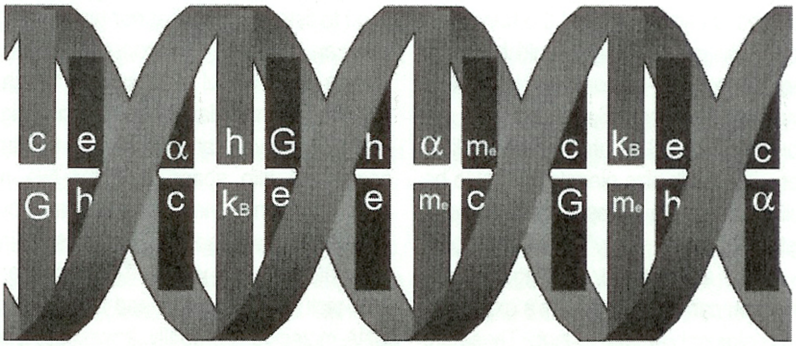
Fundamental Constants of Physics: The Genes of the Universe

by Andy Friedman

I wonder, if the speed of light
Was just a little to the right
No sunsets,
No rainbows

And if electrons didn't spin
None of us would have ever been
And maybe,
None the wiser

* * *



Everyone who has heard a bit about Einstein's Theory of Special Relativity knows that the speed of light is a constant. And as any physics textbook can attest, in international SI units, we say that the speed of light in vacuum is roughly 300,000,000 meters per second. But as many physicists and you, yourself, may have wondered, what exactly is so special about that particular value, and why couldn't it be different?

The fact that physics has never been able to come up with a reason for why that value could not be different has some rather profound physical and philosophical implications. Most importantly, the particular values of the speed of light, and indeed those of many other physical constants, such as the mass of the electron, Newton's gravitational constant, Planck's constant, and the Hydrogen fine structure constant, all have far-reaching consequences with regard to our existence.

What we find is rather startling at first. If we were to slightly change the values of any one of the important physical constants, life itself would become impossible. In other words, out of all the possible values of the physical constants, or what physicists call the "parameter space," only a very narrow range of choices are consistent with a universe that contains you and me. This is what many have termed the "fine-tuning" of the standard model parameters of physics, and this article will endeavor to discuss the many attempts physicists have made to understand and interpret what the fine-tuning really means.

The examples of fine-tuning itself are much too numerous to detail, so a few should serve to illustrate the general idea. Consider what would happen to stars, a rather crucial prerequisite for life, if we were to change the values of the gravitational constant or the speed of light. Australian philosopher J.J.C. Smart writes,

> *As [astrophysicist] Brandon Carter pointed out, if gravitation were very very slightly weaker, or electromagnetism were only very slightly stronger, all main sequence stars (of which our Sun is a typical example) would be red dwarfs, and if gravitation were slightly stronger or electromagnetism very slightly weaker, all main sequence stars would be blue giants (1).*

While different types of stars may not rule out other forms of life, it is clear that if our sun happened to be a red dwarf or a blue giant, human life could not have evolved under such conditions. Gravitational physicist Lee Smolin also notes that the portion of parameter space that allows any stars to exist at all is exceedingly small. As far as physicists and biologists are concerned today, stars are necessary conditions for life of any kind, providing the energy for evolving planets as well as the raw materials for life (2). Nuclear fusion in stars is responsible for making many of the heavy elements necessary for life such as carbon and oxygen. Powerful supernova explosions at the end of a star's life are further necessary for producing even heavier elements (iron and up) and dispersing the stardust throughout the galaxy to end up as part of new stars, planets, and people.

In addition to the effects on stars, changing some of the parameters can affect other rather crucial items such as the existence of stable chemical elements in the first place. But even with stable elements, parameter tweaking can also significantly alter the properties of biochemistry. For example, changing the parameters could lead to a universe where solid water was actually denser than liquid water, causing oceans to freeze from the bottom up during ice ages, a rather unfortunate set of circumstances for the possible marine life that may have evolved (3). Suffice it to say that the parameter values necessary for life constitute such a tiny slice of the parameter space that it appears tremendously improbable that they could be so fine-tuned without explanation.

