ALAN LIGHTMAN

## The Accidental Universe

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*To my dear friends Sam Baker, Alan Brody, John Dermon, Hok Dy, Owen Gingerich, Micah Greenstein, Bob Jaffe, Peter Meszaros, Russ Robb, David Roe, Peter Stoicheff, and Jeff Wieand*

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# The Accidental Universe

In the fifth century BC, the philosopher Democritus proposed that all matter was made of tiny and indivisible atoms, which came in various sizes and textures—some hard and some soft, some smooth and some thorny. But the atoms themselves were accepted as givens, or "first beginnings." In the nineteenth century, scientists discovered that the chemical properties of atoms repeat periodically, as in the so-called Periodic Table, but the origins of such patterns remained mysterious. It wasn't until the twentieth century that scientists learned that the properties of an atom are completely determined by the number and placement of its electrons, the subatomic particles that orbit the nucleus of the atom. These details, in turn, have been explained to high accuracy by modern physics. Finally, we now know that all atoms heavier than helium were created in the nuclear furnaces of stars.

The history of science can, in fact, be viewed as the recasting of phenomena that were once accepted as "givens" as phenomena that can now be understood in terms of fundamental causes and principles. One can add to the list of the fully explained: the hue of the sky, the orbits of planets, the angle of the wake of a boat moving through a lake, the six-sided patterns of snowflakes, the weight of a flying bustard, the temperature of boiling water, the size of raindrops, the circular shape of the sun. All of these phenomena and many more, once thought to have been fixed at the beginning of time or the result of random events thereafter, have ultimately been explained as *necessary* consequences of the fundamental laws of nature—laws found by us human beings.

This appealing and long trend in the history of science may be coming to an end. Dramatic developments in cosmological findings and thought have led some of the world's premier physicists to propose that our universe is only one of an enormous number of universes, with wildly varying properties, and that some of the most basic features of our particular universe are mere *accidents*—random throws of the cosmic dice. In which case, there is no hope of ever explaining these features in terms of fundamental causes and principles.

It is perhaps impossible to say how far apart different universes may be, or whether they exist simultaneously in time. But, as predicted by new theories in physics, the many different universes almost certainly have very different properties. Some may have stars and galaxies like ours. Some may not. Some may be finite in size. Some may be infinite. Some may have five dimensions, or seventeen. Physicists call the totality of universes the "multiverse," a word that sounds as if it came from a Robert Heinlein novel. Physicist Alan Guth, a pioneer in cosmological thought, says: "The multiple universe idea severely limits our hopes to understand the world from fundamental principles." And the philosophical ethos of science is torn from its roots. As put to me recently by the Nobel Prize–winning physicist Steven Weinberg, a man as careful in his words as in his mathematical calculations: "We now find ourselves at a historic fork in the road we travel to understand the laws of nature. If the multiverse idea is correct, the style of fundamental physics will be radically changed."

The scientists most distressed by Weinberg's "fork in the road" are theoretical physicists. Theoretical physics is the deepest and purest branch of science. It is the outpost of science closest to philosophy, and religion. Experimental scientists occupy themselves with observing and measuring the cosmos, finding out what stuff exists, no matter how strange that stuff may be. Theoretical physicists, on the other hand, are not satisfied with observing the universe. They want to know *why*. They want to explain all the properties of the universe in terms of a few fundamental principles and parameters. These fundamental principles, in turn, lead to the "laws of nature," which govern the behavior of all matter and energy. An example of a fundamental principle in physics, first proposed by Galileo in 1632 and extended by Einstein in 1905, is the following: All observers traveling at constant velocity relative to one another should witness identical laws of nature. From this principle, Einstein derived his entire theory of special relativity. An example of a fundamental parameter is the mass of an electron, considered one of the two dozen or so "elementary" particles of nature. As far as physicists are concerned, the fewer the fundamental principles and parameters, the better. The underlying hope and belief of this enterprise has always been that these basic principles are so restrictive that only one self-consistent universe is possible, like a crossword puzzle with only one solution. That one universe would be, of course, the universe we live in. Theoretical physicists are Platonists. Until the last few years, they believed that the entire universe, the one universe, was generated from a few principles of symmetry and mathematical truths, perhaps throwing in a handful of parameters like the mass of the electron. It seemed that we were closing in on a vision of our





universe in which everything could be calculated, predicted, and understood.

