Chirality, quantum mechanics and biological determinism

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ABSTRACT

The holy grail of astrobiology is the discovery of a second sample of life that has emerged *de novo*, independently of life on Earth (as opposed to extraterrestrial life that shares a common origin with terrestrial life via a panspermia process). It would then be possible to separate aspects of biology that are lawlike and expected from those that are accidental and contingent, and thus to address the question of whether the laws of nature are intrinsically bio-friendly. The popular assumption that life is an almost inevitable product of physics and chemistry, and therefore widespread in the universe, is known as biological determinism. It remains an open question whether biological determinism is correct, as there is little direct evidence in its favour from fundamental physics. Homochirality is a deep property of known life, and provides an important test case for the competing ideas of contingency versus lawfulness – or chance versus necessity. Conceivably, a chiral signature is imprinted on life by fundamental physics via parity-violating mixing of the weak and electromagnetic interactions. If so, homochirality would be universal and lawlike. On the other hand, it may be the result of chance: a random molecular accident during the pre-biotic phase. If the latter explanation is correct, one could expect that a second sample of life may have opposite chiral signature even if it resembled known life in its basic biochemistry. There is thus a curious obverse relationship between chirality and biogenesis in relation to biological determinism. If the chiral signature of life is the product of chance, we may hope to discover "mirror life" (i.e. organisms with opposite chiral signature) as evidence of a second genesis, and the latter would establish that life's emergence from non-life is quasi-deterministic. On the other hand, if the chiral signature is determined by fundamental physics, then it may be much harder to establish an independent origin for extraterrestrial life with biochemical make-up resembling that of known life. Whilst the experimental search for a second sample of life – possibly by detecting a chiral "anomaly" – continues, some theoretical investigations may be pursued to narrow down the options. Chiral determinism would be an intrinsically quantum process. There are hints that quantum mechanics plays a key role in biology, but the claim remains contentious. Here I review some of the evidence for quantum aspects of biology. I also summarize some proposals for testing biological determinism by seeking evidence for a multiple genesis events on Earth, and for identifying extant "alien microbes" – micro-organisms descended from an independent origin from familiar life.

Keywords: biophysics, homochirality, quantum mechanics, biological determinism

1. CHANCE AND NECESSITY

A landmark event in the history of biology was the publication by Jacques Monod of his foundational book *Chance and Necessity*[1]. In this work, Monod pointed out that biological organisms are shaped in part by the laws of nature and in part by happenstance, or contingency. That is, some features of organisms are in some sense preordained, fundamental and inevitable given the nature of the universe, whilst other features are purely accidental and incidental. The problem is to know which is which. Given that we have only one sample of life to study, it is extremely hard to disentangle the necessary from the contingent. A prime motivation of astrobiology is, of course, to discover a second sample of life, which would help us to identify fundamental and universal features and distinguish them from specific and accidental features. In the absence of a second sample of life, the scope for disagreement on the relative mix of chance and necessity is great. Thus Monod argued that the life is overwhelmingly the product of chance, a sentiment echoed by Stephen Jay Gould, who maintained that even features as basic as intelligence were purely contingent. On the other hand,

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Christian de Duve is convinced that life is 'a cosmic imperative,' and that although the twigs on the tree of life may be shaped mainly by chance, the basic morphology of the trunk and major branches are a product of the laws of physics and the nature of the physical universe[2]. We might call de Duve's point of view *biological determinism.*

It is tempting to try and guess which features of life might be the product of law, and therefore expected, and natural in so doing to focus on what appear to be 'fundamental' features. A candidate list for 'necessary' features might include, perhaps, the emergence of life itself (with its indispensable properties of replication, variation and selection), the existence of information checking and editing processes, diversification, symbiosis, bilateral symmetry and, arguably homochirality. In this paper I shall focus on the origin of homochirality as a testing ground for choosing between chance and necessity, and for assessing evidence for biological determinism. It is fairly clear that life could not work with achiral molecules, because they lack the necessary complexity. But what is at issue is why (with some very few exceptions) all known life uses molecules with the same chirality. Is this a result of chance, or is there an underlying law that says, in effect, that if we re-ran the tape (to use Gould's metaphor) then life would choose the same chirality next time?