A frequent attempt at explanation comes from what is called the Weak Anthropic Principle. Theoretical physicist John D. Barrow and mathematical physicist Frank J. Tipler state the principle as thus,

> *The observed values of all the physical and cosmological quantities are not equally probable but they take on values restricted by the requirement that there exist sites where carbon-based life can evolve and by the requirement that the Universe be old enough for it to have already done so.*

As Barrow and Tipler point out, this statement is not controversial, it is merely a consequence of the fact that we do exist and are thus able to make such a statement (4). In other words, if we did not exist, the point would be moot. So since we do exist, the physical constants must have values that allow us to be here, since we could not exist with the wrong constants. When cast in this way, the Anthropic Principle looks like a clever restatement of the obvious, and as such, some have taken issue with its explanatory power. Smart writes, "The fine-tuning explains (or partially explains) the existence of galaxies, stars, planets, carbon based life and minds that can formulate the problem, but these things do not explain the fine-tuning." (5). By itself, the Anthropic reasoning is circular, i.e. "we exist because we are here," so as it stands, some other postulation in addition to the Anthropic Principle must be taken into consideration in order to properly explain the fine-tuning.

One such postulation is that there are actually multiple universes like ours in existence each with different parameter values, where the ensemble of all such physically possible universes constitutes the multiverse. As Smart notes, by adding to the Anthropic Principle, "With the hypothesis of many small universes we do get something that claims to be a genuine explanation of the fine-tuning." (6).

In this scenario, the parameters are free to roam over the entire space, and the fact that we have a particular set of values is simply a result of the laws of probability. Even if all sets of parameter values are equally likely, with more universes to choose from, the multiverse makes the existence of our own universe substantially more probable than in a single universe scenario. And in fact, if the number of universes is actually infinite, our universe is guaranteed to exist, rather than just being more probable.

What makes this explanation so compelling is that several independent branches of theoretical physics all predict that there should be multiple universes. These include Inflationary Cosmology, the Many Worlds Interpretation of Quantum Mechanics, and even Superstring Theory. It is beyond the scope of this article to detail exactly how each of these theories point to multiple universes, so the explanations found in the sidebars on the following pages will be necessarily quite brief (7).

There are many strong theoretical reasons for believing that our universe is not the only one, thus providing a compelling explanation for why a universe could exist with parameter values necessary for life, even though, on the surface, each individual set of parameters seems unlikely. But what we have discussed so far only applies to multiverse theories where all sets of parameter values are regarded as equally likely, just as any random 13-card bridge hand has the same probability of occurring as any other. But what if the multiverse is more like a pair of dice, where each combination of numbers from the dice are not equally likely? For example, the dice total 7, which can happen in 6 ways, is more likely to occur than a 12, which can only happen one way. If the multiverse is indeed more like this, what would that mean for the parameters of physics and especially for our parameter values, the ones that we know for sure can lead to life?

With his theory of Cosmological Natural Selection, Lee Smolin makes, what this author views as, a spectacular attempt to answer this question. He goes a step further than the mere postulation of the multiverse, and ties together natural selection, the most powerful principle of biology, with cosmology, the most all-encompassing branch of theoretical physics. Smolin's theory provides a mechanism that explains why the individual universes attain their particular parameter values, and it challenges the traditional notion of a parameter space where each individual set of parameter values is equally likely. Smolin bases the theory on two postulates:

1. The formation of a black hole creates a "baby universe," the final singularity of the black hole tunneling right on through to the initial "Big Bang" singularity of the new universe thanks to quantum effects (9).

2. The standard model parameters of the baby universe are slightly mutated from the parent universe, in that they differ only by small and random amounts (10).

Both of the above postulates are admittedly quite speculative, but the arguments in favor of them have considerable force. The major motivation for believing the first postulate comes from the well-known theoretical physics problem of black hole evaporation and information loss. Black holes themselves are astronomical objects formed by the gravitational collapse of matter, where the center of the black hole harbors what is called a singularity, a point where space itself is infinitely warped. The most well-known fact about black holes is that once inside the black hole's event horizon, a spherical boundary surrounding the singularity, not even light can escape the monstrous gravitational pull of the black hole. As a result, no one can say for sure exactly what goes on inside a black hole's event horizon, but that has certainly not prevented people from speculating.

