

Extending cosmological natural selection

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Abstract

The purpose of this paper is to propose an extension to Lee Smolin's hypothesis that our own universe belongs to a population of universes evolving by natural selection. Smolin's hypothesis explains why the parameters of physics possess the values we observe them to possess, but depends upon the contingent fact that the universe is a quantum relativistic universe. It is proposed that the prior existence of a quantum relativistic universe can itself be explained by postulating that a process of *cosmogenic drift* evolves universes towards stable ('rigid') mathematical structures.

1 Introduction

According to current mathematical physics, there are many aspects of our physical universe which are contingent rather than necessary. These include such things as the values of the numerous free parameters in the standard model of particle physics, and the parameters which specify the initial conditions in general relativistic models of the universe. The values of these parameters cannot be theoretically derived, and need to be determined by experiment and observation. It transpires that the existence of life is very sensitively dependent upon the values of these parameters (see Barrow and Tipler 1986, for a compendious survey). If a universe had values for these parameters only slightly different from the values they possess in our own universe, then that universe would be incapable of supporting life. Hence, there is a need to explain why a life-supporting universe exists.

In fact, the problem posed by the contingent values of the free parameters can be generalised. If our physical universe is conceived to be an instance of a mathematical structure, (i.e., a structured set), then it is natural to ask why this mathematical structure physically exists and not some other. The instantiation of one particular mathematical structure is contingent, and requires an explanation.

One response to this problem of contingency is to postulate the existence of a collection of universes, which realise numerous different mathematical structures, and numerous different values for the parameters of physics. It is common

these days to refer to such a collection as a ‘multiverse’. Multiverses can be distinguished by whether or not some physical process is suggested to account for their existence. For example, Linde’s chaotic inflation theory (1983a and 1983b), and Smolin’s theory of cosmological natural selection (1997), both postulate the operation of physical processes which yield collections of universes, (or causally disjoint ‘universe-domains’, in the case of Linde’s theory). Other multiverse proposals postulate universes which are either not the outcome of a common process, or not the outcome of any process at all (Tegmark 1998, 2008).

As Tegmark points out, all such proposals which suggest that “some subset of all mathematical structures. . . is endowed with. . . physical existence,” (1998, p1), fail to explain why some particular collection of mathematical structures is endowed with physical existence rather than another. Tegmark’s own response was to suggest that *all* mathematical structures have physical existence.¹ The weak anthropic principle similarly postulates the existence of a collection of universes which is sufficiently large and varied that the conditions which permit the existence of life will be realised in at least some of the universes. Both types of proposal accept that a life-permitting universe is a highly untypical member of the universe collection, and both types of proposal are difficult, if not impossible, to empirically test. In contrast, Smolin’s proposal of cosmological natural selection explains the existence of our life-supporting universe, renders such universes highly typical, and is subject to empirical test. We now proceed to expound Smolin’s hypothesis.

2 Cosmological natural selection

To understand Smolin’s idea, it is first useful to appreciate that the conditions for natural selection to occur can be precisely defined formally, in complete abstraction from any particular physical instance. If a collection of physical systems satisfies these conditions, then that collection will, with overwhelming likelihood, evolve by natural selection, irrespective of what those systems are. The Darwinian evolution of biological systems by natural selection, is just one particular case of this.

John Barrow asserts that natural selection (or, as he calls it, ‘Darwinian evolution’), “has just three requirements:

- The existence of variations among the members of a population. These can be in structure, in function, or in behaviour.
- The likelihood of survival, or of reproduction, depends upon those variations.
- A means of inheriting characteristics must exist, so that there is some correlation between the nature of parents and their offspring. Those vari-

¹More recently, however, Tegmark (2008) has incorporated the implications of Gödel incompleteness and Church-Turing uncomputability, by considering the possibility that only computable structures, or finite computable structures, physically exist (2008, p22).

ations that contribute to the likelihood of the parents' survival will thus most probably be inherited.

It should be stressed that under these conditions evolution is not an option. If any population has these properties then it must evolve," (Barrow 1995, p21).

Smolin hypothesises that there exists a population² of universes, and that the values of the free parameters in the standard model of particle physics are variable characteristics of the universes in the population. For simplicity, let us accept that the values of the fundamental parameters of physics are fixed in each universe, but can vary from one universe to another.

Smolin hypothesises that certain types of universe in the population are reproductively active. He suggests that in those universes where black holes form, a child universe is created inside the event horizon of the black hole. Specifically, Smolin's proposal is that "quantum effects prevent the formation of singularities, at which time starts or stops. If this is true, then time does not end in the centers of black holes, but continues into some new region of space-time... Going back towards the alleged first moment of our universe, we find also that our Big Bang could just be the result of such a bounce in a black hole that formed in some other region of space and time. Presumably, whether this postulate corresponds to reality depends on the details of the quantum theory of gravity. Unfortunately, that theory is not yet complete enough to help us decide the issue," (1997, p93).

In the decade since Smolin proposed his idea, loop quantum gravity has made some significant progress, and its application to cosmology now appears to support Smolin's hypothesis. For example, in a recent review, Ashtekar asserts that "In the distant past, the [quantum] state is peaked on a classical, contracting pre-big-bang branch which closely follows the evolution dictated by Friedmann equations. But when the matter density reaches the Planck regime, quantum geometry effects become significant. Interestingly, they make gravity *repulsive*, not only halting the collapse but turning it around; the quantum state is again peaked on the classical solution now representing the post-big-bang, expanding universe," (2006, p12). Nevertheless, it is fair to say that the occurrence of such a bounce inside a black hole remains highly speculative.

