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The Fine-Tuning Evidence is Convincing

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In this essay I will argue that the evidence is convincing that in multiple ways the structure of the universe must be precisely set—that is, "fine-tuned"—for the existence of embodied conscious agents (ECAs) of comparable intelligence to humans, not merely for the existence of any form of life as Stenger often assumes.[1] Many prominent cosmologists and physicists concur—for example, Sir Martin Rees, former Astronomer Royal of Great Britain.[2] In response, Victor Stenger, my interlocutor, often argues that a satisfactory "scientific" explanation can be given of the fine-tuning, and hence there is no need to invoke God or multiverses. This objection will only work if the explanation does not merely transfer the fine-tuning up one level to the newly postulated laws, principles, and parameters. As astrophysicists Bernard Carr and Martin Rees note, "even if all apparently anthropic coincidences could be explained [in terms of some deeper theory], it would still be remarkable that the relationships dictated by physical theory happened also to be those propitious for life."[3] To explain away the fine-tuning, therefore, one must show that one's deeper explanation is itself not very special, a requirement Stenger largely ignores.

Elsewhere I have developed the fine-tuning argument in substantial detail,[4] but can only summarize the basics here. In brief, I first consider the claim that there is no God and that there is only one universe—what I call the naturalistic single-universe hypothesis. I then argue that given this hypothesis and the extreme fine-tuning required for ECAs, it is very surprising—in technical language, very epistemically improbable—that a universe exists with ECAs. I then argue that we can glimpse a good reason for God to create a universe containing ECAs that are vulnerable to each other and to the environment: specifically, such vulnerable ECAs can affect each other for good or ill in deep ways. Besides being an intrinsic good, I argue that this ability to affect one another's welfare allows for the possibility of eternal bonds of appreciation, contribution, and intimacy, which elsewhere I argue are of great value.[5] Since moral evil and suffering will inevitably exist in a universe with such ECAs, I conclude that the existence of the combination of an ECA-structured universe and the type of evils we find in the world is not surprising under theism. Thus, by the likelihood principle of confirmation theory (in which a body of evidence confirms the hypothesis under which it is least surprising), the existence of such an ECA-structured universe, even when combined with the existence of evil, confirms theism over the naturalistic single-universe hypothesis. Finally, I argue that the existence of multiple universes does not adequately account for many cases of fine-tuning: one reason is that the laws governing whatever generates the many universes would have to itself be fine-tuned to produce even one life-permitting universe; another is that the universe is not fine-tuned for mere observers—which is the only kind of fine-tuning the multiverse hypothesis can explain—but rather for ECAs that can significantly interact with each other.[6]

In this essay I will focus on the fine-tuning evidence, considering three different kinds of fine-tuning: the fine-tuning of the laws/principles of physics, the fine-tuning of the initial distribution of mass-energy in the universe, and the fine-tuning of the fundamental parameters/constants of physics. Because of limitations of space, I will only elaborate on a few of the most accessible cases of fine-tuning and respond to Stenger's objections to them. Also, I agree with Stenger that some popularly cited cases of fine-tuning do not hold up to careful scrutiny. This is why it is critical to carefully develop and evaluate each purported case. I did this for a limited number of cases elsewhere,[7] and am currently finishing a comprehensive treatment of the fine-tuning evidence; physicist Luke Barnes has also presented an extensive list of cases of fine-tuning along with an extensive critique of Stenger.[8]

■ 1. LAWS OF NATURE

As an example of the fine-tuning of the laws and principles of physics, consider the requirements of constructing atoms, the building blocks of life. As a thought experiment, suppose that one were given the law of energy and momentum conservation, the second law of thermodynamics, and three fundamental particles with masses corresponding to that of the electron, proton, and neutron. Further suppose that one were asked to decide the properties these particles must have and the laws they must obey to obtain workable building blocks for life. First, one would need some principle to prevent the particles from decaying, since by the second law of thermodynamics particles will decay to particles with less mass-energy if they can. For electrons, protons, and neutrons in our universe, this is prevented by the *conservation of electric charge* and the *conservation of baryon number*. Since there are no electrically charged particles lighter than an electron, the conservation of electric charge prevents electrons from decaying into lighter particles—such as less massive neutrinos and photons. (If an electron did decay, there would be one less negatively charged particle in the universe, and thus the sum of the negative plus positive charges in the universe would have changed in violation of this conservation law.) Similarly, protons and neutrons belong to a class of particles called baryons. Since there are no baryons lighter than these, baryon conservation prevents a proton from decaying into anything else, and allows neutrons to decay only into the lighter proton (plus an electron and neutrino).