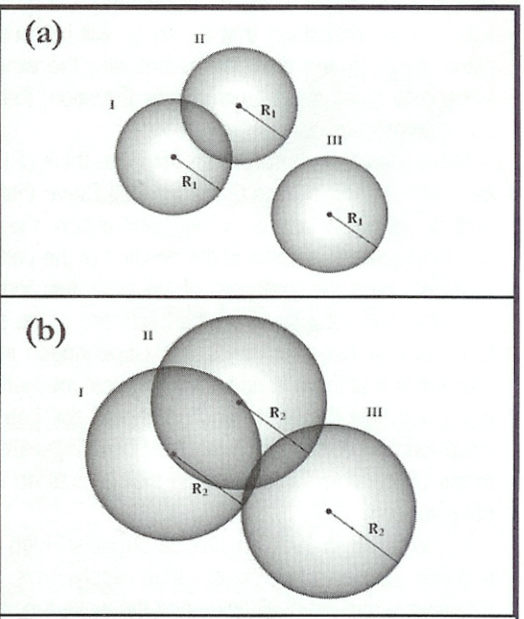
It was originally thought that black holes would continually suck up whatever matter fell within their event horizon, causing them to perpetually grow in size, and preventing the black hole from ever shrinking. But in the early 1970's, theoretical physicist Stephen Hawking showed that due

1. Inflationary Cosmology

The Theory of Inflation exists to explain mainly why distant regions of the universe could be at basically the same temperature, even though they are so distant that a light signal could not have traveled between them in the finite age of the observable universe. The temperature of causally disconnected regions is so strikingly similar that it would be as if two completely independent island civilizations just happened to develop exactly the same language, never having communicated in all of their history. As such, Inflationary theory asks how could two regions of space both "know", to be at the same temperature, if they could never have communicated this fact to one another through some signal in the time allotted?

Inflationary theory claims that the two relevant regions were originally close together and in mutual communication, but in the first instant of the universe after the Big Bang, they underwent an exponential expansion of space (i.e. inflation) that actually went faster than light and separated them out of causal contact (8). It should be noted that, while no objects within spacetime can be accelerated past the speed of light, General Relativity does not have a problem with space itself being created at a rate faster than light.

This naturally leads to regions or "bubbles" that are separated so far from each other that they are completely out of causal contact with one another, where the light-travel radius between them is larger than the light-travel radius of each of them individually. To envision causally disconnected regions, picture each point in space defining a finite sphere or bubble around it, then envision two such points surrouded by equally-sized spheres that don't share any regions of overlap. Many of these points will certainly have corresponding bubbles that do overlap, thus having partial causal connection, but you can always find two points with corresponding bubbles that do not overlap. These regions are none other than the previously discussed multiple universes required to explain the fine-tuning.



The Bubble Universes of Inflation. Each point in space defines a Bubble Universe, although only 3 are shown here. (a) At time t_1, all bubbles have radius R_1 , and bubble III is out of causal contact with I and II. (b) At time t_2, all bubbles have expanded to radius R_2, and as they start to overlap, III begins to communicate with I and II.

to quantum effects, which I will not go into here, black holes can actually evaporate, emitting what the outside world sees as a flux of thermal photons, and thus decreasing in mass due to the law of conservation of energy. The problem arises because the thermal photons we see are by definition in thermal equilibrium, with randomly distributed motions that contain absolutely no information. The more organized something is, the more information it contains, but if it is completely random, as it is here, no information can be extracted. This means that no matter what objects went into forming the black hole, a star, some planets, or maybe some bits of a nearby molecular cloud, once the stuff falls in, we are forever prevented from knowing exactly what contributed to making up the black hole. Many, who regard information as a quantity like energy, which must be conserved, view this sort of information loss as a problem, because information seems to clearly not be conserved in the process of black hole evaporation.

But if information somehow was conserved in the process, what exactly would that mean? The best explanation is that inside the black hole, beyond our view, the information on and seeds the Big Bang of another universe. In fact, as mathematical physicist John Baez notes, Caltech physicist John Preskill "...reluctantly concluded that this was the 'most conservative' solution of that famous problem!" of "the information loss paradox for black holes…" (11).