Let me first look at necessity, i.e. that the chiral signature of life is somehow imprinted on molecular biology by the underlying laws of physics. Fifty years ago this year, Lee and Yang rocked the world of physics when they predicted, correctly, that parity is not conserved in weak interactions [3]. Within a few months experiments proved them right [4]. Non-conservation of parity means, in effect, that the laws of physics can distinguish left from right, so that, if reflected in a mirror, some fundamental subatomic processes would be physically impossible. Parity isn't noticeably violated by the electromagnetic, strong and gravitational forces, but the weak force, which governs such things as beta radioactivity, is asymmetric between the real world and its mirror image. The discovery that this is so represented a paradigm shift in physics, because space itself is mirror symmetric. The symmetry is broken at a deep level in the force itself.

In the 1960's, the weak force was amalgamated with the electromagnetic force by Glashow, Salam and Weinberg using quantum field theory. The explicit amalgamation of the two forces manifests itself at the very high energies achieved in particle accelerators, but one feature of the electroweak theory is that, even at low energies, there is a small degree of mixing, or spill-over, from the weak force into electromagnetic processes. This tiny 'contamination' introduces an equally tiny left-right symmetry breaking into atomic and molecular processes at the quantum level. In the early 1990s, Salam proposed that this tiny parity violation might be somehow amplified in a prebiotic soup and thereby account for biological homochirality [5]. If correct, this would imply that the chiral signature of life is imprinted by the deepest physical properties of the universe, and is essentially quantum mechanical in nature. The alternative is that the chiral signature is entirely a matter of chance. Chance might operate on either the macroscopic or microscopic scale. For example, it has been suggested that exposure to polarized starlight will generate an enantiomeric excess, with a signature dependent on the geometry of the stellar system.[6] On the other hand, the chiral signature might have arisen at the molecular level as a result of a random fluctuation that became amplified iteratively via a cyclic chemical process. Not that although quantum mechanics might play a role in an initiating molecular fluctuation, the chance explanations are essentially classical in nature.

Is there a way to test for chance versus necessity in the case of the chirality? A direct way is to search for organisms with opposite chiral signature; Hoover and Pikuta have pioneered this approach [7]. An indirect way is to discover how sensitive life is to quantum mechanical effects. If life is deeply classical (as is conventionally supposed), then it is inconceivable that electroweak effects could be involved. But if quantum mechanics plays a non-trivial role in biology, then fundamental physics may be far more important to biology than has hitherto been acknowledged.

2. IS QUANTUM MECHANICS RELEVANT TO LIFE?

A few weeks ago, experimental results were published demonstrating convincingly that proton tunnelling plays a crucial role in tryptamine oxidation by aromatic amine dehydrogenase [8]. It is estimated that, as a result of quantum effects, the reaction rate is accelerated by three orders of magnitude. This work has served to re-focus attention on the possibility that quantum mechanics plays a crucial behind-the-scenes role in permitting life to work its physical and chemical magic. Most biochemists and molecular biologists, however, continue to regard all essential biological functions in classical ball-and-stick terms. To be sure, they concede that quantum mechanics plays an indirect role in life by, for example, explaining the shapes of molecules, crucial to the templating functions of nucleic acids and the specificity of proteins. Moreover, the Pauli exclusion principle ensures that atoms and molecules possess definite sizes, which in turn determines not just templating, but differential diffusion rates, membrane properties and many other important biological functions. Quantum mechanics also accounts for the strengths of molecular bonds that hold the machinery of life together and permit metabolism. But if the structure, stereochemistry and chemical properties of molecules are accepted as given, thereafter they are treated as essentially classical by almost all scientists. I wish to argue that this dismissive attitude towards quantum mechanics is misconceived.

Fifty years ago many distinguished physicists believed that quantum mechanics was on the verge of explaining life. Great strides had been made elucidating the atomic and subatomic structure of matter, and the realization that life's secrets lay at the molecular level encouraged the expectation that quantum mechanics might play a key role in biology too. Certainly the founders of quantum mechanics thought so. Schrödinger's book *What is Life?* appealed to quantum ideas to bolster his claim that genetic information was stored on an "aperiodic crystal" structure.[9] He also speculated that quantum effects would lead to some sort of radically new behaviour that would distinguish the living from the nonliving. "We must be prepared to find a new kind of physical law prevailing on it," he wrote. Bohr believed that the distinction between living and nonliving systems was fundamental, and actually a manifestation of his principle of complementarity[10]. In short, these physicists hoped that the qualitatively distinctive properties of life owe their origin to some aspect of "quantum weirdness". The highly non-classical aspects of quantum mechanics that might conceivably play a role in life include tunneling, entanglement, coherent superpositions, Bose-Einstein condensates and supersymmetry.