However, two theories in physics, called "eternal inflation" and "string theory," now indicate that the *same* fundamental principles, from which the laws of nature derive, lead to many *different* self-consistent universes, with many different properties. It is as if you walked into a shoe store, had your feet measured, and found that a size 5 would fit you, a size 8 would also fit, and a size 12 would fit equally well. Such wishy-washy results make theoretical physicists extremely unhappy. Evidently, the fundamental laws of nature do not pin down a single and unique universe. According to the current thinking of many physicists, we are living in one of a vast number of universes. We are living in an accidental universe. We are living in a universe uncalculable by science.

"Back in the 1970s and 1980s," says Alan Guth, "the feeling was that we were so smart, we almost had everything figured out." What physicists had figured out were very accurate theories of three of the four fundamental forces of nature: the strong nuclear force that binds the particles in atomic nuclei together, the weak force that is responsible for certain kinds of radioactive decay, and the electromagnetic force between electrically charged particles. And there were prospects for merging quantum physics with the fourth force, gravity, and thus pulling it into the fold of what physicists called the Theory of Everything. Some called it the Final Theory. These theories of the 1970s and 1980s required the specification of a couple dozen parameters corresponding to the masses of the elementary particles, and another half dozen or so parameters corresponding to the strengths of the fundamental forces. The next logical step would have been to derive (if possible) most of the elementary particle masses in terms of one or two masses, and the strengths of all the fundamental forces in terms of a single fundamental force.

There were good reasons to think that physicists were poised to take this next step. Indeed, since the time of Galileo, physics has been extremely successful in discovering principles and laws that have fewer and fewer free parameters and that are also in close agreement with the observed facts of the world. For example, the observed rotation of the ellipse of the orbit of Mercury, a tiny 0.012 degrees per century, was successfully calculated using the theory of general relativity. And the observed magnetic strength of an electron, 2.002319 magnetons, was accurately derived with the theory of quantum electrodynamics. More than any other science, physics brims with such highly accurate agreements between theory and experiment.





Guth started his physics career in this sunny scientific world. Now sixty-four years old and a professor at MIT, he was in his early thirties when he proposed a major revision to the Big Bang theory, called inflation. We now have a great deal of evidence suggesting that our universe began as a nugget of extremely high density and temperature about fourteen billion years ago and has been expanding, thinning out, and cooling ever since. The theory of inflation proposes that when our universe was only about a trillionth of a trillionth of a trillionth of a second old, a peculiar type of energy caused the cosmos to expand very rapidly. A tiny fraction of a second later, the universe returned to the more leisurely rate of expansion of the standard Big Bang model. Inflation solved a number of outstanding problems in cosmology, such as why the universe appears so homogeneous on large scales.

When I visited Guth in his third-floor office at MIT one cool day in May, I could barely see him above stacks of papers and empty Diet Coke bottles on his desk. More piles of papers and dozens of magazines littered the floor. In fact, a few years ago Guth won a contest sponsored by *The Boston Globe* for the messiest office in the city. The prize, he says, was the service of a professional organizer for one day. "She was actually more a nuisance than a help. She took piles of envelopes from the floor and began sorting them according to size."

Guth is still boyish looking. He wears aviator-style eyeglasses, has kept his hair long since the 1960s, and chain-drinks Diet Cokes. "The reason I went into theoretical physics," Guth tells me, "is that I liked the idea that we could understand everything (i.e., the universe) in terms of mathematics and logic." He gives a bitter laugh. We have been talking about the multiverse.