The second postulate can be attributed to an idea first proposed by theoretical physicist John A. Wheeler. From General Relativity and Cosmology, we know that a universe can either expand forever or eventually collapse back on itself in what many call the Big Crunch. These are commonly referred to as open and closed universes, respectively. What Wheeler originally envisioned was a closed universe that collapsed, but then went on to form another universe off the bounce from the collapse. In this scenario, the Big Crunch in our universe actually leads to the Big Bang of another universe, then the pattern repeats as each new universe finally collapses. This type of universe was often called an oscillating universe, and many debates ensued about whether the oscillation could continue forever, and whether our universe could be one of these.

What Wheeler took a step further was the idea that, on the bounce, the fundamental constants of physics from the initial universe could change during the Crunch and come out slightly different in the new universe. For Smolin's theory, what is relevant is that this same process might occur wherever there is a singularity, either a Big Bang or Big Crunch. Referencing the sidebars, in Superstring Theory terms, one could suppose that the way the extra dimensions are curled up might be slightly changed as one passes through a singularity. In quantum mechanical terms, one can draw upon the uncertainty principle to claim that a black hole itself could never perfectly "measure" the values of the constants in its parent universe, ensuring that the constants it passes on to the universe inside it are specified only to some finite and imperfect precision, thus slightly mutated from those of the parent universe. In either case, both postulates and Smolin's theory are, admittedly, an exercise in nearly pure speculation, but the result that appears is so compelling as to make it all quite worthwhile.

Accepting for now the two postulates, namely that black holes contain baby universes and that the parameter values are randomly mutated from parent to child universe, what do we get? As John Baez emphasizes,

"Now, given these hypotheses a marvelous consequence ensues: Darwinian evolution! Those universes whose parameters are such that many black holes are formed will have many progeny,

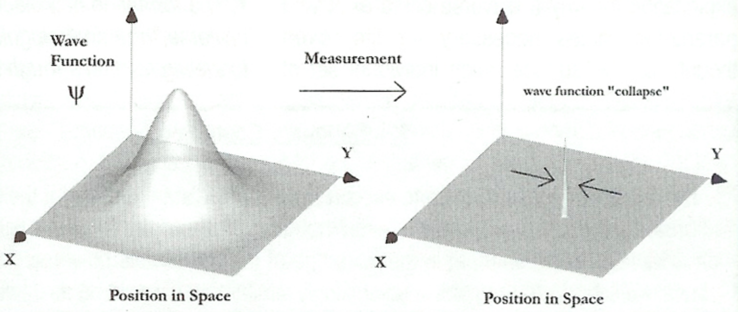
2. The Many Worlds Interpretation of Quantum Mechanics

Secondly, we must enter a brief discussion into Quantum Mechanics. In Quantum Mechanics, the central object is what physicists call the "wave function," a mathematical object whose square tells you the probability that a particle will be found at a particular place in space and time. Mathematically, the wave function is the solution to the famous Schrödinger Equation, the key equation of quantum mechanics.

In the standard interpretation, one can think of the wave function itself as something like a Gaussian Bell Curve that keeps its shape until a measurement is made, whereupon the bell curve gets squished down to a spike at the position of the particle. This is what physicists term the "collapse" of the wave function, and the idea of wave function collapse forms the backbone of the standard interpretation of quantum mechanics, the Copenhagen interpretation. The problem is that there is no known physical mechanism that explains when and how the wave function should collapse, and in addition, wave function collapse violates the Schrödinger Equation and leads to the philosophical interpretation that objects do not exist until we observe them.

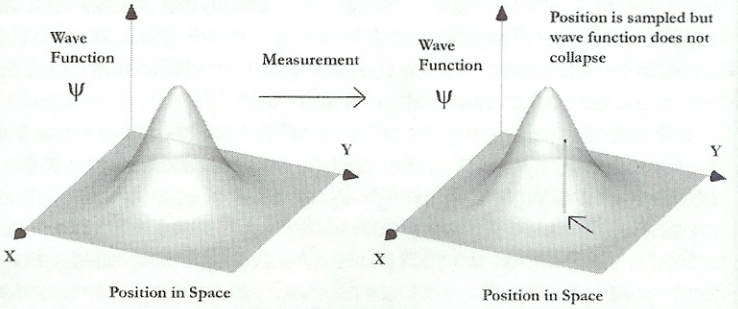
Knowing this, in 1957, theoretical physicist Hugh Everett proposed a much simpler interpretation that simply says, the Schrödinger Equation is obeyed at all times and the wave function never collapses. This means that when a measurement is made, we are not limited to a single outcome, or "spike", but in fact, all possible outcomes from the entire Bell Curve are realized somewhere. Since these other "somewheres" are quite clearly other universes, Everett's interpretation garnered the name The Many Worlds Interpretation of Quantum Mechanics.

