RESEARCH ARTICLE

Cosmological Natural Selection and the Purpose of the Universe

ANDY GARDNER[1,2] AND JOSEPH P. CONLON[2,3]

[1]*Department of Zoology, University of Oxford, Oxford, OX1 3PS, United Kingdom;* [2]*Balliol College, University of Oxford, Oxford, OX1 3BJ, United Kingdom; and* [3]*Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford, OX1 3NY, United Kingdom*

Received 22 December 2012; Revised 18 March 2013; accepted 19 March 2013

The cosmological natural selection (CNS) hypothesis holds that the fundamental constants of nature have been fine-tuned by an evolutionary process in which universes produce daughter universes via the formation of black holes. Here, we formulate the CNS hypothesis using standard mathematical tools of evolutionary biology. Specifically, we capture the dynamics of CNS using Price's equation, and we capture the adaptive purpose of the universe using an optimization program. We establish mathematical correspondences between the dynamics and optimization formalisms, confirming that CNS acts according to a formal design objective, with successive generations of universes appearing designed to produce black holes. *Complexity 18: 48–56, 2013*

Key Words: black hole; evolution; formal Darwinism; multiverse; Price's equation

INTRODUCTION

Between distances of 10^{-21} and 10^{26} m, physical reality is accurately described by the Standard Model of particle physics and the ΛCDM cosmological model [1, 2]. Together, these contain $\sim$30 input parameters [3], which are known to be constant across cosmological distances to within approximately one part in 100,000, with no strong evidence that they vary at all in time or space (e.g., see [4]). These include inter alia the strengths of the three fundamental forces, $\alpha_{SU(3)}$, $\alpha_{SU(2)}$, and $\alpha_{U(1)}$ and the Yukawa couplings (masses) of the elementary particles, such as y_e, y_μ, and y_τ. The precise numerical values of these constants determine much of the physics of our universe and pose a double conundrum for physicists and philosophers. First, the values have a high degree of arbitrariness: they are dimensionless parameters that range over eight orders of magnitude, for no known reason. Second, it is generally acknowledged that even rather small modifications to some of these values would lead to universes that are vastly less complex than our own (Ref. [3]; but see Ref. [5] for a contrary view).

For example, the cosmological constant Λ—that is, the background energy density of the universe—is empirically shown to be approximately equal to the mass-energy density of one hydrogen atom per cubic meter [6, 7]. However, quantum field theory implies the existence of calculable

Correspondence to: Andy Gardner; Department of Zoology, University of Oxford, Oxford OX1 3PS, United Kingdom.
E-mail: andy.gardner@zoo.ox.ac.uk

©2013 Wiley Periodicals, Inc., Vol. 18 No. 5
DOI 10.1002/cplx.21446
Published online 3 Month 2013 in Wiley Online Library
(wileyonlinelibrary.com)

contributions to Λ that are 60 orders of magnitude larger than this observed value (for a detailed review, see Ref. [8]). Although such predicted values are theoretically natural, the corresponding universe would expand so quickly that there would appear to be no possibility of matter accumulating to form stars, galaxies, and life. In fact, galaxy formation—which is probably necessary for the existence of life—appears to require that Λ be within a few orders of magnitude of its observed value [9]. A second example is the neutron–proton mass difference. The neutron (mass 1.675×10^{-27} kg) is heavier than the proton (mass 1.673×10^{-27} kg) by $\sim$0.1%. A free neutron decays to a proton with a half-life of 886 s. If the mass difference were reversed, the proton would be unstable and free protons would decay to neutrons via the weak interaction. This would render hydrogen unstable, and chemistry—as conventionally understood—would not exist.

Why does the universe appear so contrived? A popular answer is to invoke observer bias. In particular, the "weak anthropic principle" notes that only a universe that supports life may be observed by its residents, so we should not be surprised to find that our universe supports life [10, 11]. However, some have found this explanation unsatisfying. For example, if there is only one universe, then the weak anthropic principle explains why it is complex given that it is observed, but does not explain why it complex and observed rather than simple and unobserved (see Ref. [11] for a detailed review). Consequently, an alternative explanation has been proposed by Smolin [12–14]: the fundamental constants of nature might have been literally fine-tuned, by a process of cosmological natural selection (CNS). Specifically, Smolin [12–14] suggests that there is a population of universes—the "multiverse"—in which individual universes vary in their fundamental constants, and give birth to offspring universes via the formation of black holes, with some fidelity of transmission of fundamental constants between parent and offspring. Thus, those universes that are more likely to form black holes leave more descendant universes than their counterparts, resulting in successive generations of universes being better adapted for black-hole formation. Under this view, certain phenomena—such as atoms and stars—are simply means to the end of forming black holes, and life itself is merely an evolutionary byproduct.