These early speculations did not live up to expectations, however. If non-trivial quantum effects of the sort listed above do play a part in the machinery of life, then they are effectively masked by the stupendous complexity of biological systems. Only in recent years have there arisen several tantalizing hints that quantum mechanics may need to be taken more seriously in the life sciences. On general grounds, two possibilities suggest themselves. One is that quantum mechanics sets a limit to the fidelity with which life may execute its exquisite choreography, and will therefore serve as a negative factor. The other is that life has evolved to exploit quantum weirdness to enhance its performance. Either way, we might expect some key biological processes to have evolved to the "quantum edge" – and perhaps beyond.

Although there is no agreed definition of life, all living organisms are information processors: they store a genetic database and replicate it, with occasional errors, thus providing the raw material for natural selection. The direction of information flow is bottom up: the form of the organism and its selective qualities can be traced back to molecular processes. The question then arises of whether, since this information flows from the quantum realm, any vestige of its quantum nature, other than its inherent randomness, is manifested.

3. DID LIFE EMERGE FROM THE FERMENT OF A QUANTUM MILIEU?

Most research on biogenesis proceeds from the basic assumption that chemistry was the bridge – and a very long one at that – from matter to life. Elucidating the actual chemical pathway has been a challenging goal, initiated by the Miller-Urey experiment, and pursued by all manner of pre-biotic chemical investigations. But further progress has been frustratingly slow, and the origin of life remains one the great outstanding mysteries of science.

In this paper I want to suggest a radical solution: that quantum mechanics enabled life to emerge directly from the atomic world, without complex intermediate chemistry. Obviously life as we know it has a chemical basis: organic molecules provide the hardware for biology. But what about the software? When Schrödinger asked, "What is life?" he could already glimpse the central significance of the cell's information storage and replication processes, even though the role of DNA and the genetic code were not understood at that time. Schrödinger's work represented a radical departure from nineteenth century thinking, when life was regarded as some sort of magic matter. Indeed, we still use the term 'organic chemistry' as a hangover from the time when living and nonliving matter were considered to obey different laws. Today the cell is regarded not as magic matter but as a supercomputer – an information processing and replicating system of astonishing precision.

The shift in thinking from hardware to software places the entire problem in a different context. Biologists traditionally regard reproduction – one of the defining characteristics of life – in terms of replicating structures, whether it is DNA molecules or entire cells. But for life to get going only information needs to be replicated. Because information can be processed at the quantum level orders of magnitude more rapidly than it can classically, it is tempting to speculate that life began with a quantum information processing system, involving qubits rather than bits. Because quantum systems can use superposition, entanglement and tunneling to enhance their performance, a quantum system offers many advantages in speed over a classical system. Moreover, quantum systems can implement processes (e.g. tunneling) that are simply impossible for classical systems.

A quantum replicator is not necessarily an atomic system that clones itself. In fact, there is a quantum no-cloning theorem that forbids the replication of wavefunctions as such. Rather, the information content of an atomic system must be copied more or less intact – not necessarily in one step, maybe after a sequence of interactions. This information could be in binary form, for example, by using of the spin orientation of an electron or atom. In this way, quantum mechanics automatically implies the discretization of genetic information.

There is no need for this Atomic Adam to have been situated in a conventional prebiotic setting. It may have resided in a frigid location such as an interstellar grain, for example, or on the surface of an icy planetesimal. Quite likely, the environment would have been exceptional, and may have been physically very small (not an ocean or a 'warm little pond' a la Darwin, but maybe a microscopic crystalline structure). Wherever it was, once a population of information replicators was established, quantum uncertainty provided an inbuilt mechanism for variation. Throw in a selection mechanism and the basic principle of Darwinian evolution could begin. At some stage, primordial quantum life will have 'handed over' to familiar organic life. This step offers no obstacle of principle, because information can readily be passed from one medium to another. Possibly, quantum life co-opted large organic molecules to provide back-up memory, much as a computer processor shunts digital data to a hard disk, which is slower but more robust. Eventually the organic material would literally have taken on a life of its own. The loss in processing speed would have been offset against the greater complexity, versatility and stability of organic molecules, enabling organic life to spread beyond the confines of quantum life's cradle and penetrate a much wider range of physical environments. Of course, replicating a single bit of information is one thing, generating and replicating complex concatenations of bits is another. How complexity emerges in quantum systems is a subject still in its infancy, but the principles involved could be illuminated by applying algorithmic complexity theory to quantum information theory.