The Copenhagen Interpretation:



The wave function of a particle is shown here as a 3-D Gaussian bell curve. In the Copenhagen Interpretation, a measurement takes the bell curve and collapses it down to a point in the xy plane. To within the precision of the uncertainty principle, the particle is then said to exist only at that point in space. This excludes the possibility of other universes.

The Many Worlds Interpretation:



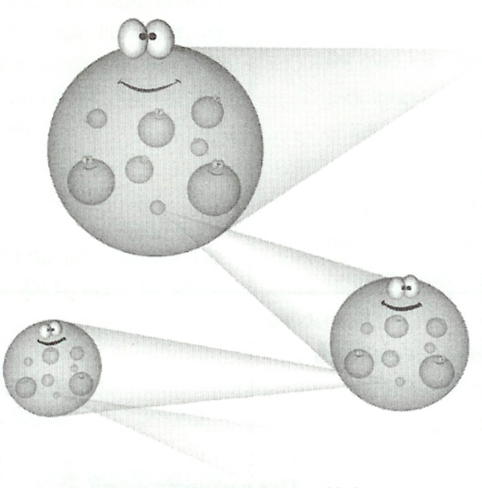
In The Many Worlds Interpretation, the measurement of a particle simply samples one of the possible positions is space from the distribution, and the wave function does not collapse. All other possible measurements are also actualized somewhere, i.e. in other universes in the multiverse.

so the constants of physics can be expected to be "tuned" for the formation of many black holes." (12).

Via the network of embedded parent-child black hole universes, this mechanism "sweeps out" the whole parameter space of all possible universes, but distinctly favors by natural selection those that produce more black holes. What this means for life will emerge shortly, but first let us consider the mechanism itself.

Picture a closed universe with a single black hole, harboring its own child universe. In time the parent universe collapses and the constants in the new resulting universe are slightly different but very close to those in the original universe. Maybe this doesn't change the number of black holes in the new universe, but maybe it does. However, sometime in the future, one way or another, the constants will have mutated enough so the parent universe produces, say, two black holes. And since the parameters in each of those two universes will be only very slightly mutated from the parent, they will almost certainly have two black holes of their own inside. In turn, these baby black holes will each harbor two more black holes, which will each have two more, and so on. In this way, the network of embedded parent and child black holes keeps extending itself, ad infinitum. Pretty soon there will be 4 black holes, then 8, then 1024, then a really gigantic number, and you have the characteristic exponential growth that one often sees in biology, in regard to, say, cell division or bacterial growth. Smolin notes that,

"No matter what assumptions we make about the collection of universes at some earlier time, it will always be the case that after a sufficient time has passed, almost all of them have parameters in the narrow ranges that produce the most black holes." (13).



Embedded Baby and Parent Universes

So merely by assuming ourselves to be a typical member of the multiverse ensemble Smolin continues, *"the parameters of the standard model of elementary particle physics have the values we find them to because these make the production of black holes much more likely than most other choices."* (14).

The relevant connection is that it just so happens that the parameter values corresponding to lots of black holes and therefore a "fertile universe" also correspond to universes favorable towards the evolution of human life (15). Our universe is believed to harbor a very large number of black holes, and as far as we can tell, the same types of parameter changes that would make life impossible, would also tend to drastically decrease the number of black holes in a given universe (16). Thus, we see that there seems to be an inextricable connection between the reproductive success of black holes and existence of life as we know it. Both require the same set of parameters, the "right" set, if you will.