This idea relies on several important assumptions, all of which are controversial. First, it is key to the ideas of Smolin [12–14] that the endpoint of black-hole formation is actually a new universe, rather than simply a quantum-mechanical state that will decay over time and ultimately disappear through Hawking radiation. In the context of the AdS/CFT correspondence (a surprising isomorphism between d-dimensional gauge theory and $d+1$-dimensional gravity; [15]), the formation and subsequent decay of a black hole occurs as a regular and unitary procedure within the dual field theory. This does not show evidence for the formation of new universes. Furthermore, a black hole has a finite entropy, given by $S = A/4$, where A is the area of the horizon in units of Planck length squared. Associated with this entropy should be a finite number of microstates, e^S, which should include the baby universes. However, while black-hole entropy is large, it is finite and, in particular, smaller than the entropy that would naturally be associated with a daughter universe.

Second, Smolin [12–14] suggests that the fundamental constants can change during the formation of new universes, but no physical mechanism is known to account for this. Third, Smolin [12–14] assumes that the new universe inherits the constants of the previous universe, up to small variations. However, in the context of the multiverse, one should expect not just the constants of the Standard Model to be ambient, but also the gauge group (set of forces) and particle content of the Standard Model to be ambient properties as well. In this case, one would expect far more dramatic changes to the physical laws (e.g., the absence of electromagnetism as a long-range force) than simply a change in numerical constants. These are all substantial caveats (see [16] for an in-depth review). Here, we proceed on the assumption that they are surmountable.

A separate concern is that Smolin's [12, 14] formal presentation of the CNS argument is nonstandard from the viewpoint of evolutionary biology, which has developed a powerful mathematical toolkit for examining the action of selection and consequent adaptation, in any medium. Specifically, Price's [17, 18] equation of evolutionary genetics has generalized the concept of selection acting upon any substrate and, in principle, can be used to formalize the selection of universes as readily as the selection of biological organisms. In this article, we will use Price's equation to formally capture the action of CNS, and we will use an optimization program to formally capture the idea that the purpose of the universe is to promote the formation of black holes. We will establish links between these two mathematical objects, confirming that CNS operates as if according to the design principle of black-hole formation, so that—in a formal sense—successive generations of universes will appear increasingly well designed to produce black holes.

MODELS AND ANALYSES

An Evolutionary Model of the Universe

We consider a multiverse—a population of universes—separated into discrete and ordered generations. We assume that every generation contains a large, finite number of universes, and we allow for an infinite number of generations. Every universe contains a non-negative integer number of black holes, and we assume a one-to-one

DOI 10.1002/cplx

mapping between the black holes in that generation and the universes in the next generation.

We consider a particular generation, and we denote the number of universes in this focal generation by $n \in \mathbb{N}$ (i.e., a natural number, excluding zero). We assign each of these universes a unique index $i \in I$, and we denote its number of black holes by $b_i \in \mathbb{N}_0$ (i.e., a natural number, including zero). We assume at least one black hole to be present in this generation, such that a subsequent generation does exist [13], but we allow for individual universes to contain zero black holes, in which case they have no descendants in any subsequent generation. We are interested in a set of N characters that vary between universes and are causally responsible for the number of black holes that form within each universe. We denote the value of a focal character in the ith universe by $c_i \in \mathbb{R}$ (i.e., a real number). The ordered list of N character values in the ith universe defines this universe's "character type," which is denoted by $t_i \in \mathbb{R}^N$. The functional relationship between character type and the manufacture of black holes is captured by $b_i = B(t_i)$. This assumes that universes develop deterministically, but we also provide results for stochastic development of universes in the Appendix. We allow for arbitrarily complicated interactions between a universe's constituent character values in determining its success in manufacturing black holes. Finally, we allow for any degree of heritability between parent and offspring universes, and we denote the focal character's arithmetic average value across the offspring of the ith universe by $c'_i = c_i + \Delta c_i$, where $\Delta c_i \in \mathbb{R}$.

Cosmological Natural Selection

We denote the arithmetic average number of black holes produced per universe across all universes in the focal generation of the multiverse by $b = \sum_{i \in I} p_i b_i$, where $p_i = 1/n$ is the weighting given to the ith universe in the focal generation (all n universes having equal weighting). Similarly, we denote the arithmetic average of the focal character's value in the focal generation by $c = \sum_{i \in I} p_i c_i$, and we denote the arithmetic average value of the focal character in the subsequent generation by $c' = \sum_{i \in I} p_i' c'_i$, where $p'_i = (b_i/b) p_i$ is the total weighting given to the offspring of the ith universe in the focal generation (all offspring universes having the same weight). From Price's [17, 18] equation, the change in the arithmetic average of the focal character's value between these two generations is given by $\Delta c = c' - c$, or:

$$\Delta c = \mathrm{cov}_I(b_i/b, c_i) + \mathrm{E}_I((b_i/b)\Delta c_i), \tag{1}$$