Next, there must be forces to hold the particles together into structures that can engage in complex interactions. In our universe, this is accomplished by two radically different forces. The first force, the *electric force*, holds electrons in orbit around the nucleus; if this, or a relevantly similar force, did not exist, no atoms could exist. Another force, however, is needed to hold protons and neutrons together. The force that serves this function in our universe is called the *strong nuclear force*, and it must have at least two special characteristics. First, it must be stronger than the repulsive electric force between the positively charged protons. Second, it must be very short range—which means its strength must fall off much, much more rapidly than the inverse square law ($1/r^2$) characteristic of the electric force and gravity. Otherwise, because of the great strength it must have—around 10^{40} times stronger than the gravitational attraction between protons and neutrons—all protons and neutrons in any solid body would be almost instantly sucked together, eliminating the building blocks necessary for life.

Finally, at least two more laws/principles are needed. First, without an additional law/principle, classical electromagnetic theory predicts that an electron orbiting a nucleus will radiate away its energy, rapidly falling into the nucleus. This problem was resolved in 1913 by Niels Bohr's introduction of the quantization hypothesis, which says that electrons can occupy only certain discrete orbital energy states in an atom. Second, to have complex chemistry, something must prevent all electrons from falling into the lowest orbital. This is accomplished by the Pauli exclusion principle, which dictates that no two electrons can occupy the same quantum state—which in turn implies that each atomic orbital can contain at most two electrons. This principle also serves another crucial role, that of guaranteeing the stability of matter, as originally proved by Freeman Dyson and Andrew Lenard in 1967.[9]

The above examples show that building blocks for highly complex, self-replicating structures require the right set of laws and principles. If, for instance, one of the above laws/principles were removed (while keeping the others in place), ECAs would be impossible. This is not all, though. For those building blocks—such as carbon and oxygen—to be synthesized (as happens in stars), and then for an adequate habitat to exist for ECAs to evolve (such as a planet orbiting a stable star of the right temperature), requires even more of the right laws. For example, a law is needed to tell masses to attract each other to form stars and planets—that is, a law of "gravity."

In various places Stenger has argued that the laws/principles of physics do not need fine-tuning because they are based on a combination of symmetry and the random breaking of it.[10] Symmetries reflect some property being the same under a specified transformation—one's face is symmetrical if it looks the same in a mirror—which transforms the part of the face that is left of center to right of center and vice versa. Since symmetries are about sameness, and since one would expect things to remain the same without an outside agent, Stenger concludes that symmetries are the natural state of affairs and therefore do not need further explanation. One cannot explain the laws of nature by merely appealing to symmetry, however: if the universe were completely symmetrical, it would remain the same under all possible interchanges of elements, and therefore would comprise one undifferentiated whole. Consequently, as the famous scientist Pierre Curie pointed out, "dissymmetry is what creates the phenomena." [11] Stenger attempts to attribute this necessary dissymmetry to *randomly* broken symmetry.[12] But why would randomly broken symmetry give rise to precisely the right set of laws required for life instead of the vast range of other possibilities? Stenger never tells us and thus evades the real issue.

2. FINE-TUNING OF INITIAL CONDITIONS

The initial distribution of mass-energy must fall within an exceedingly narrow range for life to occur. According to Roger Penrose, one of Britain's leading theoretical physicists, "In order to produce a universe resembling the one in which we live, the Creator would have to aim for an absurdly tiny volume of the phase space of possible universes."[13] How tiny is this volume? According to Penrose, this volume is one part in $10^{10^{123}}$ of the entire volume.[14] (10^{123} is 1 followed by 123 zeroes, with 10 raised to this power being enormously larger.) This is vastly smaller than the ratio of the volume of a proton ($\sim 10^{-45}$ m^3) to the entire volume of the visible universe ($\sim 10^{84}$ m^3); the precision required to "hit" the right volume by chance is thus enormously greater than would be required to hit an individual proton if the entire visible universe were a dartboard!