Smolin postulates that the reproduction which takes place is reproduction with inheritance. He assumes that "the basic forms of the laws don't change during the bounce, so that the standard model of particle physics describes the world both before and after the bounce. However, I will assume that the parameters of the standard model do change during the bounce," (1997, p94). Smolin postulates that a child universe inherits almost the same values for the parameters of physics as those possessed by its parent. He postulates that the reproduction is not perfect, that small random changes take place in the values of the parameters. Hence, Smolin postulates reproduction with inheritance and mutation. As Shimony puts it, "the variable entities are universes, and the theatre in which the variation occurs is governed by the principles of quantum

²Hereafter, a collection of universes which are related in some way, will be referred to as a 'population' of universes.

gravity (as yet not fully constructed) and the form of the standard model,” (1999, p217). Smolin’s scenario cannot explain why our universe is relativistic rather than non-relativistic, and it cannot explain why our universe is a quantum universe rather than a classical universe, because the occurrence of black holes requires a relativistic universe, and the occurrence of a ‘bounce’ inside the horizon of a black hole requires a quantum universe.

The number of black holes in a universe is determined by the parameters of physics, hence the values of the parameters in a universe determine the number of children born to that universe. If Smolin’s postulate that child universes are created inside black holes with small random parameter mutations is indeed correct, then a population that contains some black hole producing universes, will probably evolve by natural selection. In particular, a population with an exhaustive, initially uniform distribution of parameter value combinations, will come to be dominated by universes that maximise the production of black holes.

In addition to the hypothesis that there is a population of universes evolving by natural selection, Smolin suggests that the parameter values which maximise black hole production, and therefore child universe birthrate, are also the values which permit the existence of life. If the universe types with the highest birthrate are also those universes which permit life, then universes which permit life will come to dominate the population of universes.

The hypothesis that there is a population of universes evolving by natural selection is distinct from the hypothesis that the parameter values which maximise black hole production are the same parameter values which permit life. One hypothesis could be true, and the other false. Only if both are true will life-permitting universes come to dominate the population of universes. If child universes were created inside black holes with small random parameter variations, but the parameter values which maximise black hole production were *not* the same parameter values which permit life, then there would be a population of universes which evolves by natural selection, but in which life-permitting universes do not come to dominate the population.

A weak anthropic principle explanation that imagines a collection of unrelated universes, rather than a population of universes evolving by natural selection, holds that life-permitting universes are *special* members of the collection. In contrast, Smolin’s dual proposal that (i) there is a population of universes evolving by natural selection, and (ii) the parameter values which maximise black hole production are the same parameter values which permit life, holds that life-permitting universes are *typical* members of the collection. In terms of carbon and organic elements, for example, the theory of cosmological natural selection “predicts that our universe has these ingredients for life, not because life is special, but because they are typical of universes found in the collection,” (Smolin 1997, p204).

Vilenkin (2006) has recently framed an argument which poses a serious challenge to Smolin’s hypothesis. In summary,³ Vilenkin’s argument is as follows: In the far future of an eternal de Sitter space-time, black holes will be spon-

³See Smolin (2006) for a full explanation and critique of Vilenkin’s argument.

taneously created by the fluctuations of quantum fields, at a constant rate. A universe such as ours appears to be, with a non-zero positive cosmological constant Λ , will evolve towards just such a de Sitter space-time, and the black hole production from this mechanism will dominate that produced by astrophysical processes. Moreover, the black hole production rate from this mechanism is proportional to the value of the cosmological constant Λ , hence in a population of universes evolving to maximize black hole production, the value of Λ will be maximized. The small value of Λ in our own universe, argues Vilenkin, is therefore inconsistent with cosmological natural selection.

The success of Vilenkin’s argument depends largely upon the reality, or otherwise, of the proposed black hole creation mechanism in the far future of a de Sitter space-time, and its purported dependence upon Λ . Vilenkin’s argument currently rests upon empirically unverified, and theoretically controversial physics, but nevertheless constitutes a serious potential problem for cosmological natural selection.

For the purpose of this paper, however, the primary problem with Smolin’s scenario is that it cannot explain why our universe is relativistic rather than non-relativistic, and it cannot explain why our universe is a quantum universe rather than a classical universe, because the occurrence of black holes requires a relativistic universe, and the occurrence of a ‘bounce’ inside the horizon of a black hole requires a quantum universe.

Thus, Smolin’s hypothesis depends upon the assumption that there is a quantum relativistic universe at the outset. One can ask for an explanation of why there should be such a universe, rather than a universe in which, say, Newtonian gravity governs the large-scale structure of space-time, or in which classical mechanics and classical field theories govern the behaviour of any particles and fields which exist. The existence of a quantum relativistic universe seems to be contingent rather than necessary. There is, therefore, a need to explain the existence of a quantum relativistic universe.