where cov and E, respectively, denote a covariance and expectation, taken over the indicated set (see Appendix for details). Price's [17, 18] equation separates evolutionary change into two additive parts: a "selection" component, given here by the covariance term on the right hand side of Eq. (1), and a "transmission" term, given here by the expectation term on the right hand side of Eq. (1). The selection term arises as a consequence of a statistical association between a universe's character value and its production of black holes. The quantity appearing alongside character value in the covariance is, in the context of evolutionary genetics, termed the "target of selection" [19]; that is, relative Darwinian fitness. Thus, the fitness of the ith universe is given by its ability to produce black holes, b_i [13]. The transmission term arises as a consequence of offspring differing from their parents, that is, imperfect inheritance of character values, $\Delta c_i \neq 0$. Such nonselective effects arise in evolutionary genetics as a consequence of processes such as spontaneous mutation and meiotic drive [17]. In the context of CNS, the transmission term captures "mutational" differences between parent and offspring universes.

We can thus formalize the action of CNS as the change in the arithmetic average of the focal character's value owing to differential black-hole production across universes, or:

$$\Delta_S c \equiv \mathrm{cov}_I(b_i/b, c_i). \tag{2}$$

The Purpose of the Universe

The idea that an entity possesses a purpose may be formally captured using the mathematics of optimization [20]. In particular, the entity may be conceived as a maximizing agent, and its objective—and the means it has to pursue this objective—may be defined by an optimization program [21]:

$$s \max_{s \in S} f(s). \tag{3}$$

The key elements of the optimization program are: S, the set of all strategies that may be used; and f, the real-valued objective function, which describes how well the objective is realized upon adoption of each strategy (larger values are better). The optimization program captures purpose as a maximization problem: find the strategy s, belonging to the strategy set S, that maximizes the objective function f.

The optimization program permits a formal definition of optimality. An optimal strategy s^* is any member of the strategy set that cannot be bettered by any other member of the strategy set, that is, $f(s^*) \geq f(s)\ \forall s \in S$. Conversely, a suboptimal strategy (s°) is any member of the strategy set that can be bettered by at least one other member of the strategy set, that is, $\exists\ s \in S$ such that $f(s) > f(s^\circ)$. Importantly, the optimization program allows one to decouple

DOI 10.1002/cplx

TABLE 1

Connecting Dynamics and Design

Numeral	Correspondence
I	If all universes are optimal, there is no scope for CNS
II	If all universes are optimal, there is no potential for positive CNS
III	If all universes are suboptimal, but equally so, there is no scope for CNS
IV	If all universes are suboptimal, but equally so, there is potential for positive CNS
V	If universes vary in their optimality, then there is scope for CNS, and the change in the arithmetic average of every character value owing to CNS is equal to its covariance with relative attained maximand value
VI	If there is neither scope for CNS nor potential for positive CNS, then all universes are optimal

Six mathematical correspondences exist between the action of CNS (expression 2) and the optimization program (expression 4). Full details are given in the Appendix.

the notion of purpose from the notion of optimality. The program can be constructed, making the design objective concrete, without implying that optimality actually obtains.

We consider the idea that the design objective of the universe is to produce black holes [13]. Formally, the universe is considered as a maximizing agent using its character type t as a means to the end of maximizing lifetime manufacture of black holes, $B(t)$. Hence, we write:

$$t \max_{t \in \mathbb{R}^N} B(t). \tag{4}$$

This formalizes the notion of the universe having a purpose. It also permits a formal definition for optimality in relation to the design of universes: an optimal character type (t^*) is any member of the set of possible character types that cannot be bettered, that is, $B(t^*) \geq B(t) \; \forall \; t \in \mathbb{R}^N$. Conversely, a suboptimal character type (t°) is a member of the set of all possible character types that can be bettered, that is, $\exists \; t \in \mathbb{R}^N$ such that $B(t) > B(t^\circ)$.

Connecting Process and Purpose

We now establish mathematical correspondences between the dynamical Eq. (2) that formally captures the process of CNS, and the optimization program (4) that formally captures the design objective of the universe. Two concepts are of interest here. First, the idea of a "scope for CNS": there is no scope for CNS if the action of CNS on the focal character is necessarily zero and, if this is not the case, then there is scope for CNS [19]. Second, the idea of a "potential for positive CNS": there is no potential for positive CNS if there is no character type that would be favored by CNS if we were to introduce it into the multiverse by mutation of one of the existing universes, and there is potential for positive CNS if there is at least one character type that would be favored by CNS if we were to introduce it into the multiverse by mutation [19]. Scope for CNS pertains to variation already present in the focal generation; potential for positive CNS pertains to variation that may subsequently arise.