Since in standard applications of statistical mechanics, the volume of phase space corresponds to the probability of the system being in that state, it turns out that the configuration of mass-energy necessary to generate a life-sustaining universe such as ours was enormously improbable—one part in $10^{10^{123}}$. Since entropy is the logarithm of the volume of phase space, another way of stating the specialness of the initial state is to say that to support life like ours, the universe must have been in an exceedingly low entropy state relative to its maximum possible value.

Two of the most popular attempted scientific explanations of this low entropy are (1) to combine inflationary cosmology with a multiverse hypothesis, or (2) to invoke some special law that requires a uniform gravitational field, and hence maximally low entropy, at the universe's beginning. Both of these "explanations" are very controversial, with Penrose arguing on theoretical grounds that inflationary cosmology could not possibly explain the low entropy and others arguing that Penrose's solution—in which there is a special law—simply reinstantiates the problem elsewhere.[15]

I do not have space to review all the proposals here. I merely note that even if a solution is found, it will likely involve postulating a highly special theoretical framework (such as an inflationary multiverse), and will therefore involve a new fine-tuning of the laws of nature. To argue for this, I will begin by looking at Stenger's purported scientific solution to the low entropy problem, one that does not appear to require any special theoretical framework or law—namely, the claim that it is the result of the fact that the universe started out very small in size. Stenger claims that because the very early universe was equivalent to a black hole, it had the highest possible entropy for an object that size, and thus was in the most probable (and hence least special) state. Yet, he claims, this was a much lower entropy state than that of the current universe:

> I seem to be saying that the entropy of the universe was maximal when the universe began, yet it has been increasing ever since. Indeed, that's exactly what I am saying. When the universe began, its entropy was as high as it could be for an object that size because the universe was equivalent to a black hole from which no information can be extracted.[16]

Stenger's claims are completely backwards. The standard Bekenstein–Hawking formula for the entropy of a black hole shows that if the matter in the universe were compressed into a black hole, its entropy would be *far larger* than that of the current universe. As California Institute of Technology cosmologist Sean Carroll notes,

> The total entropy within the space corresponding to our early universe turns out to be about 10^{88} at early times…If we took all of the matter in the observable universe and collected it into a single black hole, it would have an entropy of 10^{120}. That can be thought of as the maximum possible entropy obtainable by re-arranging the matter in the universe, and that's the direction in which we're evolving.[17]

Thus if, as Stenger claims, the universe began as a black hole, its entropy would have been far larger than it is now, contradicting the second law of thermodynamics, which requires that entropy always increase. As Carroll notes, the challenge is to explain why the "early entropy, 10^{88}, [was] so much lower than the maximum possible entropy, 10^{120}."[18] Stenger not only has failed to address this problem, he has failed to understand the problem itself.

Apart from the above calculation, there are many fatal objections to the claim that the low entropy of the early universe was due to the universe's small size, objections that have been widely known for more than thirty years but of which Stenger seems unaware. Penrose, for instance, notes that if the universe were eventually to collapse back in on itself, the second law of thermodynamics implies that entropy will increase even though the universe would be getting smaller in size.[19] Further, it is highly implausible to postulate that the second law would be violated: if entropy were to decrease with time, then photons of light would return to burnt-out stars and cause the nuclear fuel in the stars to undergo a reverse process of fusion; buildings that had fallen into ruin would come back together; and the like. This is clearly something we would not expect.

Summarizing the current consensus, philosopher of physics Huw Price states that "the smooth early universe turns out to have been incredibly 'special', even by the standards prevailing at the time. Its low entropy doesn't depend on the fact that there were fewer possibilities available."[20]

I am not saying here that some more fundamental theory will not be found that "explains" the initial (and current) low entropy of the universe, only that the theory would almost certainly have to involve some set of special mechanisms to yield such a low entropic initial state; otherwise physicists would almost surely have found it by now.

3. FUNDAMENTAL CONSTANTS/PARAMETERS OF PHYSICS

Besides laws and initial conditions, ECAs require that the so-called fundamental constants of physics have the right values. Although there are around seven that need fine-tuning, I will only consider two of these: the constant governing the strength of gravity and the cosmological constant. (Other constants that need fine-tuning are the weak force strength, the strong force strength, the strength of electromagnetism, the strength of the primordial density fluctuations, and the neutron–proton mass difference.)