A proposal for just such an explanation will be made below. The proposal will be expressed in terms of a variation in the value of the dimensionless gravitational parameter ω , and a variation in the value of two of the fundamental dimensional ‘constants’, the speed of light c and Planck’s constant⁴ \hbar . As Kragh (2006) recounts, there is already a significant history of such proposals in the physics community, ranging from Dirac’s hypothesis of a time-varying gravitational constant G , to more recent proposals for variable speed of light (VSL) cosmologies, such as that proposed by Albrecht and Magueijo (1999). Kragh reports out that “hundreds of papers have been written within the class of VSL,” (p731) and claims that Magueijo’s (2003) invited review article in *Reports on Progress in Physics*, indicates that the subject “is considered exciting as well as belonging to mainstream, if not necessarily orthodox physics,” (p732).

There remains, however, considerable disagreement in the physics community over whether a postulated variation in the value of the fundamental *dimensional* constants is well-defined or operationally meaningful, hence the next

⁴Strictly, this is the ‘reduced’ Planck constant, $\hbar = h/2\pi$.

section will be devoted to a discussion of this issue.

3 Dimensional and dimensionless constants

The fundamental constants of physics, c , \hbar and G , are *dimensional* constants in the sense that they possess physical dimensions, and their values must be expressed relative to a choice of physical units. Recall in this context that there are three fundamental physical dimensions: length [L], time [T], and mass [M]. Each physical quantity is represented to have dimensions given by some combination of powers of these fundamental dimensions, and each value of a physical quantity is expressed as a multiple of some chosen unit of those dimensions. The speed of light has dimensions of $[L][T]^{-1}$, and in CGS (Centimetre-Gramme-Second) units has the value $c \approx 3 \times 10^{10} \text{ cm s}^{-1}$; Planck's constant has the value $\hbar \approx 10^{-27} \text{ g cm}^2 \text{ s}^{-1}$ in CGS units; and Newton's gravitational constant has the value $G \approx 6.67 \times 10^{-8} \text{ cm}^3 \text{ g}^{-1} \text{ s}^{-2}$ in CGS units.

The laws of physics define the necessary relationships between dimensional quantities. The values of these quantities are variable even within a fixed system of units, hence the lawlike equations can be said to define the necessary relationships between dimensional *variables*. Nevertheless, the laws of physics also contain dimensional *constants*. In particular, the fundamental equations of relativity and quantum theory, such as the Einstein field equation, the Maxwell equation, the Schrödinger equation, and the Dirac equation, contain the fundamental dimensional constants, c , \hbar , and G .

Ultimately, dimensional constants are necessary in equations which express the possible relationships between physical variables, because the dimensional constants change the units on one side of the equation into the units on the other side. As an example, consider the most famous case in physics, $E = mc^2$. This equation can be seen as expressing a necessary relationship between the energy-values and mass-values of a system. In CGS units the energy is in ergs, where an erg is defined to equal one $\text{g cm}^2 \text{ s}^{-2}$, and the mass is in grammes. To convert the units of the quantity on the right-hand-side of the equation into the same units as the quantity on the left-hand-side, the mass is multiplied by the square of the speed of light in vacuum, which has units of $\text{cm}^2 \text{ s}^{-2}$. One might argue that the reason why the (square root of) the conversion factor should be $\approx 3 \times 10^{10}$ in CGS units, rather than any other number, follows from the definition of the cm and the s . Like all dimensional quantities, the value of fundamental constants such as c changes under a change of physical units.

Intriguingly, the fundamental dimensional constants can also, heuristically at least, be used to express the limiting relationships between fundamental theories. Thus, classical physics is often said to be the limit of quantum physics in which Planck's constant $\hbar \rightarrow 0$, and non-relativistic physics is often said to be the limit of relativistic physics in which the speed of light in vacuum $c \rightarrow \infty$. The flip side of this coin is that \hbar is said to set the scale at which quantum effects become relevant, and c is said to set the speeds at which relativistic effects become relevant.

A system with action A is a quantum system if the dimensionless ratio A/\hbar is small. If this ratio is large, then the system is classical. As $\hbar \rightarrow 0$, A/\hbar becomes large even for very small systems, hence classical physics is said to be the limit of quantum physics in which $\hbar \rightarrow 0$. Similarly, c sets the speeds at which relativistic effects become relevant in the sense that a system with speed ν is relativistic if the dimensionless ratio ν/c is close to 1. If the ratio is a small fraction, then the system is non-relativistic. As $c \rightarrow \infty$, ν/c becomes a small fraction even for very fast systems, hence non-relativistic physics is said to be the limit of relativistic physics in which $c \rightarrow \infty$. In a similar manner, G sets the scale of gravitational forces, and determines whether a system is gravitational or not.

Duff, however, argues that no objective meaning can be attached to a variation in the values of the dimensional constants. According to Duff, “the number and values of dimensional constants, such as \hbar, c, G, e, k etc, are quite arbitrary human conventions. Their job is merely to convert from one system of units to another... the statement that $c = 3 \times 10^8$ m/s, has no more content than saying how we convert from one human construct (the meter) to another (the second),” (2002, p2-3).