The mathematical correspondences between the dynamical action of CNS and the optimization program are listed in Table 1 (full details are given in the Appendix). The first five correspondences translate scenarios in the optimization view of the universe as having a design objective of black-hole manufacture into the dynamics of CNS. The sixth correspondence translates in the reverse direction. These are analogous to the six correspondences derived by Grafen [19, 22], Gardner and Grafen [23], and Gardner and Welch [24], in relation to the concept of fitness maximization in evolutionary biology. The view of the universe as a purposeful object that is functioning to manufacture black holes has a mathematical connection to the dynamics of CNS in Smolin's [12–14] conception of the evolution of the multiverse. Put another way, CNS acts as if according to a design objective of black-hole maximization, such that successive generations of universes will be increasingly contrived—that is, appearing designed—as if for the purpose of forming black holes.

DISCUSSION

We have formalized the dynamics of CNS using Price's [17, 18] equation of evolutionary genetics. This equation provides a standard approach for capturing selection arguments within evolutionary biology and beyond [25–28]. We have also formalized the idea of the universe being a purposeful object—with the design objective of black-hole formation—using an optimization program, which is a standard approach for capturing the notions of purpose, goal, or agenda [19, 22, 29]. Finally, we have established formal connections between these two mathematical objects, confirming that CNS acts as if according to a design objective of black-hole formation. Insofar as CNS is an important driver of the evolution of the multiverse (and we make no claim that it is), successive generations of universes will appear increasingly well designed to produce black holes.

This approach mirrors the way in which ideas of selection and design are formalized and connected in evolutionary biology, that is, the theory of Darwinian adaptation [30]. Specifically, the idea of natural selection

DOI 10.1002/cplx

driving genetic change of biological populations is formally captured using Price's equation [17, 19, 22, 25–28, 31]; the idea of individual organisms appearing designed to maximize their Darwinian fitness is formally captured using an optimization program [19, 22, 29]; and the connection between these ideas is formalized by deriving correspondences between these two mathematical objects, translating dynamics into optimization and vice versa [19, 22, 29]. These mathematical results provide formal license to use intentional language in evolutionary biology: for example, selfishness, altruism, and conflicts of interest [32]. This analogy of intentionality not only provides a powerful shorthand that can be translated with fidelity into statements about gene frequency dynamics, but it also defines whole programs of scientific research: for example, parent–offspring conflict and the evolution of altruism (reviewed by Gardner [33]).

The theory of CNS was developed as an alternative to the observer-bias explanation for apparent fine-tuning of the fundamental constants of nature, that is, the weak anthropic principle [34]. This holds that we should be unsurprised by the apparent contrivance of our universe for the purpose of supporting intelligent observers, given that an alternative universe that could not support intelligent observers would not be observed. Thus, the CNS versus observer bias hypotheses concerning the apparent contrivance of the cosmos mirror the Darwinian versus Cuvierian approaches to explaining biological adaptation: although Darwin described a mechanical process that drives the evolution of adaptation, Cuvier suggested that nonadapted organisms, being unable to survive and reproduce, would not be observed, and so our observations of adapted organisms require no special explanation (reviewed by Reiss [35]). Whilst the observer bias hypothesis for apparent cosmological fine-tuning has some predictive power, it does not explain why the universe is fine-tuned and observed rather than not fine-tuned and not observed. Indeed, proponents of the observer-bias view have argued that a full explanation is only achieved by invoking a large multiverse, so that at least one universe appears sufficiently fine-tuned to support intelligent observers (see, e.g., Ref. [11] or [36]). Thus, the notion of a multiverse is central to both the CNS and the observer-bias hypotheses. One potentially desirable feature of the CNS approach is that it removes the observer from the explanation, thereby achieving greater objectivity [37].

CNS differs from biological natural selection in a number of respects. For example, although mortality and competition for resources are basic facts of biological populations, they are entirely absent in the CNS model of the evolving multiverse. These differences have been used to argue that CNS is only weakly analogous to Darwinian natural selection [16]. However, Price's [17, 18] equation captures the essence of selection occurring in any medium, whether cosmological or biological, and it emphasizes that neither mortality nor resource competition are fundamental aspects of selection. Rather, natural selection is the part of change attributable to the covariance between heritable characters and fitness. By framing the CNS hypothesis in terms of Price's [17, 18] equation, we have clarified the fundamental analogy between CNS and Darwinian natural selection.

However, the theory of CNS does differ from Darwinism in three important respects. First, Darwinism was developed as an explanatory framework that could account for apparent design in the biological world, invoking only phenomena whose existence was beyond reasonable doubt; for example, the Malthusian struggle for existence and the heritability of organismal characters [30]. In contrast, the theory of CNS invokes speculative ideas; for example, a multiverse and successive generations of universes that inherit their fundamental constants from their parents, without any evidence for the existence of either phenomenon [12–14]. However, given the importance of selection-like processes for generating apparent design in the natural world, it is arguably sensible to seek a selection-like explanation for the apparent design of our universe [13]. Second, Darwinism yields readily testable predictions, with the diversity of living organisms providing swathes of data against which these predictions may be tested. In contrast, there is only one visible universe against which the predictions of CNS may be tested. However, Smolin [13] has outlined a number of falsifiable predictions made by the theory of CNS, including a reasonably specific upper limit for the mass of neutron stars (see also Refs. [37] and [38]).