Even if we can't reconstruct the precise details of life's emergence, knowing the general principles would be a huge advance. Proving a quantum mechanical theorem that puts a bound on the probability that such-and-such a system can replicate to a certain accuracy, and evolve to a particular level of complexity, might answer astrobiology's burning question: Was the origin of known life a freak accident, or the expected outcome of intrinsically bio-friendly laws of physics? Momentous implications would flow from the answer, for the issue addresses one of the deepest questions of existence: Is life a cosmic phenomenon, or are we alone in the vastness of the universe?

4. CONCEPTUAL ARGUMENTS FOR QUANTUM RELEVANCE TO BIOLOGY

A number of arguments on very general grounds have been deployed to establish when quantum processes may or may not be important in bio-systems. For example, Schrödinger reasoned, without having any detailed knowledge of the nature of DNA or heredity, that quantum mechanics was important in the stability of genetic information, and that quantum fluctuations might be the cause of some mutations[9]. He arrived at this conclusion on general energetic grounds. Wigner used an argument simply based on enumerating the dimensionality of Hilbert space that the replication of an organism could not be described as a unitary quantum process[11]. A modern variant of this argument appeals to the quantum no-cloning theorem[12], according to which a pure quantum state cannot be quantum mechanically replicated. These arguments, whilst interesting, are probably of limited relevance to real biology, where reproduction of genetic information does not entail the exact replication of an entire quantum state.

Quantum uncertainty implies certain limitations on the fidelity of some biologically important molecular processes. For example, Wigner showed that energy-time uncertainty relation sets a fundamental limit to the operation of all quantum clocks[13 14 15]. For a clock of mass m and size l,

$$T < ml^2/\hbar. \qquad (1)$$

It is surely significant that for values of m and l of interest in molecular biology, T also takes values typical of biological processes, hinting that some biological systems might operate at the threshold of quantum stability. Suppose that some high-fidelity bio-molecular process requires choreography with a precision limited by Eq. (1), e.g. protein folding, which is well-known to be a major outstanding problem of theoretical biology[16]. In order to achieve its active conformation, a peptide chain of, say, N amino acids must fold itself into a specific three-dimensional tertiary structure. The number of possible configurations is vast, and it is something of a mystery how the chaotically-moving chain "finds" the right configuration in a time that is typically only microseconds. If the average mass and length of an amino acid are m_o, and a respectively, then Eq. (1) yields

$$T < m_o a^2 N^3/\hbar, \tag{2}$$

implying a quantum scaling law for the maximum folding time of

$$T \propto N^3. \tag{3}$$

The assumption that $l \equiv Na$ is the appropriate size factor in Eq. (1) may be justified for small proteins (N = 80 to 100) that fold in a single step, but larger proteins do not remain "strung out" for a large fraction of the folding process. Rather, they first fold into sub-domains. The opposite limit would be to replace l by the diameter of the folded protein. Assuming it is roughly spherical, this would imply $T \propto N^{5/3}$. The intermediate process of sub-domain folding suggests a more realistic intermediate scaling law of, say,

$$T \propto N^{7/3} \tag{4}$$

for large proteins. Remarkably, a power law dependence of just this form has been proposed[17] on empirical grounds, with the exponent in the range 2.5 to 3. Inserting typical numerical values from Eq. (2), the limiting values of T for a 100 and 1000 amino acid protein are 10^{-3} s and 0.3 s respectively. This is comfortably within the maximum time for many protein folds (typically 10^{-6} s to 10^{-3} s for small proteins in vitro), but near the limit for some, suggesting that quantum indeterminism may indeed be a key factor, at least in some cases, of protein folding choreography.

