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ORDER: GOD'S, MAN'S AND NATURE'S

The Principle of Continuity in Origins of Life Research

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In what follows I will introduce one of the reasoning strategies appealed to in origins of life research, called the principle of continuity (PC). Natural philosophy has a history of invoking nature's continuity – an apparently metaphysical precept that has acquired close ties with nature's lawfulness, intelligibility, and, more recently, with evolutionary thinking. I will provide some definitions and some examples of what scientists think PC is doing in their research. I'll make some suggestions about *why* it's invoked in origins research and offer a couple of case studies about how it is used and what it could possibly mean.

The philosophical questions I am treating include, what *sort* of principle is PC? If it is an a priori claim, is it legitimate, how can theorists responsibly use it, and what exactly are its empirical consequences?

Through this discussion I will be suggesting that even though PC is regularly invoked in the field of origins of life, it lacks the probative power that is attributed to it. While it functions as a commitment of sort to naturalism, its usefulness as a guide to research is very limited indeed. More problematically, however, is its use to restrict hypotheses that may not accord with nature's continuity. Sometimes continuity is invoked to rule out particular empirical hypotheses. Yet the history of biology has provided reasons to be suspicious of that particular use of PC, as it may be employed in a way that unnecessarily circumscribes empirical investigation. History furnishes cases of empirical sciences advancing in the face of purported violations of this principle.

To make a diagnostic claim, it seems that one of the shortcomings in origins of life research is the lack of widely shared heuristic principles used to integrate the diverse findings of the field into a coherent or widely accepted scenario. Diverse findings from a wide swath of sciences must be coherently brought to bear on one another, and there

are, to date, few commonly accepted principles by which to achieve that degree of coordination. A few such methodological strategies have been proposed, and here I'll focus just on one of those, known as the principle of continuity. Continuity is about the rate or type of changes involved in life's origin. PC is one among several heuristic principles, or perhaps constitutive principles, that is utilized in origins research. Other heuristic principles discussed in the literature include the search for *definitions* of life; *top-down* and *bottom-up* approaches to deciphering life's basic physical constituents; a principle of *ubiquity;* and the *signature* principle (Deamer 1994, 9). These will be worth briefly describing.

Many theorists have offered definitions of life or the living state (Maynard Smith 1986, Fleischaker 1994, Luisi 1998, Cleland and Chyba 2002, Ruiz-Mirazo et al. 2004). The definitional approach seeks to generate confidence in one definition of life, and then to use the definition to probe for its satisfaction among possible chemical systems. Contemporary life shares several constituent subsystems in common, including a DNA-based genetic system engaged in replication, transcription, and translation; a metabolism with phosphate-based energy transduction and biosynthetic pathways; and lipid bilayer membranes. Yet many theorists would find it problematic to *define* life based on its current manifestation, especially insofar as they believe life must have been different at some point before current life forms or even the Last Universal Common Ancestor (LUCA).

While a broad array of empirical studies (including those rooted in physics and atmospheric chemistry) may fall under the rubric of origins of life science, much research investigates the specific properties of the first living organisms. Such research can often be categorized as either top-down or bottom-up.[1] Top-down implies that research begins with the simplest extant microbial life and moves "downwards" (invoking the direction on the phylogenetic tree[2]) towards even simpler components or functional units.

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[1] These are not exhaustive categories. Work on the RNA world often begins with the postulated intermediate stages between early chemistry and later life.

[2] I use this complex metaphor only as an explanation of the language involved in the science, and not as an endorsement of its use. Recent studies have suggested that the "tree" metaphor is complicated by phenomena such as lateral gene transfer, and that a massively reticulated phylogenetic "bush" is a better image, contrary to Darwin's suppositions and modern phylogenetic methods. Phylogenetic inference in origins of life is compounded by extremely high error rates of replication, suggesting that there were no well-defined lineage-like relations among early gene-bearing entities (Woese 1998).

This is generally recognized as an insufficient research strategy because even the simplest forms of life that now exist are so much more complex than anything able to be produced in a laboratory from chemical building-blocks. Most researchers recognize the need to compliment top-down with bottom-up research, which involves chemical syntheses that attempt to build up the structural or functional units of life from chemical precursors that may have existed in early Earth environments.

Ubiquity is a principle that favors origin scenarios taking place within common or widespread environmental conditions over highly specialized or rare environments. Miller-Urey style amino acid synthesis can only take place in reducing atmospheres, and once it was realized that those conditions were unlikely to be very widespread on the early Earth (Kasting and Catling 2003, Abelson 1966), a strong commitment to the ubiquity principle would seem to suggest abandoning Miller-Urey approaches to biopolymer synthesis. On the other hand, if those reaction pathways are considered to be the far the most efficient way to produce organic products, some scientists de-emphasize ubiquity and postulate special isolated conditions such as volcanoes, hydrothermal vents, or the presence of oxidation-inhibitors that may have allowed the reactions to proceed (Cleaves et al. 2008).