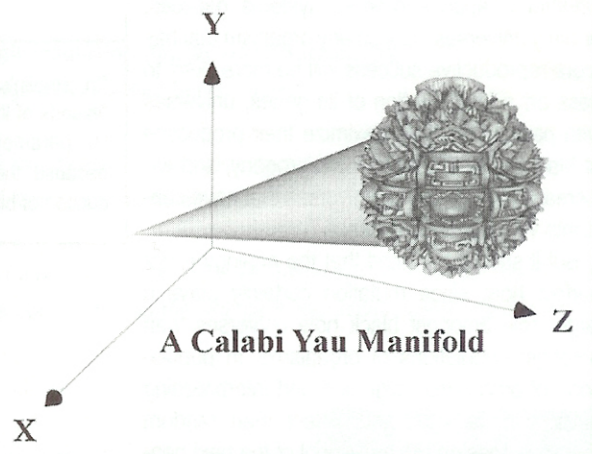
It should be noted, though, that simply having the right parameter values does not causally guarantee that life will arise, since a number of improbable events must occur in order to arrive at life. But suffice it to say, with the wrong parameter values, the events leading to life would not simply be improbable, they would be strictly impossible. In a universe without stars or without stable chemical elements, for example, no set of events could possibly lead to life such as ours. As a mathematician would state it, the right para-

3. Superstring Theory

Finally, in Superstring Theory, we have a theory that has been remarkably successful in its attempts to unify the discrepancies between our foremost physical theories, Einstein's Theory of General Relativity and Quantum Mechanics. But on the other hand, Superstring Theory has failed considerably in its other goal; to predict the values of the fundamental constants from first principles.

Superstring Theory itself postulates that elementary particles are not points but higher dimensional strings, where different particles like protons or neutrons are differentiated by the way their string is vibrating, like different notes on a violin. In addition, Superstring Theory finds that mathematically, space itself must have extra dimensions, as many as 11 or 26, if the inconsistencies of Quantum Mechanics and General Relativity are to be resolved. Since we only see three spatial dimensions around us, the others must then be tightly curled up at the microscopic level, avoiding easy detection.

What is interesting is that the geometry of the way in which the extra dimensions are curled up determines the values of the fundamental constants of physics. Change the topology of these curled up spaces, and you change the speed of light and all of its companion constants. But what Superstring theorists have found is that there are literally an infinite number of ways to curl up these spaces that are all mathematically consistent, and thus an infinite number of allowed combinations of the physical parameters. The fact that we cannot pin down a unique set of parameters and predict our own values straight from the theory, gives further credence to the idea that all possible values are just as viable and may be realized in other universes.



A Calabi Yau Manifold

In Superstring Theory, each point in space harbors extra dimensions that are "compactified" or curled up into a complex six-dimensional shape called a Calabi Yau Manifold. Since these Calabi Yau Manifolds are six-dimensional objects, and thus impossible to draw, this is only meant to be a schematic picture designed to convey the complexity of the object. The striking feature of Calabi Yau Manifolds is that they encode the values of the constants.

So to extend the genetic analogy in this article's title, if the constants are the genes of the universe, then Calabi Yau Manifolds are none other than the DNA of the universe. Just as each cell in our body contains our entire genetic code, each point in space contains all the information to reconstruct the laws of physics of its entire observable universe.

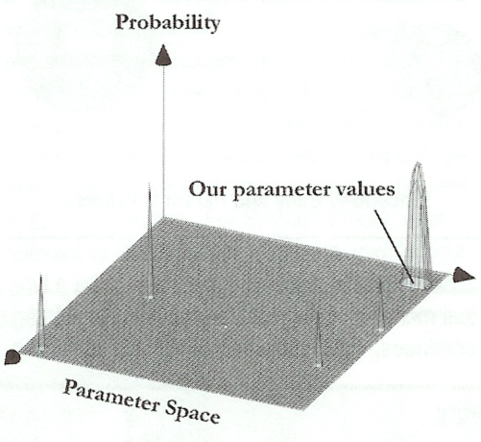
meter values are necessary, but not sufficient for life. But Smolin's explanation for the fine-tuning is significantly more compelling than simply postulating the multiverse, because it reveals a deep connection between the parameters that would be favored by cosmological natural selection and the ones that happen to be necessary for our existence!

