milbank proposes to elevate "makeability" to the status of a transcendental. The "poetic" unity of knowing and making then appears as an expression and approximation of, and indeed a participation in, what is most uniquely Christian in the history of ontology: creation *ex nihilo* as the ontological structure of reality, grounded in the self-differentiating unity of the Trinity. (pp. 166–67)

Hanby's "*ex nihilo*" language seems deliberately provocative, but it does underscore both the irreducibility and the novelty of these events from his perspective. Even though these events are precedented, Hanby considers their novelty to be in a sense *ex nihilo*.

[87]Nicholas of Cusa, *Idiota de Mente,* trans. by Jasper Hopkins, in *Nicholas of Cusa on Wisdom and Knowledge* (Minneapolis, MN: Arthur J. Banning Press, 1996), https://www.jasper-hopkins.info/DeMente12-2000.pdf, 59. See also:

> Now, the wood receives a name from the advent of a form, so that when there arises the proportion in which spoonness shines forth, the wood is called by the name 'spoon'; and so, in this way, the name is united to the form. Nevertheless, the imposition of the name is made at will, since another name could have been imposed. (p. 64)

[88]Ibid., 62.

[89]John Milbank, "Religion, Science, and Magic: Rewriting the Agenda," in *After Science and Religion: Fresh Perspectives from Philosophy and Theology*, ed. Peter Harrison and John Milbank (Cambridge, UK: Cambridge University Press, 2022), 158.

[90]Paige N. Anunson et al., "Involving Students in a Collaborative Project to Help Discover Inexpensive, Stable Materials for Solar Photoelectrolysis," *Journal of Chemical Education* 90, no. 10 (2013): 1333–40; Sarah E. Shaner et al., "Discovering Inexpensive, Effective Catalysts for Solar Energy Conversion: An Authentic Research Laboratory Experience," *Journal of Chemical Education* 93, no. 4 (2016): 650–57, https://doi.org/10.1021/acs.jchemed.5b00591.

[91]Trevor Hart, *Making Good: Creation, Creativity, and Artistry* (Waco, TX: Baylor University Press, 2014), 85.

[92]Ibid., 98, quoting H. H. Farmer.

[93]Ibid., 85. Hart later writes that "artistry may usefully serve as a paradigm case for reckoning with that wider set of 'poetic' actions and outputs in which, I shall argue, *Homo faber* is always and everywhere implicated and complicit" (p. 90).

[94]Ibid., 96–97, quoting Ingolf U. Dalferth.

[95]For example, I do not believe the "Solar Army" discovered a significant new catalyst. However, the education of the students, which is the primary point, was certainly accomplished.

[96]Consider how the poetic technique of the book of Job "seems unnervingly to place God in considerable sympathy with the emblems of the chaotic." John R. Schneider, "Recent Genetic Science and Christian Theology on Human Origins: An 'Aesthetic Supralapsarianism,'" *Perspectives on Science and Christian Faith* 62 no. 3(2010): 206, https://www.asa3.org/ASA/PSCF/2010/PSCF9-10Schneider.pdf.

[97]Stephen C. Meyer, "Not by Chance: From Bacterial Propulsion Systems to Human DNA, Evidence of Intelligent Design is Everywhere," *National Post of Canada*, December 1, 2005, https://www.discovery.org/a/3059/.

[98]Williams and Fraústo da Silva, *The Chemistry of Evolution*, 446.

[99]Klapwijk, *Purpose in the Living World?,* 209–10.

[100]Ibid., 214.