Third, although evolutionary arguments typically involve transformations through a well-defined concept of time, this is not true of Smolin's [12–14] CNS hypothesis. Cosmologically, there is no meaningful notion of absolute time even within a single universe: relativity teaches us that there are rather many equally valid time-slicings (technically space-like foliations). This problem is exacerbated by multiple universes. Happily, Price's [17, 18] equation is sufficiently versatile that it can be applied to transformations occurring between any two populations, irrespective of how these are temporally related. Following Smolin [12], we have focused on transformations between generations, where each universe is assigned to the generation immediately subsequent to that of its parent. Although this makes the question of formalizing CNS well posed, the physical meaning of this between-generation transformation remains very unclear.

ACKNOWLEDGMENT

Both authors were supported by research fellowships from Balliol College and the Royal Society of London.

DOI 10.1002/cplx

REFERENCES

1. Nakamura, K., Hagiwara, K.; Hikasa, K.; Murayama, H.; Tanabashi, M.; Watari, T.; Amsler, C.; Antonelli, M.; Asner, D. M.; Baer, H.; Band, H. R.; Barnett, R. M.; Basaglia, T.; Bergren, E.; Beringer, J.; Bernardi, G.; Bertl, W.; Bichsel, H.; Biebel, O.; Blucher, E.; Blusk, S.; Cahn, R. N.; Carena, M.; Ceccucci, A.; Chakraborty, D.; Chen, M.-C.; Chivukula, R. S.; Cowan, G.; Dahl, O.; D'Ambrosio, G.; Damour, T.; de Florian, D.; de Gouvea, A.; DeGrand, T.; Dissertori, G.; Dobrescu, B.; Doser, M.; Drees, M.; Edwards, D. A.; Eidelman, S.; Erler, J.; Ezhela, V. V.; Fetscher, W.; Fields, B. D.; Foster, B.; Gaisser, T. K.; Garren, L.; Gerber, H.-J.; Gerbier, G.; Gherghetta, T.; Giudice, G. F.; Golwala, S.; Goodman, M.; Grab, C.; Gritsan, A. V.; Grivaz, J.-F.; Groom, D. E.; Grünewald, M.; Gurtu, A.; Gutsche, T.; Haber, H. E.; Hagmann, C.; Hayes, K. G.; Heffner, M.; Heltsley, B.; Hernández-Rey, J.J.; Höcker, A.; Holder, J.; Huston, J.; Jackson, J. D.; Johnson, K. F.; Junk, T.; Karle, A.; Karlen, D.; Kayser, B.; Kirkby, D.; Klein, S. R.; Kolda, C.; Kowalewski, R. V.; Krusche, B.; Kuyanov, Yu. V.; Kwon, Y.; Lahav, O.; Langacker, P.; Liddle, A.; Ligeti, Z.; Lin, C.-J.; Liss, T. M.; Littenberg, L.; Lugovsky, K. S.; Lugovsky, S. B.; Lys, J.; Mahlke, H.; Mannel, T.; Manohar, A. V.; Marciano, W. J.; Martin, A. D.; Masoni, A.; Milstead, D.; Miquel, R.; Mönig, K.; Narain, M.; Nason, P.; Navas, S.; Nevski, P.; Nir, Y.; Olive, K. A.; Pape, L.; Patrignani, C.; Peacock, J.A.; Petcov, S.T.; Piepke, A.; Punzi, G.; Quadt, A.; Raby, S.; Raffelt, G.; Ratcliff, B.N.; Richardson, P.; Roesler, S.; Rolli, S.; Romaniouk, A.; Rosenberg, L.J.; Rosner, J.L.; Sachrajda, C.T.; Sakai, Y.; Salam, G.P.; Sarkar, S.; Sauli, F.; Schneider, O.; Scholberg, K.; Scott, D.; Seligman, W. G.; Shaevitz, M.H.; Silari, M.; Sjöstrand, T.; Smith, J.G.; Smoot, G.F.; Spanier, S.; Spieler, H.; Stahl, A.; Stanev, T.; Stone, S.L.; Sumiyoshi, T.; Syphers, M.J.; Terning, J.; Titov, M.; Tkachenko, N.P.; Törnqvist, N.A.; Tovey, D.; Trippe, T.G.; Valencia, G.; van Bibber, K.; Venanzoni, G.; Vincter, M.G.; Vogel, P.; Vogt, A.; Walkowiak, W.; Walter, C.W.; Ward, D.R.; Webber, B.R.; Weiglein, G.; Weinberg, E.J.; Wells, J.D.; Wheeler, A.; Wiencke, L.R.; Wohl, C.G.; Wolfenstein, L.; Womersley, J.; Woody, C.L.; Workman, R.L.; Yamamoto, A.; Yao, W. -M.; Zenin, O.V.; Zhang, J.; Zhu, R.-Y.; Zyla, P.A. (Particle Data Group). Review of particle physics. J Phys G: Nucl Part Phys 2010, 37, 075021.
2. Komatsu, E., Smith, K. M.; Dunkley, J.; Bennett, C. L.; Gold, B.; Hinshaw, G.; Jarosik, N.; Larson, D.; Nolta, M. R.; Page, L.; Spergel, D. N.; Halpern, M.; Hill, R. S.; Kogut, A.; Limon, M.; Meyer, S. S.; Odegard, N.; Tucker, G. S.; Weiland, J. L.; Wollack, E.; Wright, E. L. (WMAP Collaboration). Seven-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Cosmological interpretation. Astrophys J 2011, S192, 18.
