Cosmology without Design

Lawrence Krauss

Before Charles Darwin and Alfred Russel Wallace proposed the theory of evolution, the remarkable fit between living things and their environment, as Richard Dawkins observed, rationally suggested that life was designed by an intelligent creator. Darwin and Wallace gathered support for the contrary proposition: natural selection for reproductive fitness combined with genetic variations within a population would over space and time account for the complexity and diversity of living systems. This idea first intrigued and then persuaded the scientific community. One hundred and seventy years of observation and experiment, as well as the discovery of the genetic nature of variation, has made evolution the basis of biology.

If Darwin and Wallace have captured the allegiance of the scientific community, their triumph has not been entirely complete beyond it. The evidence notwithstanding, many people remain persuaded that design is needed to explain the exquisite way in which living systems seem adapted to their environment. Curiously enough, one rarely reads the claim that it is their environment that is exquisitely adapted to living systems.[1] This may seem a distinction without a difference when it comes to biology. Not so when the subject is the nature and evolution of the universe itself.

When one moves from biology to astrophysics and cosmology, the cause and effect arguments at the basis of the Evolution versus Design debate get switched. Indeed, the apparent fine-tuning of the universe has become the focal point for recent claims by advocates of intelligent design.

As our understanding of the cosmos has expanded over the past half-century, it has become clear that the existence of life on earth is strongly tied to certain properties of the physical universe. Some of these properties seem, on the surface, very fortuitous—causing both scientists and nonscientists to speculate about the significance of the correlation. If some of the fundamental constants in nature were even marginally different, life would not be possible.[2] In 1973, this notion was elevated by Brandon Carter to an anthropic principle: the laws of nature must be as they are because we are here to observe them.

The principle might suggest that *we* are evoking certain physical effects, but this is misleading. Mixing up correlations with causation is a frequent occurrence in the analysis of empirical data, and is something scientists themselves have to carefully guard against. The anthropic principle does not imply that our existence causally affects the fundamental parameters of nature. It is the correlation that counts.

One simple way to picture the problem, which I first heard expressed by Andrei Linde, is to imagine an intelligent fish. The fish might ask why its world is made of water.

No water, no fish.

If this argument is obvious, it is not trivial. Life on earth, as far as we know, is the only example of intelligence in the universe. This makes it extremely difficult to address a question of great importance when distinguishing causation from correlation: is intelligent life on earth *typical* of intelligent life? The inference of design depends crucially on the assumption that it is. If only carbon-based life evolves into intelligence, then this places constraints on the underlying parameters of a universe. Those constraints may be very different from the constraints a universe might require in order to support very different forms of intelligent life. We fish might ask ourselves the following question: if intelligent life were to form on earth, where would it typically arise? Since three-quarters of the earth's surface is covered by water, we might argue that there is a 75% chance that most intelligent life would be found underwater. The existence of human beings as the planet's dominant intelligence might seem somewhat surprising. The earth would be better suited for intelligent human life if there were more land and less ocean. Now that we understand mammalian evolutionary history, this line of argument has become irrelevant. It illustrates the dangers of using assumptions about what is typical as premises in an inference to design.

Very similar arguments have led to the claim that extreme fine-tuning of the constants of nature is required for human existence: design follows as an inference to the best explanation. The first claim needs to be carefully explored in order to discern that the inference based on it is not well founded.

Over the past century, each time some curious or anomalous feature of the physical world has surfaced, it has given rise to anthropic explanations. In the early 1950s, cosmologists observed that the formation of carbon from helium in stellar nuclear reactions depended on a particular metastable and excited state of various carbon nuclei.[3] Was this evidence that our existence had been anthropically selected? Not at all. With the development of quantum chromodynamics, physicists recognized that the configuration of nuclear states was, in fact, determined by physical principles far removed from the specifics of carbon nuclei. That anthropic argument fell out of favor, where it has remained ever since.