To understand Duff’s point, consider ‘geometrized’ units, in which the speed of light is used to convert units of time into units of length. Thus $c \cdot s$, for example, is a unit of length defined to equal the distance light travels in one second. If time is measured in units of length, then all velocities are converted from quantities with the dimensions $[L][T]^{-1}$ to dimensionless quantities, and in particular, the speed of light acquires the dimensionless value $c = 1$. In geometrized units, anything which has a speed ν less than the speed of light has a speed in the range $0 \leq \nu_{geo} < 1$:

$$\nu_{geo} = \frac{\nu_{cgs}}{c_{cgs}} .$$

Thus, the speed of light can be used to convert between velocities expressed in CGS and geometric units as follows:

$$\nu_{cgs} = \nu_{geo} \cdot c_{cgs} .$$

Similarly, in geometrized units, the gravitational constant G converts units of mass to units of length. In fact, in geometrized units all quantities have some power of length as their dimensions. In general, a quantity with dimensions $L^n T^m M^p$ in normal units acquires dimensions L^{n+m+p} in geometrized units, after conversion via the factor $c^m (G/c^2)^p$, (Wald 1984, p470).⁵

Whilst in geometrized units, $c = G = 1$, if one changes to so-called ‘natural units’ (such as Planck units), then $\hbar = c = G = 1$, and these constants disap-

⁵Some interpretations of relativity hold that the unification of space and time into space-time, entails that length $[L]$ and time $[T]$ are simply the same dimension, $[L] = [T]$. Under these interpretations, $c = 3 \times 10^{10}$ cm/s is seen as a conversion factor between units of the same dimension. However, as Flores (2007) points out, “one can consistently use units in which $c = 1$ and hold that there is nevertheless a fundamental distinction between space and time as dimensions.”

pear from the fundamental equations. Theories expressed in these natural units provide a non-dimensional formulation of the theory, and the dimensional variables therein becomes dimensionless. Duff, for example, points out that “any theory may be cast into a form in which no dimensional quantities ever appear either in the equations themselves or in their solutions,” (2002, p5). Whilst in geometrized units, all quantities have dimensions of some power of length $[L]^n$, in Planck units all quantities are dimensionless, as a result of division by l_P^n , the n -th power of the Planck length $l_P = \sqrt{G\hbar/c^3} \approx 1.616 \times 10^{-33} \text{ cm}$. In particular, in natural units all lengths are dimensionless multiples of the Planck length.

The existence of theoretical formulations in which the dimensional constants disappear, is duly held to be one of the reasons why a postulated variation in the values of the dimensional constants cannot be well-defined. However, whilst different choices of units certainly result in different formulations of a theory, and whilst the dimensional constants can indeed be eliminated by a judicious choice of units, it should be noted that the most general formulation of a theory and its equations is the one which contains the symbols denoting the dimensional constants as well as the symbols denoting the dimensional variables.

Whilst the arguments recounted above are to the effect that variations in the fundamental dimensional constants cannot be well-defined, these arguments are often conflated or conjoined with arguments that such changes are not *operationally* meaningful. In the latter case it is argued that a change in a dimensional constant cannot be unambiguously measured because there is no way of discriminating it from a change in the units of which that constant is a multiple. For example, if the length of a physical bar, stored at a metrological standards institute, is used to define the unit of length, one might try to measure a change in the speed of light from a change in the time taken for light to travel such a length. In such a scenario, it could be argued that it is the length of the bar which has changed, not the speed of light.

Whilst it is indeed true that a change in the value of a dimensional variable could be explained by a change in one’s standard units, this is a truth which applies to the measurement of dimensional *variables*, just as much as it applies to the measurement of dimensional *constants*. The logical conclusion of this line of argument is that only dimensionless ratios of dimensional quantities can be determined by measurement; individual lengths, times and masses would not be determinable, only ratios of lengths, ratios of times, and ratios of masses. Duff duly follows this line of reasoning to its logical conclusion, asserting that “experiments measure only dimensionless quantities,” (2002, p5).

However, unless the dimensional quantity being measured is itself used to define the units in which the quantity is expressed, the question of whether one can discriminate a change in a dimensional quantity from a change in the units of which that quantity is a multiple, is an empirical-epistemological question rather than an ontological question. Whilst the value of a dimensional constant does indeed change under a change of units, so does the value of a dimensional variable, and there is no reason to infer from this that a dimensional variable

is merely a human construct. For example, the rest-mass energy of a system changes under a change from MeV to keV , but this is no reason to conclude that rest-mass energy is a human construct. Hence, the question of operational meaning may be something of a red-herring.

It is, however, certainly true that the units of time and length can themselves be defined as functions of the fundamental dimensional constants. Thus, the standard unit of time is defined in terms of the frequency ν of hyperfine transitions between ground state energy levels of caesium-133 atoms:

$$\nu = \frac{m_e^2 c^{-2} e^8}{h^5 m_N} \equiv T^{-1} ,$$

where e is the charge of the electron, m_N is the mass of the neutron, and m_e is the mass of the electron. The period of any cyclic phenomenon is the reciprocal of the frequency, $1/\nu$, and in 1967 the second was defined in the International System (SI) of units to consist of 9,192,631,770 such periods.

From 1960 until 1983, the SI metre was defined to be 1,650,763.73 wavelengths (in vacuum) of the orange-red emission line of krypton-86. This is determined by the Rydberg length R_∞ :

$$4\pi R_\infty = \frac{m_e e^4}{ch^3} \equiv L .$$

As Barrow and Tipler (1986) comment, “if we adopt L and T as our standards of length and time then they are *defined* as constant. We could not measure any change in fundamental constants which are functions of L and T,” (p242). Since 1983 the metre has been defined in terms of the unit of time, the second, so that a metre is defined to be the distance travelled by light, in a vacuum, during $1/299792458$ of a second. Such considerations lead Ellis (2003) to claim that “it is... not possible for the speed of light to vary, because it is the very basis of measuring distance.”