If quantum mechanics is to play a non-trivial role in bio-systems, then some way to sustain quantum coherence at least for biochemically, if not biologically, significant time scales must be found. Simplistic calculations of decoherence rates are very discouraging in this respect – in a warm wet environment like a cell, decoherence times look to be exceedingly short[18,19]. It is possible that there are, however, ways in which decoherence might be kept at bay for long enough to enable biologically important processes to occur. If the system can be screened from the environment then decoherence rates can be sharply reduced. Very little is known about the screening properties of biological molecules. For example, a reaction region enveloped in an enzyme molecule will be partially screened from van der Waals-mediated thermal interactions from the rest of the cell. Similarly, the histone wrapping of DNA might serve to shield coding protons from decoherence. According to Matsuno, organisms may exploit thermodynamic gradients by acting as heat engines to drastically reduce the effective temperature of certain molecular complexes[20]. One example is the slow release of energy from ATP molecules at actomyosin complexes, which Matsuno claims implies an effective temperature for the actomyosin of a mere 1.6×10^{-3} K. In any event, the lesson of high-temperature superconductivity serves to remind us that in complex states of matter, simple "kT reasoning" may be misleading when it comes to decoherence times.

5. SEARCHING FOR A SECOND GENESIS ON EARTH TO TEST BIOLOGICAL DETERMINISM

The origin of life is one of the great outstanding mysteries of science. Nobody knows how a mixture of non-living chemicals can spontaneously transform itself into a living cell. As I remarked in Section 1, scientists differ sharply on how likely a biogenesis event might be. Some, like Monod, think it happened only once in the universe, while others like de Duve believe there is a deep principle, a cosmic imperative, built into the laws of nature that prompts life to form readily wherever there are earthlike conditions. Astrobiology is based on an implicit assumption of the cosmic imperative, or biological determinism – the view that life will emerge more or less automatically on earthlike planets, because there is a basic 'life principle' at work in the universe, i.e. 'life' is written into the laws of physics. A decisive confirmation of biological determinism would be the discovery of life elsewhere in the universe, e.g. Mars, *if* it could be shown that this extraterrestrial life had arisen de novo independently of life on Earth, and had not been transported there from Earth (or vice versa), via some panspermia mechanism [21].

Finding a sample of extraterrestrial life remains a distant prospect. However, there may be an easier way to test biological determinism than traveling to Mars or beyond. One planet known to be a hundred per cent Earth-like is Earth itself. If life originated on Earth, rather than being brought here from somewhere else, the question then arises as to whether life may have arisen on our planet many times over. Evidence suggests that life established itself on Earth about 4 Gyr ago, during the period of late heavy bombardment. Because the largest impacts were likely to have heat-sterilized the planet, one may envisage a series of "stop–go experiments" in which life emerged in a quiescent period after large impacts, only to be annihilated by the next large impact. This process may have been repeated many times before known life squeezed through the environmental bottlenecks created by the remaining large impacts (3.9–3.8 Gyr ago), and survived to the present day [22]. Not much is known about the duration needed for life to emerge on an Earth-like planet, but there is one crucial bit of information: Life established itself on Earth fairly quickly once conditions permitted. This is often cited as evidence in favor of the hypothesis that life forms easily and often. All life so far studied shares a genetic heritage and uses almost identical biochemical machinery. This convinces biologists it has a common origin: we are all part of the same tree of life. But if life started anew on Earth, we would expect it to have some distinctive differences. Instead of a single tree of life, there could be a forest of different trees. The descendants of another genesis would be, in effect alien organisms, raising the intriguing question of whether any such alien organisms might have survived to the present day and be co-existing with familiar life.

We don't notice any alien plants or animals. However, the vast majority of species are invisible microbes. Under a microscope, most microbes appear similar. You couldn't tell by looking whether they were aliens. When microbiologists study the innards of bacteria they use customized chemicals that recognize features of life as we know it. Such techniques wouldn't work with alien organisms, so they could easily be overlooked. Few microbes can successfully be cultured or genetically sequenced in the lab anyway: most remain unclassified. Charles Lineweaver and I have studied ways in which a second sample of life on Earth might betray its presence, through leaving traces in ancient rocks to driving inexplicable geological processes [23]. We also considered the possibility that 'alien' life might still exist on Earth. We distinguished four possibilities: (i) Life began more than once, but all samples of alien life were destroyed early on either by impacts, by other environmental insults, or by ancient ancestors of known life. (ii) At least one sample of early alien life survived and co-existed for an extended period with known life, which perhaps affected the latter's evolutionary history in some manner. (iii) Early alien life is extant, but has either gone unrecognized or is undiscovered. (iv) Alien forms of life have continued to arise on Earth throughout evolutionary history, and may still be forming today.