More recently, the resurgence of fine-tuning arguments in cosmology has been driven by the discovery of an apparent constant of nature whose value is so far beyond expectation that scientists currently have no good explanation for its existence, except for a possible anthropic one. I am referring to the cosmological constant, which seems to measure the strange energy of empty space. The cosmological constant was first proposed by Albert Einstein to justify a static, eternal, and almost empty universe. He later realized that his original equations would have allowed him to predict the expansion of the universe, and called the introduction of the cosmological constant his biggest blunder. Once let out of the bottle, the cosmological constant was not easily returned. No mathematical principle required it to be zero. But if the cosmological constant is positive, it causes the expansion of the universe to accelerate. For almost all its positive values, the universe would have expanded so rapidly that this possibility is ruled out by observation.

When Yakov Zeldovich recognized this problem in the 1960s, physicists scurried to try and find a physical reason why the constant must be zero, but without success. Not only does there appear to be no underlying reason for the constant to be zero, but positive estimates based on particle physics suggest a ludicrously large value. If the cosmological constant is greater than zero, this implies that empty space possesses a nonzero energy density, its scale proportional to the magnitude of the cosmological constant. The larger the scale, the faster the expansion rate of the universe. In particle physics, possible scales of energy are determined by the magnitude of the masses of fundamental particles. The lightest particle is the electron. If the scale of the cosmological constant were comparable to the energy associated with the electron mass, the net rate of the universe's expansion would be roughly thirty-eight orders of magnitude larger than its observed rate of expansion today.

To make matters worse, if empty space were to have a nonzero energy density, fundamental theoretical arguments suggest that its scale would be comparable to the scale at which quantum mechanics impacts gravity itself. In quantum field theory, the contribution of virtual particles determines the net energy of the vacuum, and the Heisenberg uncertainty principle implies that virtual particles of arbitrarily large mass can be produced during arbitrarily small times. This would result in a very large cosmological constant. In the absence of a complete quantum theory of gravity, physicists estimate that all virtual particles up to the Planck mass—beyond which the theoretical approximations used to make estimates break down—could contribute to the cosmological constant. Such an estimate predicts a value that is roughly 120 orders of magnitude larger than that consistent with the observed expansion of the universe.

I have referred to this in my lectures as the worst prediction in all of physics. Physicists were sufficiently embarrassed by it that conventional wisdom, at least when I was a student and young researcher, suggested that some new, as yet undiscovered, physical principle would ensure that the energy of empty space would be zero. So far so good. By 1995, when I published a paper on the subject with Michael Turner, there was mounting indirect evidence that the energy of empty space remained obdurately greater than zero.[4] In 1998, two competing observational groups measured the expansion rate and confirmed its non-zero value. Leaders of the groups were awarded the Nobel Prize in 2011. Their discovery was significant because it flew in the face of reason. A nonzero cosmological constant was one thing, but one 120 orders of magnitude smaller than what naive estimates suggested seemed difficult to explain. There has been no satisfactory fundamental explanation of its value in the twenty years since it was discovered. The reason that I, and numerous colleagues, have referred to this as the ultimate fine-tuning problem is because, in units of Planck mass, the currently measured cosmological constant is 0.000… with the first nonzero digit at the 120th decimal place. We know of no mathematical mechanism to ensure that the cosmological constant remains so small, but not zero.

There has been one explanation for the observed value of the cosmological constant, although it is entirely phenomenological and does not directly involve new fundamental physics. In 1987, Steven Weinberg predicted that if there were many different universes and the energy of empty space a free random variable over them, then only in universes in which the cosmological constant was not much larger than its observed value could galaxies have had time to form. Without galaxies, there would be no stars. And without stars, no planets. And without planets, no life.

Weinberg's anthropic explanation of the cosmological constant is, to date, the only one that appears to suggest a value comparable to the observed value, though it does rely on the yet-untested proposal that our universe is one among many. Plausibility is one thing; correctness, quite another. Time and time again, anthropic explanations of fundamental quantities have gone by the wayside as more fundamental physical understanding was gained.

Nevertheless, the fact that one of the most important single parameters describing our universe seems so implausible has persuaded some design enthusiasts that this is awfully suggestive evidence for design in nature. Religious design proponents argue that God is more plausible than a multiverse. When considering such a claim, we can learn a lot from the biological debates that have taken place since Darwin and Wallace proposed their theory of evolution.