Magueijo and Moffat (2007) acknowledge that if the unit of length is defined in such a manner, then the constancy of the speed of light is indeed a tautology. However, they then provide the following riposte: “An historical analogy may be of use here. Consider the acceleration of gravity, little g . This was thought to be a constant in Galileo’s time. One can almost hear the Ellis of the day stating that g cannot vary, because ‘it has units and can always be defined to be constant’. The analogy to the present day relativity postulate that c is an absolute constant is applicable, for the most common method for measuring time in use in those days did place the constancy of g on the same footing as c nowadays. If one insists on defining the unit of time from the tick of a given pendulum clock, then the acceleration of gravity is indeed a constant by definition. Just like the modern speed of light c . And yet the Newtonian picture is that the acceleration of gravity varies,” (p1-2).

Whilst there is considerable disagreement that the values of fundamental dimensional constants have any theoretical significance, there is a consensus that each different value of a fundamental dimensionless constant, such as the

fine structure constant $\alpha = e^2/\hbar c$, defines a different theory. The values of the dimensionless constants are, by definition, invariant under any change of units, they remain obstinately in the dimensionless formulation of a theory, and their values have to be set by observation and measurement. Dimensionless constants, however, are themselves merely functions $f(c, \hbar, G)$ of dimensional constants, in which the dimensions of the units cancel. If the variation of dimensionless constants is meaningful, and if dimensionless constants are functions of the dimensional constants, then one might ask how variation in the former can be achieved without variation in the latter. As Magueijo (2003) comments: “If α is seen to vary one cannot say that all the dimensional parameters that make it up are constant. Something - e , \hbar , c , or a combination thereof - has to be varying. The choice amounts to fixing a system of units, but that choice has to be made... In the context of varying dimensionless constants, that choice translates into a statement on which dimensional constants are varying.”

Kragh claims that “Magueijo and Albrecht were aware of [objections such as those which Duff later raised] in their 1999 paper, where they argued that physics necessarily involves dimensional quantities and that a time variation of these can be determined on grounds of conventionalism. Moreover, they pointed out that although it is a matter of convenience to decide which dimensional quantities are variable and which are constant, the choice has physical implications as it will typically lead to different predictions,” (2006, p734). (However, if such choices do indeed lead to different predictions, then such a choice would involve more than a matter of mere convention).

We will see in the next section how the proposed variation in the dimensional constant G leads to a generalisation of general relativity containing a dimensionless parameter ω , whose limit $\omega \rightarrow \infty$ corresponds to general relativity. There is, as yet, no comparable generalisation of relativistic quantum theory, hence the questions of stability under deformation which we consider below, must first be evaluated for the dimensional constants c and \hbar . Thus, in the presentation below for extending cosmological natural selection, the proposal will be expounded in terms of the dimensional constants c and \hbar , and the dimensionless parameter ω .

4 Stable mathematical structures

As a first step to explaining the type of universe population postulated by Smolin, the following conjecture is proposed:

Conjecture 1 *At some level, the structure of our physical universe is a stable mathematical structure.*

A stable (‘rigid’) mathematical structure is a structure for which any deformation, in some specified class of deformations, merely leads to an isomorphic structure (see Mazur 2004). A deformation is a continuous variation of a structure by means of some parameter(s). Intriguingly, some of the most fundamental

structures which describe our universe are, indeed, stable structures (Faddeev 1991; Vilela Mendes 1994).

Firstly, whilst the Lie algebra of the inhomogeneous Galilei group, the local symmetry group of Galilean relativity, is an unstable structure, it deforms into a family of Lie algebras, parameterised by the speed of light c . All of these 10-dimensional Lie groups are mutually isomorphic to the Poincare group, the local space-time symmetry group of general relativity. This family of Lie groups transforms into the Galilei group in the limit $c \rightarrow \infty$.

Secondly, whilst the Lie algebra defined by the Poisson bracket on the space of observables in a classical physical theory is an unstable Lie algebra, it deforms into a family of Lie algebras, parameterised by Planck's constant \hbar . All of these Lie algebras are mutually isomorphic to the Lie algebra defined by the commutator on the space of observables in the corresponding quantum theory. If one thinks of each value of \hbar as defining a different quantum theory, then this amounts to the deformation of a classical theory into a family of quantum theories. The same type of deformation can be performed using C*-algebras: “the classical algebra of observables is ‘glued’ to the family of quantum algebras of observables in such a way that the classical theory literally forms the boundary of the space containing the pertinent quantum theories (one for each value of $\hbar > 0$),” (Landsman 2005, Section 4.3). The family of quantum theories transforms into classical theory in the limit $\hbar \rightarrow 0$.

At least some of the parameters of physics are therefore the deformation parameters of mathematical structures, and a relativistic quantum universe, such as our own, corresponds in at least some respects to a stable structure.