Direct evidence for (i) would be difficult to obtain. The terrestrial record of early life on Earth has been largely obliterated by impacts, tectonic activity, and erosion. Hypotheses (ii) and (iii) imply that alien life was able to survive the late heavy bombardment, perhaps in subsurface or orbital refugia. Hypothesis (iv) is normally discounted based on the reasoning that once life had become established on Earth it expropriated all the raw materials required to generate life de novo a second time. However, microbial life may not have been completely efficient in consuming available resources. Also, this objection ignores the possibility of "genetic takeover"—that life might originate with one chemical system, and then evolve another [24]. Finally, the objection assumes that only one general form of life is possible. If different forms of life can emerge in different physical and chemical environments, then the exhaustion of one life form's resources would not preclude the emergence of another life form at a later date. A different objection to hypothesis (iv) is that one life form would gain the edge and eventually come to predominate, driving the other form to extinction. However, bacteria and archaea are distinct forms of life that occupy similar ecological niches, yet they have peacefully co-existed for at least 2 billion years.

In my view, it is entirely conceivable that if biological determinism is correct, then more than one form of life may have arisen on Earth. The question then arises as to how we might identify a second sample of life. Alien life would in all probability be restricted to microbes. Scientists have devised a suite of tools customized for studying known life; alien microbes are likely to be missed or discarded in even the most general microbiological analyses involving bio-prospecting [25]. Alien microbes might inhabit niches beyond the reach of familiar life, i.e., in locations as yet poorly explored by microbiologists. Or, they may be dormant and inactive, awaiting physical conditions different from those associated with known life. We could be surrounded by living, dormant, or dead alien microbes without being aware of it.

Evidence for alien life on Earth might be found in a number of ways. Alien organisms might transform the geological, atmospheric, and marine environments in novel ways that are inexplicable by conventional biological or abiological processes. Chirality could be a crucial factor here. If the chiral signature of life is *not* a result of physical law, but the product of chance, then if life started a second time there would be a probability of 0.5 that it would be have the opposite chiral signature to familiar life. This "mirror life" might in all other respects be very similar to our form of life, yet it could peacefully co-exist alongside us without competition for resources or any direct conflict. Amino acids with opposite chirality occur naturally in the environment. Their origin is usually attributed to the racemization of decaying organisms [26]. However, it is conceivable that some of this material arises from the decay products of reversed-chiral alien life. Experiments with suites of amino acids and any reversed-chirality organic molecules found in association with them might provide convincing biomarkers for past anti-chiral life. These speculations formed the basis of the recent experiments of Hoover and Pikuta reported in this volume[7].

A second possibility is that alien life might occupy environments lethal to known life, e.g. deep ocean hydrothermal vents where the water temperature exceeds the upper limit for familiar life, or the high atmosphere [27], the very deep subsurface [28], grossly contaminated aquifers and lakes, high radiation and heavy-metal polluted environments such as the tailings of uranium mines, and very low-temperature locations.

On the other hand, if alien life flourishes in similar environments as known life, we need to devise a means by which to separate known from alien microbes. Any physical characteristic, e.g., size, membrane structure, might differentiate between them. One possibility is that alien life would use a different suite of amino acids from familiar life (and a different genetic code). A worthwhile experimental project would be to determine the amino acid complement of micro-organisms that prove impossible to cultivate or sequence, to determine if it departed radically from the normal mix.

6. CONCLUSION

Scientists remain deeply divided over whether life is a freak accident, unique in the observable universe, or an inevitable and expected product of intrinsically bio-friendly laws – a doctrine known as biological determinism. Yet the entire astrobiology program is predicated on the assumption that life is widespread and highly probably on other earthlike planets. In an effort to address this foundational question, the subject of biological homochirality commends itself. Is it the product of chance or law? Both would have far-reaching consequences. If the chiral signature of life is a product of fundamental physics, it suggests that quantum mechanics has a key role to play in biological processes, a claim that is sometimes made but that is so far supported by little experimental evidence. On the other hand, if life's chiral signature is the product of chance, then chirality could be a decisive indictor of a second genesis, either extraterrestrial or, conceivably, terrestrial. The discovery of multiple genesis events would serve to establish biological determinism, and the concomitant implication that the universe is teeming with life.

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