The gravitational constant G appears in Newton's law of gravity, $F = Gm_1m_2/r^2$, along with Einstein's law of gravity. (Here F is the force between two masses, m_1 and m_2, separated by a distance r.) The value of G depends on the units one uses: for example, in the Standard International (SI) units of meters, kilograms, seconds, its value is $6.674 \times 10^{-11}\ \mathrm{m^3/kg/s^2}$, whereas in Planck (or so-called natural) units its value is stipulated to be 1. To avoid this dependence on units, physicists often use a unitless measure of the strength of gravity, α_G, commonly defined as $\alpha_G \equiv G(m_p)^2/\hbar c$, where m_p is the mass of the proton, $\hbar$ is the reduced Planck's constant (i.e., $h/2\pi$), and c is the speed of light.[21] Since the units of G, m_p, $\hbar$, and c all cancel out, α_G is a pure number ($\sim 5.9 \times 10^{-39}$) that does not depend on the choice of units, such as those for length, mass, and time. In the Internet preprint (November 2010) of his essay in this volume and elsewhere, [22] Stenger has fallaciously claimed that since the strength of gravity could be defined in terms of the mass, m_x, of any elementary particle (i.e., $\alpha_G \equiv G(m_x)^2/\hbar c$), there can be no fine-tuning of α_G. The freedom to define α_G in terms of other elementary particles, however, clearly does not affect the fine-tuning of $G(m_p)^2/\hbar c$, only whether one calls it the "strength of gravity." Thus Stenger's claims are irrelevant to whether $G(m_p)^2/\hbar c$ is fine-tuned.

Next, I define a constant as being fine-tuned for ECAs if and only if the range of its values that allow for ECAs is small compared to the range of values for which we can determine whether the value is ECA permitting, a range I call the "comparison range." For the purposes of this essay, I will take the comparison range to be the range of values for which a parameter is defined within the current models of physics. For many physical constants, such as the two presented here, this range is given by the Planck scale, which is determined by the corresponding Planck units for mass, length, and time. As Cambridge University mathematical physicist John Barrow notes, Planck units define the limits of our current models in physics:

> Planck's units mark the boundary of applicability of our current theories. To understand [for example] what the world is like on a scale smaller than the Planck length, we have to understand fully how quantum uncertainty becomes entangled with gravity.[23]

Barrow goes on to state that in order to move beyond the boundary set by Planck units, physicists would need a theory that combines quantum mechanics and gravity; all current models treat them separately. Consequently all fine-tuning arguments are relative to the current models of physics. This does not mean that the arguments must assume that these models correspond to reality, only that the variety of cases of fine-tuning in our current models strongly suggests that fine-tuning is a fundamental feature of our universe, whatever the correct models might be.

Since Planck units are defined by requiring G, *c*, and $\hbar$ to be 1, the above definition of α_G implies that $\alpha_G = m_p^2$. Thus, in Planck units, α_G is determined by the mass of the proton. Now, the Planck scale is reached when the particles of ordinary matter exceed the Planck mass. For the proton, this is about 10^{19} of its current mass, corresponding to a 10^{38} increase in α_G (since $\alpha_G = m_p^2$ in Planck units), making it very close to the strength of the strong nuclear force. This yields a theoretically possible range for α_G of 0 to 10^{38} α_{G0}, where α_{G0} represents the value of α_G in our universe.

One type of fine-tuning of α_G results from planetary constraints, as illustrated by considering the effect of making α_G a billion-fold larger in our universe, still very small compared to the Planck scale. In that case, no ECAs could exist on Earth since they would all be crushed. Suppose, however, that one both increased α_G and reduced Earth's size. Would that solve the problem? No, for three reasons. First, since ECAs seem to require a minimal brain size, if Earth were too small, there would not be a large enough ecosystem for ECAs to evolve. Second, smaller planets cannot produce enough internal heat from radioactive decay to sustain plate tectonics. It is estimated that a planet with less than 0.23 the mass of the Earth, or less than about one-half Earth's radius, could not sustain plate tectonics for enough time for ECAs to evolve.[24] Plate tectonics, however, is generally regarded as essential to both stabilizing the atmosphere (by recycling carbon dioxide [CO_2]) and keeping mountains from being eroded to sea level;[25] thus without it, terrestrial ECAs would be impossible. Because the force *F* of gravity on a planet's surface is proportional to its radius *R* when the density