While challenging the Platonic dream of theoretical physicists, the multiverse idea does explain one aspect of our universe that has unsettled some scientists for years: according to various calculations, if the values of some of the fundamental parameters of our universe were a little larger or a little smaller, life could not have arisen. For example, if the nuclear force were a few percent stronger than it actually is, then all of the hydrogen atoms in the infant universe would have fused with other hydrogen atoms to make helium, and there would have been no hydrogen left. No hydrogen means no water. Although we are far from certain about what conditions are necessary for life, most biologists believe that water is necessary. On the other hand, if the nuclear force were substantially weaker than what it actually is, then the complex atoms needed for biology could not hold together. As another example, if the relationship between the strengths of





the gravitational force and the electromagnetic force were not close to what it is, then the cosmos would not harbor some stars that explode and spew out life-supporting chemical elements into space and other stars that form planets. Both kinds of stars seem necessary for the emergence of life. In sum, the strengths of the basic forces and certain other fundamental parameters in our universe appear to be fine-tuned to allow the existence of life.

The recognition of this fine-tuning led the British physicist Brandon Carter to articulate in 1968 what he called the anthropic principle, which states that the universe must have many of the parameters it does because we are here to observe it. Actually, the word "anthropic," stemming from the Greek word for "man," is a misnomer. If these fundamental parameters were much different from what they are, it is not only we human beings who would not exist. No life of any kind would exist.

If such conclusions are correct, the great question, of course, is *why* do these fundamental parameters happen to lie within the range needed for life? Does the universe care about life? Intelligent Design is one answer. Indeed, a number of theologians, philosophers, and even some scientists have used fine-tuning and the anthropic principle as evidence for the existence of God. For example, at the 2011 annual Christian Scholars' Conference at Pepperdine University, Francis Collins, a leading geneticist and director of the National Institutes of Health, said, "To get our universe, with all of its potential for complexities or any kind of potential for any kind of life form, everything has to be precisely defined on this knife edge of improbability . . . you have to see the hands of a Creator who set the parameters to be just so because the Creator was interested in something a little more complicated than random particles."

Intelligent Design is an answer to fine-tuning that does not appeal to most scientists. The multiverse offers another explanation. If there are zillions of different universes with different properties—for example, some with nuclear forces much stronger than in our universe and some with nuclear forces much weaker—then some of those universes will allow the emergence of life and some will not. Some of those universes will be dead, lifeless hulks of matter and energy, and some will permit the emergence of cells, plants and animals, minds. From the huge range of possible universes predicted by the theories, the fraction of universes with life is undoubtedly small. But that doesn't matter. We live in one of the universes that permits life because otherwise we wouldn't be here to ponder the question.

The explanation is similar to the explanation of why we happen to live on a planet that has so many nice





things for our comfortable existence: oxygen, water, a temperature between the freezing and boiling points of water, and so on. Is this happy coincidence just good luck, or an act of providence, or what? No, it is simply that we could not live on planets without such properties. Many other planets exist that are not so hospitable to life, such as Uranus, where the temperature is –371 degrees Fahrenheit, or Venus, where the rain is sulfuric acid.

The multiverse idea offers an explanation to the fine-tuning conundrum that does not require the presence of a Designer. As Weinberg says: "Over many centuries science has weakened the hold of religion, not by disproving the existence of God, but by invalidating arguments for God based on what we observe in the natural world. The multiverse idea offers an explanation of why we find ourselves in a universe favorable to life that does not rely on the benevolence of a creator, and so if correct will leave still less support for religion."

Some physicists remain skeptical of the anthropic principle and the reliance on multiple universes to explain the values of the fundamental parameters of physics. Others, such as Weinberg and Guth, have reluctantly accepted the anthropic principle and the multiverse idea as together providing the best possible explanation for the observed facts.

If the multiverse idea is correct, then the historic mission of physics to explain all the properties of our universe in terms of fundamental principles—to explain why the properties of our universe must *necessarily* be what they are—is futile, a beautiful philosophical dream that simply isn't true. Our universe is what it is simply because we are here. The situation can be likened to that of a group of intelligent fish who one day begin wondering why their world is completely filled with water. Many of the fish, the theorists, hope to prove that the cosmos necessarily has to be filled with water. For years, they put their minds to the task but can never quite seem to prove their assertion. Then a wizened group of fish postulates that maybe they are fooling themselves. Maybe, they suggest, there are many other worlds, some of them completely dry, some wet, and everything in between.