There are also some suggestive facts from the standard model of particle physics, where each gauge force field has an ‘internal’ symmetry group, called the gauge group. A gauge group must be a compact, connected Lie Group. In our universe, the gauge group of the electromagnetic force is $U(1)$, the gauge group of the electroweak force is $U(2) \cong SU(2) \times U(1)/\mathbb{Z}_2$, and the gauge group of the strong force is $SU(3)$. Now, the vanishing of the second cohomology group of a Lie algebra entails that the Lie algebra is stable (see Vilela Mendes 1994). Semi-simple Lie algebras have a trivial second cohomology group, hence semi-simple Lie algebras are stable structures. Every simple Lie algebra is semi-simple, and $SU(2)$ and $SU(3)$ are simple Lie groups, hence the Lie algebras of $SU(2)$ and $SU(3)$ are stable structures. Moreover, the Lie algebra of $U(1)$ is \mathbb{R} , and, as the only 1-dimensional real Lie algebra, this is also a stable Lie algebra.

There are, however, many simple, compact, connected Lie groups. The list of the simply connected ones alone, contains the special unitary groups $SU(n)$, $n \geq 2$; the symplectic groups $Sp(n)$, $n \geq 2$; the spin groups $Spin(2n+1)$, $n \geq 3$; the spin groups $Spin(2n)$, $n \geq 4$; and the five exceptional Lie groups E_6 , E_7 , E_8 , F_4 , and G_2 , (Simon 1996, p151). Hence, structural stability alone can only go so far towards explaining why the gauge fields which exist in our universe are those which have either $U(1)$, $U(2) \cong SU(2) \times U(1)/\mathbb{Z}_2$, or $SU(3)$ as their gauge groups. The gauge fields which exist in our universe might have to be explained by a combination of structural stability and additional constraints on the permissible gauge fields.

To reiterate, a stable structure is defined to be a structure which remains isomorphic ‘under a specified class of deformations’. Hence, whether or not a structure is stable depends upon the class of deformations under consideration, and the proposal that our physical universe is a stable mathematical structure is only meaningful with respect to a designated class of deformations. This requirement is supplied by the next proposal, which postulates that there is a physical process which randomly changes the parameters of physics:

Conjecture 2 *There is a physical process which randomly changes deformation parameters such as c and \hbar .*

The proposal, then, is that our physical universe is a stable structure with respect to the class of deformations corresponding to this physical process.

Despite the difficulties of defining or unambiguously ascertaining by observation and measurement whether the dimensional parameters of physics are actually subject to variation, the proposal above constitutes a potentially testable conjecture, and is therefore a scientific conjecture. The existence of such a physical process will inevitably result in a relativistic quantum universe, even if it started with a classical universe, or a non-relativistic universe. Moreover, with the imposition perhaps of further constraints, such a process might produce a universe with gauge fields like our own, even if it started with quite different gauge fields. If so, then a quantum relativistic universe with the gauge force fields we observe, would be a stable region in the mathematical ‘landscape’.

However, such a conjecture only goes so far; the mathematical structures which describe our universe can only be cast as stable structures at a quite general level. Whilst a quantum relativistic universe can be said to be a stable structure, the specific structures of the particles and fields in such a universe cannot. For example, the coupling constant of a gauge field with gauge group G corresponds to a choice of metric in the Lie algebra \mathfrak{g} , (Derdzinski 1992, p114-115), and the particular metrics chosen in our own universe are not stable in any sense; different coupling constants correspond to non-isometric structures in the gauge group Lie algebras.

Thus, to explain the detailed mathematical structure of our universe, the notion of evolution towards stable mathematical structures must be combined with Smolin’s scenario of cosmological evolution by natural selection:

Conjecture 3 *Our universe belongs to a population of quantum relativistic universes, evolving by natural selection.*

To reiterate, Smolin’s scenario explains how parameters of the standard model, such as the coupling constants of the gauge fields, come to possess the values we observe. It is proposed in this paper that the evolution of universes which occurs within Smolin’s scenario, takes place within a context established by the prior evolution of a stable mathematical structure, at a more general level than the level at which the natural selection process operates. In fact, the evolution of universes in Smolin’s scenario is *dependent* upon the prior evolution of a quantum relativistic structure. It is proposed in this paper that

there are random processes which deformed the structure of the universe, or a region thereof, into a quantum relativistic universe, and thereon, the processes postulated in Smolin's evolution by natural selection produced a multiverse of quantum relativistic universes.

The other fundamental parameter of physics, along with c and \hbar , is the gravitational constant G . To introduce this into the theory of cosmological evolution, the Brans-Dicke theory of gravitation can be deployed. Brans-Dicke theory is a generalisation of general relativity, in which the reciprocal of the gravitational constant $1/G$, is replaced by a scalar field ϕ . The scalar field ϕ is an effective (reciprocal of the) gravitational constant, which is capable of varying from place to place, and from time to time. The Einstein field equations of general relativity generalise to the Brans-Dicke field equations, in which the combination of the matter stress-energy tensor T and the scalar field ϕ generate the metric tensor. These field equations contain a dimensionless parameter ω called the Brans-Dicke coupling constant. For each different value of ω , there is a different Brans-Dicke theory.

The value of ω has to be set by experiment and observation, and current astronomical observations have established a lower bound such that $\omega > 40,000$ (Bertotti *et al* 2003). General relativity is obtained from the family of Brans-Dicke theories in the limit $\omega \rightarrow \infty$ (with some exceptions; see Faroni 1999). This means that general relativity is unstable in the space of mathematical structures. A deformation of general relativity takes it into the space of Brans-Dicke theories. Hence, if we postulate that ω is subject to the same random variation to which c and \hbar are subject, then from the theory of cosmogenic drift we obtain the prediction:

Conjecture 4 *The correct theory of classical gravitation in our universe is the Brans-Dicke theory, for some value of ω .*

Whilst a quantum relativistic universe is a stable universe, it seems that a strictly general relativistic universe is unstable. We are currently unable to place a finite upper bound on the value of ω in our universe, hence we are currently unable to observationally distinguish our Brans-Dicke universe from a general relativistic universe. This, however, may simply be a result of the inadequacy of current observational technology; after all, the current lower bound on ω is 40,000, which is still a long way from ∞ .