The signature principle asserts that prebiotic processes should leave a signature – some causal trace -- in contemporary biochemistry. Morowitz considers the signature principle a "general principle" about the origin of life (1992, 154), and for him it is actually a consequence of the principle of continuity. "The signature principle is a powerful heuristic tool because it provides a protocol for going from richly detailed current knowledge to hypotheses about early life" (27). The high degree of biochemical connectivity in, e.g., metabolism, makes it very difficult to change elements of the system once the network is in place. Appreciating such difficulties "makes the study of current-day biochemistry a rich mine of information about pre-biochemistry" (155). Thus, knowledge of contemporary biochemistry is able to *travel* backwards in time: knowledge about the present applies to the past as well. Notions of "leaving a mark" play an important role in origins of life theorizing, where the aim of the science is to decipher the long-past structures and processes. Those past structures and processes may be very difficult to decipher without some specific downstream effects. Philosopher Carol Cleland has argued for a fundamental methodological difference between historical science (such as origins of life) and experimental science that is based on the historical sciences'

need to explain traces of long-past events. “Traces provide evidence for past event just as successful predictions provide evidence for the generalizations examined in the lab” (Cleland 2002, 480). The difficulties in origins of life research such as the Miller-Urey style experiments, she notes, is that:

> the logical relation between the hypothesis actually tested in the lab and the target hypothesis (about the origin of life on Earth) is very convoluted, winding through numerous highly speculative assumptions, ranging from conditions on early Earth to biochemical possibilities for producing amino acids and whole cells. This is fairly typical of experimental work associated with hypotheses about the remote past (2002, 484).

While these various heuristic principles each merit attention, I will train my attention primarily on the principle of continuity.

2.

The idea of a ‘principle of continuity’ enjoys a long history in natural philosophy. Conceptually, continuity implies some kind of unity or plenum; its opposite, discreteness, implies plurality.[3] Leibniz took it to mean (at least) that no physical change happens through a leap, and employed it in his philosophy of physics to argue against atomism. Since collisions between perfectly hard, inelastic atoms would entail that their speeds and directions must change instantaneously (and discontinuously), all bodies must be elastic, and such elasticity entailed, according to Leibniz, having parts that can move with respect to one another (Ariew and Garber 1989, 132-133). So, contrary to the central thesis of atomism, all bodies must have parts.

Famously formulated as *natura non facit saltus* – “nature doesn’t make leaps” – Leibniz was insisting that natural processes were in some respect “unbroken” or “uninterrupted” or “without gaps.” For Leibniz, the principle was not just a way to argue against atomism and Cartesian laws of motion, but a deeply held metaphysical belief used in support of a number of other tenets regarding conservation laws and the intelligibility of nature. It was “a contingent principle of order grounded not in brute necessity, but in divine benevolence” (Mcdonough 2008). God could have made the world differently, but that would not have been the best world.

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[3] Continuity has a related life in mathematics, where it has evolved through increasingly specific uses as infinitesimals and then limits.

This principle's invocation on the topic of origins of life makes sense given the long period of questioning whether the category "life" could really be on a continuum with "non-life." Especially once spontaneous generation had fallen out of favor, it may have been difficult to conceive of life as anything other than a discrete metaphysical category wholly apart from the mechanistic and law-governed world of physics and chemistry. Certainly that was the case for J.S. Haldane, though he was hardly the only one who doubted the satisfactory investigation of biological phenomena through physical and chemical methods. Both he and J.H. Woodger believed that the question of life's emergence from chemical precursors was unintelligible. On the other hand, given that a spirit of Darwinian gradualism was taking root by the 1930s and animating much of biological theorizing, the suggestion that life is on a spectrum with non-life would fit squarely within the trend of accounting for biological change via incremental steps. That this principle of continuity is now posited as a *condition* for scientific investigation into the phenomena of life's initial emergence testifies to the multiple ways it has been conceived and used in the history of science. Once an explicitly theistic principle, it is now utilized as a commitment to naturalism – a kind of stipulation that God isn't interfering with the normal order of things. For Leibniz, continuity was God's way of instantiating natural order; for contemporary scientists, it is simply nature's way.

What follows are some definitions of the principle of continuity as it is used in the contemporary scientific literature on origins of life. While there are some obvious differences that appear in these attempts at definition, my focus will not be on the differences between the explicit formulations. One reason is because scientists have not inherited philosophers' fixation with precise definitions. My sense is that shared terminology is very often a *product* of empirical inquiry that often isn't settled until problems have been pursued to a sufficient extent. I think it is not uncommon for nomenclature to admit some vagueness and imprecision, especially in early stages of inquiry. Yet these definitions each reveal something important about the term's currency in the scientific discourse, so my emphasis will be on how the term gets *used* in scientific practice rather than just how it is spoken of.

A contemporary undergraduate textbook on biology offers the following definition:

> Because life probably evolved from nonlife by a continuous, gradual process, any process in life's evolution that we propose should be derivable from preexisting states. In other words, we should not expect to find sudden major changes (Purves 2001, 451).

Notwithstanding the "in other words," this first definition seems to propose two quite distinct criteria: derivability and gradual change. These criteria may or may not be closely aligned, but in any case the basic idea is: No saltatory transitions in past events or in their reconstruction in present theory. The text expresses confidence in a scientific study of this past event because, by implication, our contemporary scientific "derivations" will mirror the actual events of the past, and insofar as the processes scientists propose in the present will be continuous processes, there were no discontinuities in the past, original events that would break this mirroring.

The principle appears not just in introductory texts but in specialized tracts on origins of life as well. After noting that "the foundations of fact and experiment… are uncomfortably thin in origins-of-life research," Deamer and Fleischaker note that "plausible arguments" must also be relied upon to arrive at an adequate understanding of past biochemical events. The first of their three such plausible arguments is the principle of continuity. They describe PC:

> Those models that most clearly demonstrate a continuous evolutionary pathway leading from proposed origins to extant life forms are considered to be more plausible than models requiring a discontinuity between origins and evolved form (1994, 9).

I call this a description rather than a definition because of its obvious problems circumventing its own terminology, employing its own words in its definition. In any case, the notion arising here is focused more explicitly on contemporary scientific models of life's origin rather than on metaphysical grounds of what must have happened in the past. It is about the preferential status of contemporary theories that are relatively completed models spanning the full explanatory breadth of the origin of life. Rather than one small transition that may have been relevant to the origin story, this definition just says that those models are preferable that could offer the more complete account. While piecemeal bits of the story may be cobbled together, the ideal account is one that accounts for the transitions all the way from origins to extant life forms.