3. Tegmark, M.; Aguirre, A.; Rees, M.J.; Wilczek, F. Dimensionless constants, cosmology and other dark matters. Phys Rev D 2006, 73, 023505.
4. King, J.A.; Webb, J.K.; Murphy, M.T.; Carswell, R.F. Stringent null constrain on cosmological evolution of the proton-to-electron mass ratio. Phys Rev Lett 2008, 101, 251304.
5. Stenger, V.J. The Fallacy of Fine-Tuning: Why the Universe is not Designed for Us. Prometheus Books: Amherst, NY, 2011.
6. Riess, A.G., Filippenko, A. V.; Challis, P.; Clocchiatti, A.; Diercks, A.; Garnavich, P. M.; Gilliland, R. L.; Hogan, C. J.; Jha, S.; Kirshner, R. P.; Leibundgut, B.; Phillips, M. M.; Reiss, D.; Schmidt, B. P.; Schommer, R. A.; Smith, R. C.; Spyromilio, J.; Stubbs, C.; Suntzeff, N. B. and Tonry, J. (Supernova Search Team Collaboration). Observational evidence from supernovae for an accelerating universe and a cosmological constant. Astron J 1998, 116, 1009–1038.
7. Perlmutter, S., Aldering, G.; Goldhaber, G.; Knop, R. A.; Nugent, P.; Castro, P. G.; Deustua, S.; Fabbro, S.; Goobar, A.; Groom, D. E.; Hook, I. M.; Kim, A. G.; Kim, M. Y.; Lee, J. C.; Nunes, N. J.; Pain, R.; Pennypacker, C. R.; Quimby, R.; Lidman, C.; Ellis, R. S.; Irwin, M.; McMahon, R. G.; Ruiz-Lapuente, P.; Walton, N.; Schaefer, B.; Boyle, B. J.; Filippenko, A. V.; Matheson, T.; Fruchter, A. S.; Panagia, N.; Newberg, H. J. M.; Couch, W. J. and The Supernova Cosmology Project (Supernova Cosmology Project Collaboration). Measurements of Ω and Λ from 42 high-redshift supernovae. Astrophys J 1999, 517, 565–586.
8. Weinberg, S. The cosmological constant problem. Rev Mod Phys 1989, 61, 1–23.
9. Weinberg, S. Anthropic bound on the cosmological constant. Phys Rev Lett 1987, 59, 2607–2610.
10. Barrow, J.D.; Tipler, F.J. The Anthropic Cosmological Principle. Oxford University Press: Oxford, 1986.
11. Bostrom, N. Anthropic Bias: Observation Selection Effects in Science and Philosophy. Routledge: London, 2002.
12. Smolin, L. Did the universe evolve? Class Quant Grav 1992, 9, 173–191.
13. Smolin, L. The Life of the Cosmos. Oxford University Press: Oxford, UK, 1997.
14. Smolin, L. Cosmological natural selection as the explanation for the complexity of the universe. Physica A 2004, 340, 705–713.
15. Aharony, O.; Gubser, S.S.; Maldacena, J.; Ooguri, H.; Oz, Y. Large N field theories, string theory and gravity. Phys Rep 2000, 323, 183–386.
16. Vaas, R. Is there a Darwinian evolution of the cosmos? In: Proceedings of the MicroCosmos–MacroCosmos Conference, Aachen, 1998. Available at: http://arXiv.org/abs/gr-qc/0205119. Last accessed April 10, 2013.
17. Price, G.R. Selection and covariance. Nature 1970, 227, 520–521.
18. Price, G.R. Extension of covariance selection mathematics. Ann Hum Genet 1972, 35, 485–490.
19. Grafen, A. A first formal link between the Price equation and an optimization program. J Theor Biol 2002, 217, 75–91.
20. Dawkins, R. River Out of Eden. Weidenfeld & Nicolson: London, 1995.
21. von Neumann, J.; Morgenstern, O. Theory of Games and Economic Behavior. Princeton University Press, Princeton, 1944.
22. Grafen, A. Optimization of inclusive fitness. J Theor Biol 2006, 238, 541–563.
23. Gardner, A.; Grafen, A. Capturing the superorganism: A formal theory of group adaptation. J Evol Biol 2009, 22, 659–671.
24. Gardner, A.; Welch, J.J. A formal theory of the selfish gene. J Evol Biol 2011, 24, 1801–1813.
25. Frank, S.A. George Price's contributions to evolutionary genetics. J Theor Biol 1995, 175, 373–388.
26. Frank, S.A. Foundations of Social Evolution. Princeton University Press: Princeton, 1998.
27. Okasha, S. Evolution and the Levels of Selection. Oxford University Press: Oxford, 2006.