First, the anthropic argument puts an upper but not a lower bound on the cosmological constant. The observed value of the cosmological constant is not optimally fine-tuned for life: it is *consistent* with its existence. No more. It is true that if the cosmological constant were much larger than it is, then life as we know it on earth would have been impossible; but if the energy of empty space were far smaller, even if zero, then galaxies would still be forming today, the universe proving even *more* conducive to life in the long run. It is true that the measured value of the cosmological constant appears unnaturally small. But the natural value of the cosmological constant is zero. The value is natural because it would result from additional cosmic symmetries. A cosmological constant set to zero would have been a far better bet for a good designer. The anthropic argument makes quantitative sense.

Design does not.

But beyond this misunderstanding, what is still missing from the argument for design is the fact made obvious when considering the evolution of life on earth. Life on earth is fine-tuned for the universe, not the other way around. Until recently, it appeared that life required certain specific conditions to evolve and survive on the surface of this planet or in its oceans. But in the past few decades, we have found that life is ubiquitous. Extremophiles survive in conditions of hellish heat, high pressure, and even in highly acidic environments.

Life as we know it is based on carbon, powered by ATP (adenosine triphosphate), and controlled by DNA. One might wonder if the earth were designed for life, but given the nine or more planets in our solar system, it seems more reasonable to suppose that life evolved on earth because it could adapt itself to prevailing circumstances. It is quite possible that there may be other such niches in our solar system, in the warm oceans inside Europa or Enceladus, perhaps. Astronomers are now learning that there are likely millions, or perhaps billions, of earth-like planets in our own galaxy. Perhaps life exists on some of these systems.

When we speculate about life, we are inevitably tempted by parochialism. It is earth-like life that prompts our curiosity. In this, we are like the fish. Since we have no clear idea how life originated on the earth, we have far less understanding of what other forms of life might be possible. Could silicon-based rather than carbon-based life, like the Horta in Star Trek, exist elsewhere? Or maybe something far more exotic, like the gaseous life-forms imagined in Fred Hoyle's *The Black Cloud*? The ubiquity of windbags on earth might suggest this possibility in space.

When one imagines such possibilities, the connection between the small values of the cosmological constant and the inference to design flickers briefly and then disappears. In a universe where the cosmological constant is quite different, different forms of life might arise. Could diffuse gas clouds encode intelligence? Groups of electrons and positrons? In a universe that rapidly expands early on, electrons and positrons would not be able to collide frequently enough to annihilate each other and would have roughly equal cosmic abundance today. Such life-forms might then wonder, like the intelligent fish, why the universe seemed such a good fit for *their* existence.

Two decades ago, Irit Maor, Glenn Starkman and I considered how Weinberg's anthropic calculation for the cosmological constant might be changed by varying the requirement that life of any sort in any universe should mimic life as we know it.[5] Not surprisingly, our predictions varied all over the map. Conclusions about life in the universe are, in general, drastically constrained because we know of only one example. If we assume that we are typical of all possible life-forms, we derive one result. If not, other predictions are possible. This is always the case given statistical arguments based on a single sample.

To assume that the universe is fine-tuned for life because we exist in a universe in which we can exist—this is a little like a single individual, alone in the world, looking down at his legs and finding that they are remarkably fine-tuned to touch the ground. A millimeter shorter and they wouldn't make it. A millimeter longer and they would be buried underground. Thanks to gravity, no such fine-tuning is required. In a cosmic sense, we are like the isolated individual. We simply do not know enough to ascribe significance to things that may be accidental, or that may be governed by some underlying principle, like the existence of gravity.

We are either alone in the universe, or we are not. If we are, then we have essentially won a cosmic lottery. Of the billions of planets in our galaxy, and the billions of galaxies in the universe, a series of conditions arose allowing roughly four billion years of quiescent evolution, interrupted by periodic catastrophes—like the meteor that sixty five million years ago wiped out the dinosaurs—that altered the course of evolution but did not exterminate life. If we find we are alone in the universe, or at least find no evidence for life anywhere else, does this suggest that the universe was created for us? It would seem an awful waste of space. To design a whole universe requiring over 100 billion galaxies, each containing 100 billion stars lasting over 13 billion years, just to allow the evolution of one species on one planet less than a million years ago, seems like a remarkably inefficient design.