The most striking example of fine-tuning, and one that practically demands the multiverse to explain it, is the unexpected detection of what scientists call "dark energy." Little more than a decade ago, using robotic telescopes in Chile, Hawaii, Arizona, and outer space that can comb through nearly a million galaxies a night, astronomers discovered that the expansion of the universe is accelerating. As mentioned previously, it has been known since the late 1920s that the universe





is expanding, a central aspect of the Big Bang model. Orthodox cosmological thought held that the expansion is slowing down. After all, gravity is an attractive force, which pulls masses closer together. So it was quite a surprise in 1998 when two teams of astronomers announced that some unknown force appeared to be jamming its foot down on the cosmic accelerator pedal. The expansion is speeding up. Galaxies are flying away from one another as if repelled by antigravity. Says Robert Kirshner, one of the team members, "This is not your father's universe." (In October 2011, members of both teams were awarded the Nobel Prize in Physics.)

Physicists call the energy associated with this unexpected cosmological force dark energy. No one knows what it is. Not only invisible, dark energy apparently hides out in empty space. Yet, based on our observations of the accelerating rate of expansion, dark energy comprises a whopping three-quarters of the total energy of the universe. Dark energy is the ultimate éminence grise. Dark energy is the invisible elephant in the room of science.

The amount of dark energy, or more precisely the amount of dark energy in every cubic centimeter of space, has been measured to be about one-hundred-millionth ($10^{-8}$) of an erg per cubic centimeter. (For comparison, a penny dropped from waist high hits the floor with an energy of about 300,000—that is, $3 \times 10^5$—ergs.) This may not seem like much, but it adds up in the vast volumes of outer space. Astronomers were able to determine this number by measuring the rate of expansion of the universe at different epochs. If the universe is accelerating, then its rate of expansion was slower in the past. From the amount of acceleration, astronomers can calculate the amount of dark energy.

Theoretical physicists have several hypotheses for the identity of dark energy. It may be the energy of ghostly subatomic particles that can briefly appear out of nothing before annihilating and slipping back into the vacuum. According to quantum physics, empty space is a pandemonium of subatomic particles, rushing about and then vanishing before they can be seen. Dark energy may also be associated with an hypothesized but as-yet-unobserved force field called the Higgs field, which is sometimes invoked to explain why certain kinds of matter have mass. Theoretical physicists ponder things that other people do not. [Note: A year after this essay was written, in the summer of 2012, physicists claimed to have observed the Higgs field. See "The Symmetrical Universe."] According to string theory, dark energy may be associated with the way in which extra dimensions of space—beyond the usual





length, width, and breadth—get compressed down to sizes much smaller than atoms, so that we do not notice them.

These various hypotheses give a fantastically large range for the *theoretically possible* amounts of dark energy in a universe, from something like $10^{115}$ ergs per cubic centimeter to $-10^{115}$ ergs per cubic centimeter. (A negative value for dark energy means that it acts to *decelerate* the universe, in contrast to what is observed.) Thus, in absolute magnitude, the amount of dark energy actually present in our universe is very, very small compared to what it could be. This fact alone is surprising. If the theoretically possible values for dark energy were marked out on a ruler stretching from here to the sun, the value of dark energy actually found in our universe ($10^{-8}$ ergs per cubic centimeter) would be closer to the zero end than the width of an atom.

On one thing most physicists agree. If the amount of dark energy in our universe were only a little bit different than what it actually is, then life could never have emerged. A little larger, and the universe would have accelerated so rapidly that matter in the young universe could never have pulled itself together to form stars and hence complex atoms made in stars. And, going into negative values of dark energy, a little smaller and the universe would have decelerated so rapidly that it would have recollapsed before there was time to form even the simplest atoms.