D is kept constant ($F \propto \alpha_G DR$),[26] this means that any planet in our universe on which ECAs evolved would have a surface gravitational force at least one-half that of Earth's (assuming a similar composition). This gives a twofold leeway in increasing α_G before the surface force on any ECA-containing planet would have to be proportionally greater. If, for instance, α_G were increased by 100-fold, the surface force on any planet with terrestrial ECAs would be at least fifty times as large. Even if terrestrial ECAs could exist on such a planet, it would be far less optimal for them to develop civilization, especially advanced scientific civilization (think of the difficulty of building houses or forging metals with the surface force of gravity fifty times larger). Thus α_G appears to be not only fine-tuned for the existence of ECAs, but also fine-tuned for civilization. Using the theoretically possible range for α_G, this consideration yields a degree of fine-tuning of at least $100/10^{38}$—that is, 1 part in 10^{36}.[27]

Third, to retain an atmosphere, the average kinetic energy of the molecules in the atmosphere must be considerably less than the energy required for a molecule to escape the planet's gravitational pull—called the molecule's "gravitational binding energy," $E_{G.}$ For a life-permitting planet, this energy is fixed by the temperature required for liquid water—between 0°C and 100°C. In our universe, it is estimated that a planet with a mass of less than 0.07 that of Earth, or a radius of two-fifths that of Earth, would lose its atmosphere by 4.5 billion years.[28]

Now $E_G \propto \alpha_G R^2$, whereas $F \propto \alpha_G R$, as noted above.[29] This means, for instance, that if α_G were increased by a factor of 100 and the radius of Earth were decreased by the same factor, the force on the surface would remain the same, but E_G would have decreased by a factor of 1/100 (i.e., $100 \times (1/100)^2$). This would be a far greater decrease in E_G than the factor of $(2/5)^2 \sim 1/5$ allowable decrease calculated using the lower radius limit above. Increasing α_G therefore can only be partially compensated for by decreasing planetary size if the planet is to remain life-permitting. In fact, simple calculations reveal that even with the maximal compensatory shrinking of the planet, the force must increase as the square root of the increase α_G after the factor 2/5 leeway mentioned above is taken into account.[30] If, for example, one increased α_G by 10,000, the minimal gravitational force on the surface of any ECA-permitting planet would increase by a factor of 40 (i.e., $\sqrt{10{,}000} \times [2/5]$). In addition to these two reasons, there are several other stringent constraints on α_G for the existence of life-sustaining stars.[31] So the constraints on gravity are significantly overdetermined.

In his Internet preprint of the accompanying chapter, Stenger claims that α_G's fine-tuning has a natural scientific explanation that involves no surprise. Says Stenger, "The reason gravity is so weak in atoms is the small masses of elementary particles. This can be understood to be a consequence of the standard model of elementary particles in which the bare particles all have zero masses and pick up small corrections by their interactions with other particles."[32] Although correct, Stenger's claim does not explain the fine-tuning, but merely transfers it elsewhere.

The new issue is why the corrections are so small compared to the Planck scale. Such small corrections seem to require an enormous degree of fine-tuning, which is a general and much discussed problem within the standard model. As particle physicist John Donoghue notes, for the various particles in the standard model, "their 'bare' values plus their quantum corrections need to be highly fine-tuned in order to obtain their observed values [such as the relatively small mass of the proton and neutron]."[33] Stenger's attempt to explain away this apparent fine-tuning is like someone saying protons and neutrons are made of quarks and gluons, and since the latter masses are small, this explains the smallness of the former masses. Such an explanation would merely relocate the fine-tuning.