Francis Crick provided the earliest use of the term I am aware of in contemporary molecular biological study. In a 1968 paper on the origin of the genetic code, he invoked the Principle of Continuity to argue against a sequential increase in the size of the reading frame from one base at a time (giving 4 codons) to two bases at a time (giving 16 codons) and then to our present triplet code (with 64 codons). Crick writes that PC makes it unlikely that such sequential development took place because any change in

codon size "necessarily makes nonsense of all previous messages and would almost certainly be lethal" (372). Each new protein-coding system would have had to evolve from scratch three separate times on that formulation, with no cumulative advantage being gained from the previous system. (The term "principle of continuity" appears without explanation or citation in Crick's paper; it is capitalized as a proper noun in the first instance of use, but not in the second.)

In the very next article in the same journal, biochemist Leslie Orgel, who frequently co-authored with Crick, used the term as well. Orgel was most likely the one responsible for the principle's transport into origin of life studies, where he is counted as one of the field's luminaries. In a paper discussing the origin of the genetic code, his formulation differed from the ones above. He wrote that PC:

> requires that each stage in evolution develops "continuously" from the previous one. It is very difficult to see how a totally different biological organization could have undergone a continuous transition to the nucleic acid-protein system with which we are familiar. Thus, at least until such time as a reasonable detailed model of a novel system is suggested and a means for its evolution into the present system is proposed, I feel justified in supposing that certain features of the contemporary genetic system emerged very early in the development of life (1968, 381).

This definition contains more content: it stipulates a certain kind of biochemical continuity that is shared between all life forms. The biochemistry of today is most likely the biochemistry of early life. Because of continuity *plus* the lack of any account of how a "totally different" organization could have transformed into the contemporary nucleic acid – protein system, we can content ourselves with the study of the contemporary biochemical system rather than worry about other possible, non-actual biochemistries.

This is a significant constraint, because a major burden of the field, as James Griesemer (2009) has pointed out, involves characterizing life in a way that doesn't beg all of the relevant questions about what life *must* be like. Prima facie, it seems that life might have been very different than it in fact is now, and it might have originated in forms that it currently doesn't display. Orgel claims we're justified in investigating our nucleic acid-protein world because it emerged very early on: it couldn't be a late-comer. With no viable alternative models of genetic and metabolic processes, we can safely assume it is the only organization worth investigating.

The basic idea behind these various formulations is that PC is the sort of principle that is required to secure confidence in a scientific investigation of a historical event. PC is supposed to link the inquiries of contemporary science with the ostensible

events of the past. Any metaphysical discontinuity in the actual genesis of life – any "magic spark" that animated the first microbe – would frustrate any present hopes to accurately reconstruct those events using naturalistic assumptions.

Broadly, I suggest that there are two sorts of uses that are sometimes proposed for this principle. PC is sometimes used to *guide* research and *restrict* hypotheses. In the former capacity, the hope is to use the idea as a kind of posit that helps you look for particular things – processes that connect in causally relevant ways with other chemical processes that we have reason to think are important to life's origin. It would allow you to align your research program with features that you are more confident in – e.g. contemporary protein synthesis, or an RNA world. The researcher begins with what she is confident in, and explores outwards from there. If confidence in an RNA world is a starting point, then investigating the possible synthesis pathways for ribose sugars (a constituent of RNA) is one natural route to proceed. But such methods hardly require their own principle or nomenclature, insofar as it will amount to nothing more than "being rational" in whatever fashion is deemed acceptable by the contemporary standards of the science.

In the latter capacity, PC might be used to restrict research that doesn't live up to its standard. It could rule out of bounds some hypotheses that conflict with a central principle that seems to have been so useful in the history of evolutionary thinking. This could be a helpful tool in a field increasingly crowded with theories. Henceforth I will be arguing that PC fares well (though trivially) in its first capacity, but that its use in the second capacity is more problematic.

In what follows I will suggest a couple of reasons why I think PC is invoked in origins of life research. Unlike the explicit uses to which it is put that I outlined above, these following motivations are more often implicit and unarticulated, yet I believe both are reasonable hypotheses given the structure and history of the field.

3.

A first reason PC is invoked is because continuity between *theories* is a kind of ideal within an incredibly fragmented field. There is no "discipline" of origins of life. There is not a single department of origins of life. The community is a heterogeneous collection of scholars that may have little knowledge of the other diverse fields of inquiry that investigate origins.

Any widely gratifying “answer” to how life arose from a prebiotic environment would seem to require an impressive synthesis of diverse findings from equally diverse subspecialties. One of the most interesting social-epistemic aspects of the field is the extent to which each apparently simple claim in the origin scenario depends so strongly on other fields. When the biochemist wants to make a claim, she finds herself constrained by the atmospheric chemistry, the geology, and the myriad environmental concerns that constrain chemical possibilities on a prebiotic Earth. Hence “continuity” may find appeal as an ideal that not only describes nature’s fundamental workings, but guarantees that theories will actually link up and that there will be a consistent scientific narrative that incorporates constraints and insights from several different fields of study.

A second reason why I think the principle of continuity is invoked is because of its particular history in biological theorizing. Figures and ideas can loom large over a field even when scientists themselves don’t necessarily acknowledge those historical antecedents. But theoretical biologist David Penny at least does nod to history when he says of the principle of continuity “Basically, we aim to explain the past by, in Lyell’s phrase, ‘causes now in operation’” (2005, 637). It will be worth briefly reviewing what Lyell was up to in order to better understand this zeitgeist of continuity that seems so attractive to contemporary origins of life theorists.