An intelligent designer could have done better, would have done better, and should have done better. Similar biological arguments apply to the poor design of humans.

We live in a very big, very old universe. In such a universe, unlikely events happen more often than intuition might suggest. Stars may explode once per hundred years per galaxy, but with so many galaxies, a star is exploding every minute. Black holes may collide with other black holes with an infinitesimally small probability, but in a big universe, we regularly detect the signal from such cosmic catastrophes, the LIGO detector doing just that. Even if the conditions of life are so stringent as to seem almost impossible, in a big universe it is not surprising to find them realized somewhere, at least once.

If, on the other hand, the universe is teeming with life, it is likely we will soon observe it. Doing so will change everything. It will tell us if DNA-based life is ubiquitous and whether earth-like planets are required for its existence. We are apt to be surprised. If there are more things in heaven and earth than are dreamt of in our philosophy—the lesson of science over the past four centuries—then we may find that the conditions for life are a little less special than we imagined. We may even find evidence that our universe is not unique, providing further support for anthropic arguments on the cosmic scale.

Even if we continue to find that we are less special than we once thought, this should not depress us. If we are just a cosmic accident, we may still revel in our brief moment. Either way, to those who want to use fine-tuning to insert an intelligent designer into cosmology, we can continue to respond as Pierre-Simon Laplace responded when Napoleon asked why the name of God did not appear in his treatise on celestial mechanics: "Sire, I have no need of that hypothesis."

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1. There is at least one counterexample: a cogent treatise by Lawrence Henderson entitled *The Fitness of the Environment: An Inquiry into the Biological Significance of the Properties of Matter*, delivered as lectures at the Lowell Institute in February 1913. Henderson, a professor of biological chemistry at Harvard University, argued that, while Darwinian evolution sufficed to explain how life could naturally evolve to appear remarkably tuned to the earth's environment, the striking fitness of the chemistry of the earth itself for the existence of life within it was more surprising. He laid out his thesis in as much scientific detail as he could amass at the time. While he was clearly tempted to suggest a teleological explanation for something he could not otherwise explain, he avoided assuming any metaphysical purpose for life in the cosmos. He rather suggested that there might be some unknown physical principle that could explain what he otherwise found to be unexpected. Alas, at the time, the physics of stellar evolution and nucleosynthesis had not yet been worked out, as this seems to provide the sort of general principle he sought. Fundamental nuclear physics implies that stellar nucleosynthesis will inevitably produce elements such as carbon, nitrogen, oxygen, and of course hydrogen in great abundance. We now know that water appears ubiquitous in the cosmos. Apropos of arguments I present later in this essay, Henderson did recognize that it is quite possible that totally different forms of life could rely on totally different chemistry, if indeed locations existed where such conditions were possible—locations that were unimaginable in 1913.
2. These arguments go back further than might be expected. In an 1834 volume, William Whewell wrote:

   > It has been shown in the preceding chapters that a great number of quantities and laws appear to have been *selected* [emphasis original] in the construction of the universe; and that by the adjustment to each other of the magnitudes and laws thus selected, the constitution of the world is what we find it, and is fitted for the support of vegetables and animals, in a manner in which it could not have been, if the properties and quantities of the elements had been different from what they are.

   William Whewell, *Astronomy and General Physics Considered with Reference to Natural Theology* (London: William Pickering), 141–2.
3. Fred Hoyle, "On Nuclear Reactions Occurring in Very Hot Stars. I: The Synthesis of Elements from Carbon to Nickel," *Astrophysical Journal, Supplement Series* 1 (1954): 121—46, doi:10.1086/190005.
4. Lawrence Krauss and Michael Turner, "The Cosmological Constant Is Back," *General Relativity and Gravitation* 27 (1995): 1,137–44, doi:10.1007/BF02108229.
5. Irit Maor, Lawrence Krauss, and Glenn Starkman, "Anthropic Arguments and the Cosmological Constant, with and without the Assumption of Typicality," *Physical Review Letters* 100, no. 4 (2008), doi:10.1103/PhysRevLett.100.041301.

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