Here we have a clear example of fine-tuning: out of all the possible amounts of dark energy that our universe might have, the actual amount lies in the tiny sliver of the range that allows life. There is little argument on this point. It does not depend on assumptions about whether we need liquid water for life or oxygen or particular biochemistries. It depends only on the requirement of atoms. As before, one is compelled to ask the question: Why does such fine-tuning occur? And the answer many physicists now believe: the multiverse. A vast number of universes may exist, with many different values of the amount of dark energy. Our particular universe is one of the universes with a small value, permitting the emergence of life. We are here, so our universe must be such a universe. We are an accident. From the cosmic lottery hat containing zillions of universes, we happened to draw a universe that allowed life. But then again, if we had not drawn such a ticket, we would not be here to ponder the odds.

The concept of the multiverse is compelling not only because it explains the problem of fine-tuning. As I mentioned earlier, the possibility of the multiverse is





actually predicted by modern theories of physics. One such theory, called eternal inflation, is a revision of Guth's inflation theory developed by Paul Steinhardt, Alex Vilenkin, and Andrei Linde in the early and mid-1980s. In the inflation theory, the very rapid expansion of the infant universe is caused by an energy field, like dark energy, that is temporarily trapped in a condition that does not represent the lowest possible energy for the universe as a whole—like a marble sitting in a small dent on a table. The marble can stay there, but if it is jostled, it will roll out of the dent, roll across the table, and then fall to the floor (which represents the lowest possible energy level). In the theory of eternal inflation, the dark energy field has many different values at different points of space, analogous to lots of marbles sitting in lots of dents on the cosmic table. Each of these marbles is jostled by the random processes inherent in quantum mechanics, and some of the marbles will begin rolling across the table and onto the floor. Each marble starts a new Big Bang, essentially a new universe. Thus, the original, rapidly expanding universe spawns a multitude of new universes, in a never-ending process.

String theory, too, predicts the possibility of the multiverse. Originally conceived in the late 1960s as a theory of the strong nuclear force but soon enlarged far beyond that ambition, string theory postulates that the smallest constituents of matter are not subatomic particles, like the electron, but extremely tiny one-dimensional "strings" of energy. These elemental strings can vibrate at different frequencies, like the strings of a violin, and the different modes of vibration correspond to different fundamental particles and forces. String theories typically require seven dimensions of space in addition to the usual three, which are compacted down to such small sizes that we never experience them, like a three-dimensional garden hose that appears as a one-dimensional line when seen from a great distance. There are, in fact, a vast number of ways that the extra dimensions in string theory can be folded up, a little like the many ways that a piece of paper can be folded up, and each of the different ways corresponds to a different universe with different physical properties.

It was originally hoped that from a theory of these strings, with very few additional parameters, physicists would be able to explain all the forces and particles of nature—all of reality would be a manifestation of the vibrations of elemental strings. String theory would then represent the ultimate realization of the Platonic ideal of a fully explicable cosmos in terms of a few fundamental principles. In the last few years, however, physicists have discovered that string theory does not predict a unique universe, but a vast number of pos-





sible universes with different properties. It has been estimated that the "string landscape" contains $10^{500}$ different possible universes. For all practical purposes, that number is infinite.

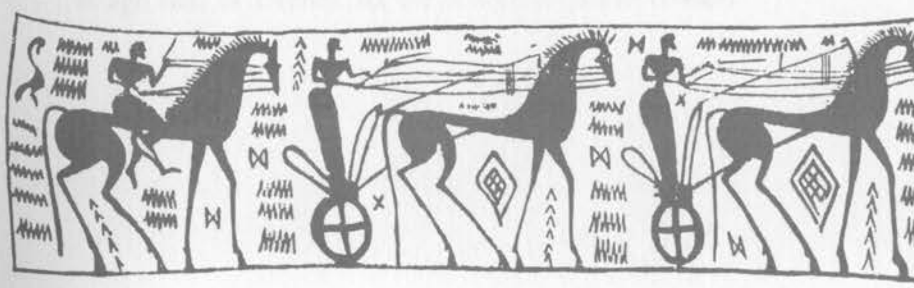
It is important to point out that neither eternal inflation nor string theory has anywhere near the experimental support of many previous theories in physics, such as general relativity or quantum electrodynamics. Eternal inflation or string theory, or both, could turn out to be wrong. However, some of the world's leading physicists have devoted their careers to the study of these two theories.