DOI 10.1002/cplx

28. Gardner, A. The Price equation. Curr Biol 2008, 18, R198–R202.
29. Grafen, A. Formalizing Darwinism and inclusive fitness theory. Philos Trans R Soc B 2009, 364, 3135–3141.
30. Darwin, C.R. On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life. John Murray: London, 1859.
31. Fisher, R.A. The Genetical Theory of Natural Selection. Clarendon Press: Oxford, 1930.
32. Grafen, A. Formal Darwinism, the individual-as-maximizing-agent analogy and bet-hedging. Proc R Soc Lond B 1999, 266, 799–803.
33. Gardner, A. Adaptation as organism design. Biol Lett 2009, 5, 861–864.
34. Carter, B. Large number coincidences and the anthropic principle in cosmology. In: Confrontation of Cosmological Theories with Observational Data; Longair, M.S. Ed.; Reidel: Dordrecht, 1974; pp 291–298.
35. Reiss, J.O. Not by Design: Retiring Darwin's Watchmaker. University of California Press: London, 2009.
36. Susskind, L. The anthropic landscape of string theory. In: Universe or Multiverse? Carr, B., Ed.; Cambridge University Press: Cambridge, 2007; pp 247–266.
37. Smolin, L. Scientific alternatives to the anthropic principle. In: Universe or Multiverse?; Carr, B., Ed.; Cambridge University Press: Cambridge, UK, 2007.
38. Brown, G.E.; Lee, C.-H.; Rho, M. Kaon condensation, black holes and cosmological natural selection. Phys Rev Lett 2008, 101, 091101.
39. Grafen, A. Developments of the Price equation and natural selection under uncertainty. Proc R Soc Lond B 2000, 267, 1223–1227.

DOI 10.1002/cplx

APPENDIX: CNS UNDER UNCERTAINTY

Here, we show that Eq. (1) arises as a consequence of the notation defined in the main text. We additionally allow for stochastic formation of black holes, not considered in the main text. Stochasticity in the formation of black holes implies that, if we census the focal generation of the multiverse at the moment of initialization of its constituent universes, there is uncertainty in the number of black holes that will be produced in each of these universes. Hence, we consider that there is a (potentially very large) number of different outcomes for black-hole formation in the focal generation of the multiverse (e.g., universe 1 producing one black hole and all other universes producing zero black holes, universe 1 producing two black holes and all other universes producing zero black holes, etc.) and we assign each of these outcomes a unique index $\omega \in \Omega$, where Ω is the set of all possible outcomes. The probability of outcome ω is denoted q_ω, where $0 \le q_\omega \le 1 \ \forall \omega \in \Omega$ and $\sum_{\omega\in\Omega} q_\omega = 1$. We denote the number of black holes formed in the ith universe in the ωth outcome as $b_{i\omega}$, and the expectation of this quantity over uncertainty is $b_i = \sum_{\omega\in\Omega} q_\omega \, b_{i\omega}$. We assume that the multiverse is sufficiently large that uncertainty in the average number of black holes per universe is negligible, that is, $\sum_{i\in I} p_i b_{i\omega} = b \ \forall \omega \in \Omega$. There is no uncertainty regarding the representation $p_i = 1/n$ of the ith universe in the focal generation, but there is uncertainty regarding the representation of the offspring of the ith universe in the subsequent generation, and so we write $p'_{i\omega} = (b_{i\omega}/b)p_i$. Similarly, there is no uncertainty regarding the value of any character c_i that is exhibited by the ith universe in the focal generation, but there is uncertainty regarding the arithmetic average value of the character among the ith universe's offspring in the subsequent generation, and so we write $c'_{i\omega} = c_i + \Delta c_{i\omega}$.