The theoretical topology of 1830s geology prominently featured the debate between two camps that Whewell dubbed *catastrophists* and *uniformitarians*.[4] Catastrophists like Cuvier argued that the past was interrupted by events quite unlike what were presently experienced. In practice, catastrophism was typically linked with some sort of directionalism: the idea that an overall direction could be discerned in Earth’s history (simple to complex, lower life to human). Indeed it was the catastrophes that helped to bring about the world in its current state, which is demonstrably different than it used to be, based on fossil and other geologic evidence.

Against this background, Charles Lyell’s *Principles of Geology* was the primary text arguing to the contrary that earth history was a gradual process with no apparent directional change at all, but rather a protracted geological oscillation of incremental natural changes.

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[4] Whewell seemed to have a knack for just the right neologisms. He coined the word “scientist” as well.

To be more specific, Lyell seemed to have three distinct goals in mind (Ruse 1979). The first, *actualism*, involved explaining the past in terms of the *type* of causes now in operation. The second, *uniformitarianism*, involved explaining the past in terms of the same *degree* of causes now in operation. You could obviously have the first without the second, but Lyell sometimes conflated the two, often lumping them together. Jointly they contribute to the core of his Principles. Third, Lyell argued for a *steady-state* view of the earth, which implied a perpetual cycle of degradation and eruption, with no overall direction or progress in either the organic or inorganic world. (The one exception he made to the no progress rule was distinctly human mental capacities.) It seems that the first two goals are still held relevant in thinking about origins research.

Lyell's insight was that a massively extended time scale "flattens out" the apparently catastrophic events into long-term fluctuations about a mean, leading to his ability to postulate incremental, gradual history. But Lyell tried to label catastrophism as unscientific, and his interpretation has exerted tremendous influence on the history of science (Bowler 2003, 131) – including, perhaps, in origins of life research.[5]

Catastrophism wasn't a silly theory; it was not just based on miracles or satisfying literal readings of religious scriptures (though initially it may have been moreso). It was a fruitful area of science that helped to generate a theoretical basis for major developments in stratigraphy, the science of rock layering (Bowler 2003, 116). In a sense, Lyell and Cuvier were talking past one another when it came to the issue of the pace of change. Lyell could out-catastrophy anybody by just insisting that the event in question, say, that recent glacial retreats across Europe, weren't catastrophic at all – that it must have been slow and gradual, according to the dictates of his uniformitarian thinking that causes we now find in operation explain Earth history.

I think this history matters to origins of life theorizing, largely because of what (and who) came after Lyell. Darwin not only appealed to Lyell's gradualism but considered it central to his own theory. Michael Ruse and many others have labeled Darwin an "extreme Lyellian", which puts Lyell squarely on the "right" side of history --

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[5] Other parties also had a role to play in forging links between catastrophism and religious doctrines. The early 20th century self-instructed Adventist geologist George McCready Price referred to his Biblically-literalist flood geology as "the new catastrophism", which was then equated with "creationism" by his students (Numbers 1999).

that is, with Darwin. Peter Bowler writes that "Darwin's theory of evolution is a classic expression of the principle of continuity in biology" where the principle is here taken to mean that "all changes are both natural and gradual" (2003, 9). However, Lyell's own commitment to a steady-state history would have precluded Darwin's insistence on a progressive evolution.

This legacy of affiliation with Darwin has placed Lyell in the pantheon of scientific theorizing for some. (Martin Rudwick referred to this historically reconstructed Lyell who handily appeared for Darwin's benefit the "Baptist to Darwin's Messiah" (1970).) But we've seen that Lyell himself made more of his theory than it required. Bowler writes of Lyell's uniformitarianism: "he extended it far beyond the limits accepted by modern science" (132).

Darwin himself rarely wrote on the topic of life's origin, but he seemed to have continuity on his mind when he wrote in 1882, near the end of his life, that "Though no evidence worth anything has as yet, in my opinion, been advanced in favour of a living being, being developed from inorganic matter, yet I cannot avoid believing the possibility of this will be proved some day in accordance with the law of continuity" (February 28, 1882 letter to Mackintosh). This passage followed a reference to Wohler's synthesis of urea, significant for its demonstration, for the first time, that organic products like urea could be synthesized from inorganic materials: there was no metaphysical gap between the inorganic and the organic realms. Shortly later, Darwin penned "the principle of continuity renders it probable that the principle of life will hereafter be shown to be a part, or consequence of some general law" (March 28 1882 letter to George Charles Wallich). Darwin was aware of the apparent consequences of his theory of evolution for an account of life's initial appearance, but didn't believe that the time was ripe to investigate life's origin. He seemed hopeful for a future answer to the question provided within a secular, scientific framework (Pereto et al. 2009).

It is important to note how Darwin's sense of "continuity" may have affected his own work. In several passages from *Descent of Man* and *Formation of the Vegetable Mould*, Darwin supposes that mental faculties like love, imagination, curiosity, reason, and judgment must be found in nascent forms in "lower animals" including earthworms. The arguments are generally of the species that biological (including mental) powers are differences of degree and not kind. Such strong commitments to finding mind in other animals, and thus discounting qualitative differences between humans and other animals, may very well be a result of his commitment to this continuity.

These have been my attempts to say how and why the principle of continuity is so often invoked in origins of life research: that it represents a sort of hope that it might be used to coordinate disparate areas of research, and because of its history in evolutionary thinking, where Darwin's *Origin* (and by implication, subsequent evolutionary theory) are seen as grounded in a principle of continuity. Now I will present an example of how PC arises in origins of life research.

4.