Next, I turn to the most widely discussed case of fine-tuning in the physics literature, that of the cosmological constant, or more generally, the "dark energy" density of the universe. This fine-tuning has been discussed for more than thirty years and is still unresolved, as can be seen by searching the physics archive at http://arxiv.org/find. Dark energy is any energy existing in space that, if positive, would of itself cause the universe's expansion to accelerate; in contrast, normal matter and energy (such as photons of light) cause it to decelerate. If the dark energy density, ρ_d, is too large, this expansion will accelerate so fast that no galaxies or stars can form, and hence no complex life.[34] The degree of fine-tuning of ρ_d is given by the ratio of its life-permitting range to the range of possible values allowed within our models. Assuming ρ_d is positive, it can have a value from zero to the Planck energy density, which is approximately 10^{120} times the standardly estimated maximum life-permitting value, ρ_{dlife}, of the dark energy density. Hence the commonly cited value of this fine-tuning is 1 part in 10^{120} ($\rho_{dlife}/10^{120}\rho_{dlife}$). This fine-tuning problem is given added force by the fact that a central part of the framework of current particle physics and cosmology invokes various fields that contribute anywhere from $10^{53}\rho_{dlife}$ to $10^{120}\rho_{dlife}$ to ρ_d. This seems to require the postulation of unknown fields with extremely fine-tuned energy densities that exactly, or almost exactly, cancel the energy densities of the fields in question to make ρ_d less than $\rho_{dlife.}$

Could this fine-tuning be circumvented by postulating a new symmetry or principle that requires that the dark energy be zero? This proposal faces severe problems. First, inflationary cosmology—the widely accepted, though highly speculative, framework in cosmology—requires that the dark energy density be enormously larger than ρ_{dlife} in the very early universe. Thus one would have to postulate that this symmetry or principle only began to apply after some very early epoch was reached—a postulate that in turn involves a "fine-tuning" of some combination of the laws, principles, or fundamental parameters of physics. Second, in the late 1990s it was discovered that the expansion of the universe is accelerating, which is widely taken as strong evidence for a small positive value of ρ_d. A positive value of ρ_d, however, is incompatible with any principle or symmetry requiring that it be zero. Perhaps, as Stenger often suggests, some set of laws or principles requires that it have a very small nonzero value. Even if this is correct, the fine-tuning is likely to be transferred to why the universe has the right set of laws/principles to make ρ_d fall into the small life-permitting range (0 to ρ_{dlife}) instead of somewhere else in the much, much larger range of conceivable possibilities (0 to 10^{120} ρ_{dlife}). Stenger never addresses this issue, seemingly oblivious to this transference problem.[35]

4. CONCLUSION

The above cases of fine-tuning alone should be sufficient to show that, apart from a multiverse hypothesis, the issue of fine-tuning is not likely to be resolved by future physics. Even if physicists found a theory that entailed that initial conditions of the universe and the constants of physics fall into the ECA-permitting range, that would still involve an extreme fine-tuning at the level of the form of the laws themselves. Finally, note that the cases of fine-tuning are multiple and diverse, so even if one cannot be certain of any given case, together they provide a compelling case for an extraordinarily fine-tuned universe.

NOTES

1. I would like to thank Nathan Van Wyck, Øystein Nødtvedt, David Schenk, and physicists Luke Barnes, Daniel Darg, Stephen Barr, and Don Page for helpful comments on the penultimate version of this chapter. Finally, I would especially like to thank the John Templeton Foundation and Messiah College for supporting the research that undergirds this chapter. This essay was written before Stenger published his recent book (*The Fallacy of Fine-Tuning: Why the Universe Is Not Designed for Us* (Amherst, NY: Prometheus Books, 2011)) and so mostly references his previous work on fine-tuning.

2. Martin Rees, *Just Six Numbers: The Deep Forces That Shape the Universe* (New York: Basic Books, 2000).

3. Bernard Carr and Martin Rees, "The Anthropic Principle and the Structure of the Physical World," *Nature* 278 (1979): 612.

4. See, Robin Collins, "The Teleological Argument: An Exploration of the Fine-Tuning of the Universe," in *The Blackwell Companion to Natural Theology*, ed. William Lane Craig and J. P. Moreland (Chichester: John Wiley & Sons, 2009), 202–281.

5. See Robin Collins, "The Connection Building Theodicy," in *The Companion to the Problem of Evil*, ed. Dan Howard-Snyder and Justin McBrayer (Malden, MA: Wiley-Blackwell, forthcoming).

6. For this last argument, see Robin Collins, "The Anthropic Principle: A Fresh Look at its Implications," in *A Companion to Science and Christianity*, ed. James Stump and Alan Padgett (Malden, MA: Wiley-Blackwell, 2012).

7. Robin Collins, "Evidence for Fine-Tuning," in *God and Design: The Teleological Argument and Modern Science*, ed. Neil A. Manson (London: Routledge, 2003), 178–199.