When such a mechanism is in place, it is simply no longer acceptable to treat individual sets of parameter values as equally likely. In fact, Smolin's model shows that the probabilities become weighted exponentially for the cases favorable towards maximal black hole production and coincidentally, (or maybe not?), human life. Most other multiverse theories simply postulate a unique set of parameter values for each universe and explain the existence of life by relying on the notion that, with an infinite or almost infinite number of universes, *at least one* universe has to have the right numbers. Whereas other multiverse theories show thus how it is *possible* to have a universe with constants that seem as uniquely fine-tuned as ours, Smolin's theory claims not that it is merely possible, but how it is practically *inevitable*.

Having made the intuitive leap of applying natural selection to entire universes, the power of the idea becomes clear. Natural selection is such a broadly applicable principle that it applies to *any* evolving complex system, whether it happens to be ecosystems, galaxies, or baby universes. Just as any organism that has more reproductive success will be more likely to pass on a large portion of its genes, universes with parameters that maximize their production of black holes will have more progeny, and will increase the number of universes that have constants very similar to theirs.

But it should be noted that the analogy is not perfect here since mutation certainly plays a larger role amongst black hole universes than amongst populations of organisms. In populations of organisms, migration and interbreeding have a more immediate effect than random mutation does on the gene pool of the next generation. But since black hole universes are by definition out of causal contact, migration can only occur slowly, as previously disconnected bubbles grow in size at the speed of light until they finally overlap and become causally connected. But since this takes a great deal of time by any measure, mutation becomes the primary shaper of their "gene" pool.

However, the genetic analogy still carries a great deal of power, and it should be no surprise that the broad-sweeping ideas of evolution and natural selection find a home even amongst truly cosmological concepts. In this way, the fundamental constants of physics can no longer be viewed as unexplained numbers that merely happen to let us exist. In fact they take on a newer, grander importance, as the creations of cosmological natural selection, and none other than the genetic code of universes.



"In Smolin's model, there may be many possible "islands of life" in parameter space, but our particular parameters are among the most probable because these parameters favor the maximal production of black holes."

References:

(1) Smart, J.J.C., "God and Cosmology," Our Place in the Universe: A Metaphysical Discussion, Oxford, Blackwell, 1989, pg. 170.

(2) Smolin, Lee, The Life of the Cosmos, Ch. 3, Oxford University Press, 1997.

(3) For more physical details of the fine-tuning, see Barrow, John D. and Tipler, Frank J., The Anthropic Cosmological Principle, Ch. 8. "The Anthropic Principle and Biochemistry" is particularly rich with detailed insights on how fortuitous chemistry happens to be for life.

(4) Barrow and Tipler, pg. 16.

(5) Smart, pg. 173.

(6) Smart, pg. 173.

(7) For more see, Guth, Alan, The Inflationary Universe, Reading, Massachusetts, Perseus Books, 1997; Deutsch, David, The Fabric Of Reality, New York, Penguin Books, 1997; Greene, Brian, The Elegant Universe, New York, W.W. Norton & Co.,1999; and Smolin, Lee, The Life of the Cosmos, Oxford University Press, 1997.

(8) Inflationary Theory as put forth originally by Guth and revised later by Linde, Albrecht, Steinhart, and Moss.

(9) Baez, John, "This Week's Finds in Mathematical Physics," Wk. 31, Feb. 18, 1994. http://math.ucr.edu/home/baez/week31.html

(10) Smolin, pg. 95.

(11) Baez, John, "This Week's Finds," Wk. 31, Feb. 18, 1994.

(12) Baez, John, "This Week's Finds," Wk. 31, Feb. 18, 1994.

(13) Smolin, pg. 100.

(14) Smolin, pg. 96.

(15) Smolin, Ch. 7.

(16) More enticingly, Smolin's conclusion leads to a testable aspect of the theory, which states that, "Most changes in the parameters of the laws of physics will decrease the rate at which black holes are being produced in our universe" (Smolin, pg. 107). By studying how stars and galaxies (the seeds of black holes) form within this universe, we can determine what the effects of varying the parameters would be on black hole formation. If we can show, for example, that a large change in one or several parameters leads to significantly greater black hole pro duction, then the theory will be ruled out. According to Karl Popper's criteria for physical theories, the fact that this model is falsifiable makes it a viable theory on its own (Smolin, Ch. 8).