To see how the principle of continuity has functioned in scientific research I will assess its use in a controversy over the proposal of a novel theory of life's origin, called the "clay" theory or "genetic take-over" theory.

Graham Cairns-Smith (GCS), a contemporary Glasgow University chemist, is well known for what is often dubbed his "genetic take-over" or "clay" theory (1982, 1985). Cairns-Smith began with an environmental consideration: Like many others, he was skeptical about the possibility of reducing conditions apparently needed for biomolecular accumulation. (Traditional Miller-Urey scenarios producing amino acids only take place in reducing atmospheres, but the chemistry underlying that process, called the strecker synthesis is inhibited by neutral or oxidizing atmospheres, which are generally favored by contemporary atmospheric scientists.) He noticed also that ultraviolet radiation is responsible for other processes that produce an oxidizing effect, also evidence against the traditional organic origin scenarios. So he postulated that the most likely environment for life's emergence is as far away from the sun as possible – perhaps in submarine hydrothermal systems, where reducing conditions are known to exist amidst the mineral-laden geothermal vents.

Cairns-Smith assigns a large role to this mineral chemistry, arguing that the usual organic chemistry is too complex to be suitable for origin scenarios. While some organic biomolecules like amino acids can be relatively easily synthesized, many other important components of life, most notably nucleic acids, are notoriously difficult to assemble in prebiotic environments (Bada and Lazcano 2009). Cairns-Smith's own calculations on the possibility of a precise stepwise reactions of proteins, sugars, and nucleic acids make such a process vastly improbable. He writes: "There was not enough time, and there was not enough world" for that (1985, 47).

Cairns-Smith's focus on the mineral world allows what he thinks is a more probable route to organic life, but it is a route in which inorganic components serve as

scaffolding for later, organic life. On his model, clay minerals serve as “crystal genes” which can evolve by natural selection. Clay minerals are complex crystals, and Cairns-Smith suggests important similarities between those minerals and other macromolecules. He contends that crystal growth and break-up can code for information based on the distribution of electrical charges on their surface. He argues further that such genes could replicate, direct the synthesis of a new layer on the mineral surface, thus contributing to the evolution of more stable and complex structures better suited to their environment. During this process, organic compounds could be synthesized on the surface of these structures, providing distinct survival advantages in the development of novel organic structures. Eventually, organic genes – some kind of nucleic acids – “took over” the structure, the mineral scaffolding was no longer required, and life as we know it later developed [Fig 1].

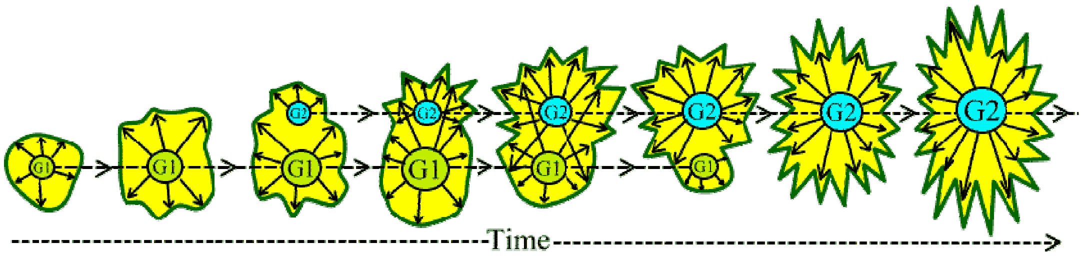

Figure 1: Diagram of the genetic takeover. G1 represents the original crystal gene. This primordial inorganic gene helps to catalyze the organic gene, G2, which eventually takes over the phenotypic expression, as represented by the arrows. Image taken from the website: http://originoflife.net/takeover/

Cairns-Smith emphasizes the intricate, circular nature of biochemical organization, where “everything depends on everything”. How could such systems develop without a designer? Richard Dawkins (1996) likened the naturalistic solution to this problem to an arch of stones representing biological organization. Could this kind of architecture develop one stone at a time in nature? Not in midair, on its own, but it could arise with scaffolding – in a pile of rocks which built up the arch, and which then slowly dissolved, leaving the arch in place. The scaffolding is initially necessary, but later on unnecessary.

Cairns-Smith writes: “before the various components of contemporary biochemistry could lean on each other, they had to lean on something else.” That “something else” – the scaffolding -- is the clay crystals. Other organic replicators –

eventually DNA – was introduced later on, and the latter proved to be so much more efficient at replication that the original replication system was left behind.

Genetic takeover theory was received well by the theoretical biology community; it was used by Richard Dawkins to exemplify "the properties that any satisfying theory of the origin of life must have" (1996, 149) and to explain why apparently improbable theories of life's origin must be precisely what scientists hope to find. (He argues there that an event such as life's emergence that happened roughly once in a billion years would appear to our all-too-human, naturally-selected brains as unlikely. We would intuitively consider any such event 'miraculous,' because our brains were made to assess probabilities against the background of timescales we can easily imagine, namely a few decades.) As a novel solution to the problem of life's origin, Cairns-Smith's theory has been widely noticed, but for a variety of reasons is less popular now than was in the past twenty years. Empirical evidence does not strongly favor the theory, but that does not distinguish the clay theory from other approaches, which are likewise vastly underdetermined by the evidence. What's interesting is that responses to Cairns-Smith are not always empirical in nature, but often, conceptual.

In addition to other objections, Harold Morowitz notes that contemporary organisms show "no vestiges" of clay intrusions, and their historical role in biogenesis would be difficult to decipher. Morowitz thinks that takeover theory fares poorly by the lights of continuity and is effectively "ruled out" as are other theories positing a role for mineral catalysis of organic ingredients to life.