A population of universes in which gravity is governed by Brans-Dicke theory, is still a population of relativistic universes, and, crucially, black holes exist within all the Brans-Dicke theories. Exact vacuum solutions of the Einstein field equations, supplemented by the addition of a scalar field which is such that $\phi = 1$ everywhere, become exact vacuum solutions of any Brans-Dicke theory. Hence, a population of Brans-Dicke universes can evolve by natural selection just as much as a population of general relativistic universes.

5 Cosmogenic drift

In evolutionary biology it is known that evolution by natural selection is not the only important evolution process, and that in the absence of selection pressures, the evolution of a population will be dominated by random variations in the genome, a process called genetic drift. Similarly, the proposal made here suggests that the values of the parameters of physics cannot be wholly explained by cosmological evolution by natural selection. However, whilst genetic drift is a process which applies to a population of biological entities reproducing with inheritance and random mutation, the cosmological process postulated here is not restricted to reproducing entities, and in particular is postulated as a necessary prelude to the creation of a population of reproducing universes. Moreover, genetic drift does not couple the idea of random variation to the notion of stable structures. Nevertheless, one might wish to refer to the postulated process which produced a quantum relativistic universe as *cosmogenic drift*.

To best explain cosmogenic drift, we shall need a concept from evolutionary biology known as the *fitness landscape*. Each point on this landscape corresponds to a different combination of genes, and the height of the landscape at each point represents the average number of progeny produced by an organism with that combination of genes, which themselves survive to reproduce. The height of the landscape therefore represents the ‘fitness’ of each possible genotype. Each progenitor produces offspring with genomes in a small neighbourhood of the position of the progenitor in the landscape. In those parts of the landscape where selection pressures are weak, none of the progeny will have a greater fitness. When selection pressures are weak, the fitness landscape is therefore almost flat. Evolution of a biological population across a flat part of the fitness landscape will be driven by random diffusion. In contrast, in those parts of the landscape where selection operates, the landscape will possess gradient. In these parts of the landscape, some of the progeny produced within a small neighbourhood of one genotype will lie at a slightly greater height because they yield a greater number of progeny which themselves survive to reproduce. As a consequence, the population will come to be dominated by this new genotype, and will take a step-up to a slightly greater height in the fitness landscape. This is biological evolution by natural selection.

Smolin (1997) suggested that there is a cosmic fitness landscape analogous to the biological one, with each point corresponding to a combination of values for the parameters of physics, and the height at each point representing the number of progeny produced by a universe with that combination of parameters. This proposal can be extended by postulating that the cosmic fitness landscape has a lowest level plateau, corresponding to all the possible types of universe which do not reproduce. Each point in the lowest level of the cosmic landscape has zero height because none of these universes yield any progeny, and the landscape is flat here because natural selection cannot operate in the absence of reproduction. Evolution does, nevertheless, occur in this part of the cosmic landscape. Universes, it is proposed, evolve by random diffusion in flat parts of the cosmic fitness landscape; in particular, universes which cannot reproduce,

inhabiting the lowest level of the landscape, evolve by such cosmogenic drift. Eventually, a universe undergoing random cosmogenic drift will evolve into a quantum relativistic universe, a universe type which is capable of reproduction. The part of the cosmic fitness landscape which contains universes capable of reproduction, corresponds to a region of precipitous elevation in the landscape. This part of the landscape possesses a variety of gradients, and evolution by natural selection operates, as suggested by Smolin, in the same manner that it operates in the biological fitness landscape.

There is no necessity for cosmogenic drift to be the type of evolution which falls under the aegis of the Lagrangian-Hamiltonian dynamics of conventional physical theory. It is true that some of the modern VSL cosmologies replace the constant speed of light c with a scalar field $\psi = c(x)$, and propose a modified Lagrangian incorporating the Lagrangian \mathcal{L}_ψ of that scalar field, and the Brans-Dicke theory is indeed obtained by replacing G with a scalar field which results in a modified Lagrangian. Nevertheless, it is not proposed that the dimensionless gravitational constant ω evolves according to Lagrangian-Hamiltonian dynamics. Nor, if there is a generalisation of quantum relativistic theory which contains comparable dimensionless parameters, is it proposed that these parameters would evolve according to Lagrangian-Hamiltonian dynamics. The type of evolution proposed here is pure random diffusion, and has nothing to do with the Lagrangian-Hamiltonian dynamics of any quantum relativistic field ψ , for the evolution of a quantum relativistic universe is itself the proposed outcome of this process. As Magueijo and Moffat (2007) point out, “it is not true that a theory has to be defined by a Lagrangian or a Hamiltonian... Absence of a Lagrangian formulation is far from being a general feature of VSL, but we argue that it may be the point of those that attack the philosophical foundations of physics at its most fundamental level, introducing the concept of intrinsic evolution in the laws of physics,” (p4).