8. Luke A. Barnes, "The Fine-Tuning of the Universe for Intelligent Life," http://arxiv.org/abs/1112.4647. My manuscript is tentatively entitled *Cosmic Fine-Tuning: The Scientific Evidence.*

9. Elliott Lieb, "The Stability of Matter," *Reviews of Modern Physics* 48, no. 4 (1976): 553–569.

10. For example, see Victor J. Stenger, "Natural Explanations for the Anthropic Coincidences," *Philo* 3, no. 2 (2000): 50–67.

11. Quoted in Elena Castellani, "On the Meaning of Symmetry Breaking," in *Symmetries in Physics: Philosophical Reflections*, ed. Katherine Brading and Elena Castellani (Cambridge: Cambridge University Press, 2003), 324.

12. Stenger, "Natural Explanations."

13. Roger Penrose, *The Emperor's New Mind: Concerning Computers, Minds, and the Laws of Physics* (New York: Oxford University Press, 1989), 343.

14. Ibid.

15. See Roger Penrose, *The Road to Reality: A Complete Guide to the Laws of the Universe* (New York: Alfred A. Knopf, 2004), 753–757. Also see Collins, "Teleological Argument," Section 6.3, 262–272.

16. Victor J. Stenger, *God: The Failed Hypothesis: How Science Shows That God Does Not Exist* (Amherst, NY: Prometheus Books, 2007), 120.

17. Sean Carroll, *From Eternity to Here: The Quest for the Ultimate Theory of Time* (New York: Dutton, 2010), 62.

18. Ibid., 63.

19. Penrose, *The Emperors' New Mind*, 329.

20. Huw Price, *Time's Arrow and Archimedes' Point: New Directions for the Physics of Time* (Oxford: Oxford University Press, 1996), 81–82.

21. One could also define α_G relative to other elementary particles, but the mass of the proton or neutron is the usual choice in these contexts because they constitute almost the entire mass of normal atomic matter.

22. Victor J. Stenger, "The Universe Shows No Evidence for Design," http://www.colorado.edu/philosophy/vstenger/Fallacy/NoDesign.pdf (accessed January 10, 2011); and Stenger, *The Fallacy of Fine-Tuning*, 151–152.

23. John Barrow, *The Constants of Nature: The Numbers That Encode the Deepest Secrets of the Universe* (New York: Vintage Books, 2004), 43.

24. Darren M. Williams, James F. Kasting, and Richard A. Wade, "Habitable Moons Around Extrasolar Giant Planets," *Nature* 385 (January 16, 1997): 235.

25. Ibid.

26. By Newton's law of gravity, $F \propto \alpha_G M/R^2 \propto \alpha_G DR^3/R^2 = \alpha_G DR$, where M is the mass of the planet for the variation of surface force considered here. The density is largely independent of the size of the planet.

27. Equivalently, in Planck units m_p must be fine-tuned to 1 part in 10^{18}.

28. Williams et al., "Habitable Moons," 235.

29. $E_G \propto \alpha_G M/R \propto \alpha_G DR^3/R = \alpha_G DR^2$.

30. Since $E_G \propto \alpha_G R^2$, to hold E_G constant (and thus retain an atmosphere), R can only decrease by the square root of the increase in α_G. Hence, since $F \propto \alpha_G R$, F must increase by the square root of the increase in α_G.

31. See Collins, "Evidence for Fine-Tuning," 192–194, and Bernard Carr, "The Anthropic Principle Revisited," in *Universe or Multiverse?*, ed. Bernard Carr (Cambridge: Cambridge University Press, 2007), 79.

32. Stenger, "Universe Shows No Evidence."

33. John F. Donoghue, "The Fine-Tuning Problems of Particle Physics and Anthropic Mechanisms," in *Universe or Multiverse?*, ed. Bernard Carr (Cambridge: Cambridge University Press, 2007), 231.

34. ρ_d could also be negative. If ρ_d is too large in the negative direction $(-\rho_d < -\rho_{\text{dlife}})$, the universe would collapse too soon for life to develop.

35. Even if the acceleration is due to something else, such as a small correction term in Einstein's general theory of relativity, the fine-tuning would merely be transferred elsewhere—e.g., to why the correction term is so small compared to the Planck scale.

FOR FURTHER READING

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