> The principle of continuity may be introduced to critique proposed theories asserting that microstructures of clays or other minerals such as pyrite were essential elements in the transition to life. Since no clay structures or vestiges of clay structures exist in contemporary cells and since nothing in the logic of clay chemistry is unique, the introduction of the clay hypothesis violates continuity without persuasive arguments for the logical necessity for such a violation. The introduction of clays or pyrites… needlessly complicates origins of life theory (Morowitz 1992, 27).

This is a revealing passage for several reasons. It follows Morowitz's introduction of PC in which he likens it with Ockham's Razor. It is clear that adherence to PC is a methodological principle that is applied antecedent to scientific investigation, closely connected with "theoretical virtues" such as simplicity. His sense of the principle's significance is indicated by its placement alongside other esteemed metaphysical doctrines. Morowitz writes: "Continuity is a special aspect of the metaphysical principles of connectedness, simplicity, and causality" (27). Also, it seems that there is a high

burden for any proposal to override the principle of continuity. Something like "logical necessity" is required for a theory to offset continuity. Lacking strong evidence to the contrary, continuity selects against theories that complicate the story of life's emergence.

In a later discussion directed specifically at clay theories, Morowitz repeats his claim that the transitions discussed by Morowitz (and another theory based on pyrite surface metabolism) violate continuity, and should be ruled out.

> The role of clays in biogenesis does not, however, hold up well to the criterion of continuity….The same argument developed for clays based on the principle of continuity can be directed to the theory of pyrite surfaces (Wachtershauer 1988). Again a persuasive case has been made for catalytic surfaces, but this in itself seems insufficient for the principle of continuity (Morowitz 1992, 91).

Likewise, Maizels and Weiner (1999) write that there is good reason to believe that a theory like Cairns-Smith's is simply looking in wrong place. Because molecular evolution is incredibly conservative in nature, the bits that remain now can be seen as fossilized clues to ancient past. They write that any sufficiently sophisticated structure would be very likely to be preserved, and that it would be very risky to change. Since the number of interactions within cell components is so high, a change in one molecule requires compensatory changes in many others. "When a change in one molecule would entail an impossibly large number of simultaneous compensatory changes in other molecules, then the necessity of coevolution can effectively freeze a molecule in time" (81). Thus evolution does not "obliterate its own tracks" – and as a consequence, we have reason to investigate the origin of components of *contemporary* biochemistry: that is, organic proteins, lipids, nucleic acids. If the mineral genes worked so well, they would have left some trace, if not stuck around altogether. Conversely, the ubiquity of organic replication materials we find today mean they were around from the beginning.

This idea that continuity secures the universality of protein-nucleic acid biochemistry has been put to use by other researchers as well. Citing the work of Maizels, Kunin (1999) uses PC to validate the view that the mutual catalytic dependence of RNA and protein "was a primary feature of the very first living systems" (461), thus also ruling out any pre-nucleic acid accounts of origins.

Cairns-Smith responds to the conceptual challenges such as those of Morowitz and Maizels by arguing that the principle of continuity must be discarded, because without his proposed inorganic origin, the conventional organic origin scenarios need to appeal to miracle-like low probabilities or singular events not covered by scientific

explanation. He argues that positing the "unity" of biochemistry falters to the extent that it's not providing forthcoming, fruitful results. He interprets research along those lines as stagnant. In support of his theory, Cairns-Smith points to several decades of mostly failed attempts to synthesize key macromolecules like RNA and proteins in plausible prebiotic conditions (Hazen 2005, 161).

Cairns-Smith explicitly concedes that he's giving up on biochemical continuity of the sort proposed by Orgel. While he accepts his departure from a kind of genetic or biochemical continuity, he still sees himself as playing by the "rules of the game." He doesn't see his work as unscientific and he is certainly not invoking any gods or other metaphysically suspect entities. Indeed, there is a real sense in which, according to his own logic, Cairns-Smith is the one who can claim the mantle of continuity. The reason is because he puts more emphasis on the problems with the origin of the RNA world "from scratch." Conventional accounts of an RNA world have been very popular, but still have little evidence for how the RNA world came to exist in the first place. This leaves a "gap" between the pre-RNA world and the simplest organisms we can conceptually postulate. Cairn-Smith's own theory is an attempt to bridge just that gap. He cautions: "This gap can be seen more clearly now. It is enormous" (1985, 4).

Mineral catalysis theories such as those of Wachterhauser and Cairns-Smith are attempts to account for the origin of the organic, nucleic-acid based systems of replication that probably appeared early in the development of life. Other accounts for the origin of those (typically RNA-based) systems have been plagued by chemical difficulties assembling the constituent subunits of RNAs. Upon surveying that research, Cairns-Smith declares that the probabilities for the natural chemical assemblage into self-reproducing RNAs is fantastically low – low enough to propose an alternative genetic system that could have been built up from inorganic components. Other theorists, including Morowitz, take the latter move as one that violates the principle of continuity. It is methodologically suspect to the extent that it introduces a complex narrative of inorganic mineral chemistry into what had been a (arguably simpler) narrative of a gradual increase in the complexity of organic chemistry.

Part of the stalemate here arises from the need for theorists to evaluate the work of other scientists. Origins of life is a distinctly multi-disciplinary pursuit, and very few theorists are familiar with all the disparate areas of research that compose the field. Different scientists have different expectations for the likelihood of success in other areas of study. This matters when it comes to clay theory: Cairns-Smith believes that

organic accounts are plagued by intractable problems, and that his account is worth investigation. Many of those who work on organic accounts see their field as progressive and likely to bear fruit, and if that is so then the appeal to non-organic genetic systems seems quite radical indeed. In both cases, the community needs to assess the prospects of *other* areas of study.