The expected change in the arithmetic average of the character value between the focal and subsequent generation is given by $\Delta c = c' - c$, or:

$$\Delta c = \sum_{\omega\in\Omega}\sum_{i\in I} q_\omega p'_{i\omega} c'_{i\omega} - c. \tag{A1}$$

Making the substitutions $p'_{i\omega} = p_i(b_{i\omega}/b)$ and $c'_{i\omega} = c_i + \Delta c_{i\omega}$, and rearranging, we obtain:

$$\Delta c = \sum_{i\in I} p_i (b_i/b) - c + \sum_{\omega\in\Omega}\sum_{i\in I} q_\omega p_{i\omega}(b_{i\omega}/b)\Delta c_{i\omega}. \tag{A2}$$

Using E and cov to, respectively, denote the expectation and covariance of random variables defined by drawing random universes or outcomes out of the indicated sets with the appropriate weightings, we can rewrite expression (A2) as:

$$\Delta c = \mathrm{cov}_I(b_i/b, c_i) + \mathrm{E}_\Omega(\mathrm{E}_I((b_{i\omega}/b)\Delta c_{i\omega})), \tag{A3}$$

which is the Price equation separation of selection and transmission, averaged over uncertainty [17, 18, 39]. In the special case of deterministic development of universes, that is, only one outcome in set Ω, we may drop the redundant E_Ω and ω notation, recovering Eq. (1) of the main text. However, even in the more general scenario of arbitrary uncertainty over the development of universes, expression (2) of the main text exactly captures the action of CNS, and the subsequent results derived in the main text continue to hold, provided that we understand b_i to represent the expected number of black holes that will be produced by the ith universe.

PROOFS OF THE CORRESPONDENCES

I. *If all universes are optimal, there is no scope for CNS*. If all universes are optimal, according to expression (4), then $b_i = B(t^*) = b^*$ for all $i \in I$, and so $b_i/b = 1$ for all $i \in I$. Hence, from expression (2), $\Delta_S c = \mathrm{cov}_I(b_i/b, c_i) = 0$.

II. *If all universes are optimal, there is no potential for positive CNS*. Mutate a random universe, replacing its character type with $t^\bullet$, and hence its black-hole production is $b^\bullet = B(t^\bullet)$. Note that all other universes have character type t^*, and hence black-hole production $b^* = B(t^*)$. In addition, assign every universe a new character, $\wp = 1$ if it is the mutant universe and $\wp = 0$ if it is an unmutated universe. From expression (2), the response to CNS is $\Delta_S c = \mathrm{cov}_I(b_i/b, \wp_i) = \mathrm{E_I}((b_i/b)\wp_i) - \mathrm{E_I}(\wp_i) = qb^\bullet/(qb^\bullet + (1-q)b^*) - q$, where $q = 1/n$ is the population frequency of the mutant universe. Note that, since $b^\bullet \le b^*$, owing to expression (4), then $\Delta_S c \le 0$ for all $t^\bullet \in \mathbb{R}^N$.

III. *If all universes are suboptimal, but equally so, there is no scope for CNS*. If all universes are equally suboptimal, according to expression (4), then $b_i = B(t^\circ) = b^\circ$ for all $i \in I$, and so $b_i/b = 1$ for all $i \in I$. Hence, from expression (2), $\Delta_S c = \mathrm{cov}_I(b_i/b, c_i) = 0$.

IV. *If all universes are suboptimal, but equally so, there is potential for positive CNS*. Mutate a random universe, replacing its character type with t^*, and hence its black-hole production is $b^* = B(t^*)$. Note that all other universes have character type t°, and hence black-hole production $b^\circ = B(t^\circ)$. In addition, assign every universe a new character, $\wp = 1$ if it is the mutant universe and $\wp = 0$ if it is an unmutated universe. Thus, from expression (2), $\Delta_S c = \mathrm{cov}_I(b_i/b, c_i) = \mathrm{E_I}((b_i/b)c_i) - \mathrm{E_I}(c_i) = qb^*/(qb^* + (1-q)b^\circ) - q$, where $q = 1/n$ is the population frequency of the mutant universe. Note that, as $b^* > b^\circ$, owing to expression (4), then $\exists \ t^\bullet \in \mathbb{R}^N$ such that $\Delta_S c > 0$ (i.e., $t^\bullet = t^*$).

DOI 10.1002/cplx

V. *If universes vary in their optimality, then there is scope for CNS, and the change in the arithmetic average of every character value owing to CNS is equal to its covariance with relative attained maximand value*. From expression (2), the response to CNS is $\Delta_S c = \mathrm{cov}_I(b_i/b, c_i)$.

VI. *If there is neither scope for CNS nor potential for positive CNS, then all universes are optimal*. There are three basic possibilities concerning the optimality status of the multiverse: the universes may all be optimal, all equally suboptimal, or they may vary in their optimality. If they vary in their optimality, then there is scope for CNS (correspondence V). Hence, if there is no scope for CNS, then universes cannot vary in their optimality. If they are equally suboptimal, then there is potential for positive CNS (correspondence IV). Hence, if there is no potential for positive CNS, then universes cannot be equally suboptimal. Putting this together, if there is neither scope for CNS nor potential for positive CNS, then all universes must be optimal.

DOI 10.1002/cplx