Random diffusion is a type of *stochastic process*, so if the theory of cosmogenic drift is to be further developed, and if observable predictions are to be derived from it, it will be necessary to employ the mathematics of stochastic processes, a brief explanation of which is duly required.

Mathematicians define a stochastic process to be a time-ordered family of random variables X_t upon a probability space Ω . Whilst this is not particularly illuminating in itself, the implicit idea is that Ω is the path-space for the system under consideration. In other words, each point in this probability space, $\omega \in \Omega$, represents a possible history of the system.⁶

By definition, a random variable X is a function on a probability space Ω which possesses a probability distribution over its range of possible values, by virtue of the probability measure on the subsets of the probability space Ω . In the case of a stochastic process, X_t is a function on the path-space of the system which represents the position of the system at time t .⁷ Thus $X_t(\omega)$, the value of the random variable X_t at the point $\omega \in \Omega$, is the position

⁶In the case of a stochastic process, these histories will typically be non-differentiable.

⁷‘Position’ here can be taken to be spatial position, or any sort of state-defining value, such as the price of a financial stock.

of the system at time t in history ω . X_t takes different values at different points because the different points in Ω correspond to different histories of the system. The probability measure on Ω , the space of histories, determines the probability distribution over the range of each random variable X_t , and thereby determines a probability distribution over position at each time t . Different positions at time t have different probabilities because different histories have different probabilities.

A stochastic process can also be defined by a function $G(x, x'; t)$ which specifies the probability of a transition from x to x' over a time interval t . Given an initial probability distribution $\rho(x, 0)$, this determines the probability distribution $\rho(x', t)$ at a future time t :

$$\rho(x', t) = \int G(x, x'; t) \rho(x, 0) dx .$$

In fact, given the transition probabilities $G(x, x'; t)$ and an initial probability distribution $\rho(x, 0)$, a probability measure on the path-space Ω , and the time evolution of the probability distribution $\rho(x, t)$, are both determined.

In the special case of a discrete stochastic process, with the transition probability of going from x to y in one time-step denoted as $T(x, y)$, the probability $p(\gamma)$ of a path γ defined by the sequence of positions (x_0, \dots, x_n) is defined to be:

$$p(\gamma) = T(x_{n-1}, x_n) \dots T(x_0, x_1) \rho(x_0, 0) .$$

As a stochastic process, random diffusion comes in a number of different varieties, so the first question one might pose to the cosmogenic drift hypothesis, is to ask which specific type of diffusion is postulated to operate. The simplest type of diffusion is Brownian motion, (also termed a Wiener process), which is a simple random walk in which the increments between random variables S_t have a normal distribution with a mean value of zero. Geometric Brownian motion, in contrast, is such that each random variable S_t has a lognormal distribution. Moreover, Brownian motion and geometric Brownian motion can each possess a drift, which ensures that the mean values of the random variables S_t evolve as if under the action of an external force. For example, the Black-Scholes equation, used to calculate the price of financial options, assumes that the value of underlying stocks will evolve according to geometric Brownian motion with drift. This stochastic process is typically denoted as

$$dS_t = \mu S_t dt + \sigma S_t dW_t ,$$

where μ is the percentage drift due to the expected risk-free rate-of-return on the underlying stock, μS_t is the drift-rate, σ is the volatility of the stock, σS_t is the diffusion rate, and dW_t is a standard Wiener process.

In terms of the probability distribution ρ on the range of the random variables S_t , in the case of simple Brownian motion it evolves according to the diffusion equation,

$$\partial\rho/\partial t = D\nabla^2\rho ,$$

whilst in the case of Brownian motion with drift tending towards a terminal drift-rate ν , it evolves according to the diffusion equation with drift:

$$\partial\rho/\partial t = D\nabla^2\rho - \nu\nabla\rho .$$

D here is the so-called diffusion coefficient, ∇^2 is the Laplacian, and ∇ is the gradient.

To explain the prior evolution of a quantum relativistic universe, diffusion seems to work equally well as diffusion-with-drift. Simple random diffusion will eventually evolve a sterile universe into a quantum relativistic universe, at which point reproduction will be triggered, and evolution by natural selection can kick-in. Diffusion-with-drift towards the relevant part of the cosmic fitness landscape will produce a quantum relativistic universe in a shorter time-scale, but given a presumably eternal length of time, a sense of urgency seems unnecessary. The form of the stochastic process distribution ρ , whether it is normal, lognormal, or otherwise, is also largely unimportant to the outcome, (although if negative values of the parameters are to be excluded, then one might stipulate geometric Brownian motion). All of which, unfortunately, seems to mitigate against the possibility of deriving potentially observable predictions from the theory. It might still be possible to observe the variations in the parameters of physics within our own universe, and thence to infer the nature of the stochastic process, but that information would then have to be fed back into the theory, rather than derived from it.

One can also ask which stochastic differential equation is satisfied by the random variation of parameters in Smolin's scenario, and given an answer, one could ask why cosmological natural selection utilises one particular type of random process rather than another. However, because Smolin's scenario is placed within the context of a quantum relativistic universe, it could be suggested that this type of stochastic evolution is determined by the rules of quantum gravity. In contrast, *any* type of random cosmogenic drift, from an arbitrary starting point, would eventually evolve a quantum relativistic universe as a stable structure, and from that point, a population of reproducing universes would ensue.

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