If this debate is not dispute about the empirical merits of Cairns-Smith's model, I think it is actually more about the signature principle than about continuity. Recall that Morowitz believed in a tight link between the two principles, arguing that continuity entailed the signature principle. The signature principle seems to have much more concrete empirical consequences than does continuity – it is a much stronger principle. Although they frame their criticisms under the label of a violation of continuity, several of the comments of Morowitz and Maizels make it seem as if the real objection to theories like Cairns-Smith's is over the lack of a trace of any mineral or clay structures in current biochemistry. Their working assumption is that life's origin came about through a gradual increase in complexity of organic ingredients – just the ones that are pervasive today. Their research programs are delimited according to that initial assumption.

The signature principle seems to be in danger of making unwarranted assumptions about evolutionary history. In particular, it assumes that prebiological process must somehow be manifest in contemporary biochemistry, which can be investigated in the laboratory. It further assumes that the ingredients of current life are the ingredients that constituted ancient life. It construes biogenesis as a gradual process of construction from the same materials that eventually became highly interdependent and now evolutionarily conserved. Of course evolution rarely works the way that human engineers would. Evolution doesn't have an "end" in view, and it has no plan for the finished system. Evolution's "tinkering" complicates the way that we might think life was formed. Life could very well have emerged with different components than it has now.

Perhaps the dangers posed by the signature principle are outweighed by some sort of methodological benefit from its use. The signature principle may not be committed to any specific evolutionary histories, but only to a methodological restriction on what makes sense for scientists to investigate. Without it, maybe scientists would be at a loss for what to study, given the myriad alternate possibilities. I don't know whether the alternate possibilities really are myriad or whether it's true that scientists need to restrict their scope in just this manner. These concerns about the signature principle will

need to await further analysis. My point so far is only that PC is being used in a way such that its defenders believe it has real empirical significance. In this debate between defenders of inorganic surface catalysis and defenders of organic origins, it seems that PC is actually not doing the work that its advocates believe it is doing.

The concern is that a principle is being upheld for its own sake while prohibiting research into the merits of an alternative genetic system. Recall that Orgel's formulation of biochemical continuity was qualified: he claimed that *insofar as* scientists lacked "reasonably detailed" models of alternative genetic systems, he was justified in restricting his focus to contemporary genetic systems of DNA and protein. To then invoke this principle as a *reason* not to investigate other possible genetic systems would be an unfair restriction on empirical research – research that appears badly needed in this field. My point here is not to argue in favor of Cairn-Smith's particular model of genetic takeover, but to elucidate how the principle of continuity is used and some attendant dangers of that use.

5.

In its first capacity, as guide to research, PC seems to function as a pragmatic aid to practice, and its use is very old indeed. Origin of life scientists typically search for incremental changes that could have allowed novel mechanisms to emerge from simpler biochemical constituents. But if modern science will successfully appeal to this kind of stipulation, it must be sensitive to new empirical knowledge. Scientists routinely revise what they thought was possible or even "continuous" in light of learning new things about the world. For example, witnessing spontaneous crystallization in sodium acetate may very well evoke the sense that you had just witnessed a discontinuous jump. You might see this spontaneous switch from liquid to solid and see a "saltum" – at least, that is, until you acquire the cognitive and empirical resources to understand a few things about supersaturation or crystallization.

In its second capacity as a decision criteria and standard by which to judge results, PC is too weak to do its job because of the number of background assumptions that do not seem to be shared in common between different researchers. Aside from whether they even share the same definition of PC, the relevant assumptions for the application of PC include the assessment of fruitfulness of *other* areas of inquiry, and the permissiveness towards "alternative" life forms that differ from contemporary life.

David Penny writes: “it is still hard to imagine and experiment with completely different forms of life” (2005, 638). Part of the question, then, is What can you imagine? In Kyle Stanford’s (2006) terms, what are the ‘unconceived alternatives’ to the universal biochemistry of today? It seems like what you can imagine is a cognitive and empirical question, the exploration of which should not be ruled out by an a priori stipulation.
PC is not sufficiently precise to serve as standard, and it seems bound to be either too strict or too loose to do much heavy lifting in origins of life research. If it is formulated precisely as to have specific empirical consequences, then it is too strict and will prohibit research that could be successful. If it is a loose commitment to naturalism, then it amounts to nothing other than just “being scientific” or even “being rational”. I think there are compelling reasons not to be too committed to PC, where that idea has any strong empirical content. There are good historical precedents for such a worry.

One of Lyell’s many gifts to Darwin’s theorizing was a principled reason to think that the fossil record was incomplete. Paleontology was in its infancy yet, and becoming a fossil is not at all easy: it requires a very particular process, and entails that many ancient living forms may never have achieved this fossilized state. That insight helped Darwin to answer questions about why we found so few transitionary forms.

But that was the 1840s. In the 1970s, Eldridge and Gould (1972) shocked the biological community when they suggested taking the fossil record at face value: while some transitionary forms had been discovered (such as archaeopteryx, an intermediary between reptiles and birds), the fossil record mostly shows long periods of stasis followed by relatively fast bursts of new morphological divergence. The conclusion reached by Gould and Eldridge was to model their theory after the data: the result is what they called punctuated equilibrium. [See Fig 2]

EOLSS - PATTERNS AND RATES OF SPECIES EVOLUTION

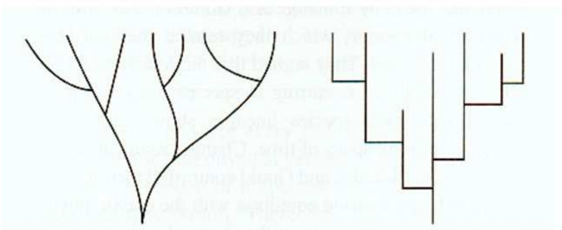

Fig. 3. Contrasting expectations of species-level evolution, the classic phyletic gradualism model (A), and the punctuated equilibrium model (B). Modified from various sources.

Fig 2: On the left is the standard model, called phyletic gradualism, where the x axis is morphology space. On the right is punctuated equilibrium.

Even though their theory had built upon some well-known tenets of speciation first established by Ernst Mayr, punctuated equilibrium generated quite a controversy, attracting criticism for the fact that it violated Lyellian gradualism (see Sterelny 1992 for a review of the controversy). Some critics claimed that these fast bursts of morphological innovation were contrary to our understanding of slow, continuous evolutionary change. Eldridge and Gould responded that their evolutionary bursts of innovation might be "fast" in geological time, but that such changes accrued over tens of thousands of years, and hardly represented any miraculous jumps. Geologically fast can still be biologically slow.

I take it that this important episode from biopaleontology exemplifies the ways in which continuity can be used to unnecessarily restrict scientific advance. The intuition that some changes are just "too fast" carries little empirical content or warrant on its own.

So far I have shown two examples from origins of life research and likened it to another example from evolutionary theory; perhaps the principle of continuity emerges relatively unscathed from these few arguments to the defender of PC. But it gets worse for continuity, for reasons that have little to do with the genetic takeovers or punctuated evolution. That's because Cairns-Smith is right that the idea of takeover (depending on how exactly that's construed) is hardly inimical to spirit of evolution. Standard evolutionary theorizing accounts for many cases where traits evolved for one function, and then ended up serving a different role. Gould and Vrba (1982) dubbed such changes, "exaptations". Exaptations are characters that are fit for their current roles, but were not selected for those roles – they were selected for some other function (or not selected at all), and were then co-opted for a new role. Common exaptations include bird feathers, which initially evolved for insulation but then aided flight, and bones, which initially served as storehouses of calcium phosophates needed for muscular metabolism before they served their structural roles for terrestrial vertebrates.

These exaptations are a kind of *functional takeover*, and very few theorists doubt that those are ruled out of bounds by standard evolutionary theory. James Griesemer (2009) highlights a case of exaptive research traditions *within* contemporary origins of life debates that have to do with the origin of the ribosome. Griesemer discusses two competing accounts of the origin of the ribosome, the molecule responsible for translating the genetic code from messenger RNA into a peptide chain of amino acids. It is unknown how this molecule originated, and the two accounts propose different

mechanisms. Both hypotheses involve fairly serious alteration in function – not just "change" in function – the way that many Darwinian processes are described, but exchanges or transfers in function. Griesemer distills their logic into categories of functional *exchange* and functional *transfer*:

•Exchange
A does F, B does G
A does G, B does F

•Transfer
A does F to B
B does F

The question is whether these changes fit within the confines of the continuity principle. Both hypotheses on the origin of the ribosome are hard-won products of empirical labor; both are open to varieties of evidence for or against them, and neither should be ruled out based on the tenets of what counts as continuous. Exchange or transfer of function may prove to be the kind of takeover that Morowitz rejects, but they seem to be within the spirit of a weaker formulation of continuity – the kind that proposes naturalistic causes for all or incremental transitions. The point is that lacking any specific conditions that would discriminate between unacceptable "jumps" and other well-established instances of evolutionary functional exchange or transfer, PC appears insufficiently precise. It lacks the rules needed for its own application.

6.

PC is widely recognized as a heuristic principle in origins of life research. It can be interpreted strongly, in a way that has real empirical import, or weakly, in a way that merely stipulates that each natural change has a cause that is recognized as possible in light of whatever contemporary science admits as legitimate.

Exaptation cases suggest PC has difficulties if constructed in a specific or strong sense, because there are myriad cases of functional takeovers in evolutionary history. Furthermore, if construed in any specific sense, it may be used to rule out important possibilities for further research.

The history of science shows that notions of precisely which phenomena count as "continuous" might be subject to change or to empirical revision. If one is inclined to salvage PC through these various revisions, then it ends up being a broadly applicable

yet mostly empty dictum. It would seem to exclude little other than spontaneous, non-natural events with

PC is being invoked as if it has serious probative or justificatory power. But it doesn't. It would appear to be a boon for scientists if it did, as the field of origins of life is lacking shared heuristic principles that would allow for the synthesis of diverse empirical data. But if the field is going to find reasoning principles common to different subspecialities, it will have to look for something other than continuity.

What then is PC doing in this literature? I am compelled to look to history: Lyell was using it to keep his science separate from his religion. In fact, the original intention of Lyell's Principles of Geology was to be a popular work entitled "Conversations in Geology" (Rudwick 1970). While the form of the work changed into a more detailed treatise for experts, it retained its original rhetorical intention of combating those who were using science to establish the possibility of a literal interpretation of the Mosaic narrative.

Invoking PC is one way to put forward your naturalistic credentials: it's a bulwark against non-naturalism. This is not insignificant given the social and epistemic space occupied by the science of life's origins. But in terms of contributing to the details of the research itself, it's just not that informative. Today's research landscape is hardly haunted by fears of ecclesiastical opposition, as it may have been 150 years ago. Conversely, few if any scientists are tempted to look for any "magic sparks" in the biochemical origin of life – such prohibitions appear now nearly built in to "methodological naturalism," (Tanona 2010), and scientists hardly need an additional "principle" that operates to serve just those ends.

The concern is that this principle could generate unacceptable constraints on scientific inquiry. That's not just a hypothetical worry: it has happened in scientific practice.

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