Back to the intelligent fish. The wizened old fish conjecture that there are many other worlds, some with dry land and some with water. Some of the fish grudgingly accept this explanation. Some feel relieved. Some feel like their lifelong ruminations have been pointless. And some remain deeply concerned. Because there is no way they can prove this conjecture. That uncertainty also disturbs many physicists who are adjusting to the idea of the multiverse. Not only must we accept that basic properties of our universe are accidental and uncalculable. In addition, we must believe in the existence of many other universes. But we have no conceivable way of observing these other universes and cannot prove their existence. Thus, to explain what we see in the world and in our mental deductions, we must believe in what we cannot prove.

Sound familiar? Theologians are accustomed to taking some beliefs on faith. Scientists are not. Such arguments, in fact, run hard against the long grain of science. All we can do is hope that the same theories that predict the multiverse also make other predictions that we can test here in our local universe. But the other universes themselves will almost certainly remain a conjecture.

"We had a lot more confidence in our intuition before the discovery of dark energy and the multiverse idea," says Guth. "There will still be a lot for us to understand, but we will miss out on the fun of figuring everything out from first principles." One wonders whether a twenty-five-year-old Alan Guth, entering science today, would choose theoretical physics.





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# WHY SCIENCE DOES NOT DISPROVE GOD

AMIR D. ACZEL

wm
WILLIAM MORROW
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# Contents

# WHY SCIENCE DOES NOT DISPROVE GOD

systems are also hypersensitive to precise initial conditions: no one can predict how the butterfly's flapping wings will change the dynamics of a system. This quality of highly nonlinear systems represents a huge hole in our knowledge of nature and demonstrates once again that there are, and always will be, things we cannot predict in a satisfactory way. And what does this say about our ability to understand nature?

**IT IS IMPORTANT** to understand that chaos is *not* randomness. A chaotic system is perfectly nonrandom; it is *deterministic* in the sense that one outcome leads directly to another without any randomness, but we cannot know which one.

The fact that a system can be fundamentally nonlinear and unpredictable and yet not random is very important. It tells us that nature has processes and outcomes that are even outside of *probabilistic* analysis. Such things are intrinsically *unknowable* to us and, in a sense, lie in the realm of the gods—well outside human understanding and control.

What is so surprising is that chaotic, catastrophic, and highly nonlinear phenomena do not necessarily require many variables and inputs to get started. The fact that our double pendulum made of two bits of metal and a piece of string *immediately* exhibits chaotic behavior tells us that even very simple-looking processes can be unpredictable. And if we fail in our efforts to understand even the simplest of natural processes, how can we ever pretend to have knowledge that is so complete and so powerful that we can claim to have disproved the existence of God?



# 11

# Between God and the Anthropic Principle

This is the book's most important chapter, in which we consider the anthropic principle, which argues that the universe is the way it is because if it were any different, we humans wouldn't be here. The anthropic principle has been one of the most important tools in the hands of atheists in their battle against the notion of a God-created world.

The universe we see around us is characterized by extremely finely tuned constants—numbers such as the mass of the electron and the strength of gravity, on which the existence of our world depends. This has led some to believe that if we are here, then the world must be as it is. We have to live in the only universe hospitable to us so, within an infinite multiverse, we find ourselves in that universe in which we *can* exist. The anthropic principle, plus the existence of an infinite collection of (mostly inhospitable) universes, is seen by some as a good substitute for a God who purposely *made* the constants of nature what they are so that we could live.

As science broke new ground in the twentieth century, truths as strange as quantum theory emerged. Roger Penrose has spent a lifetime trying to understand the workings of the universe. And he has come to a stunning conclusion: if the entropy (a measure of disorder commonly used in physics) of space had been off from what it currently is by even a tiny fraction, the universe would not exist. Thus the universe has to have been "fine tuned" to a degree that we can hardly comprehend. Penrose writes, in *The Road to Reality:*

> Can the anthropic principle be invoked to explain the very special nature of the Big Bang? Can this principle be incorporated as part of the inflationary picture, so that an initially chaotic (maximum entropy) state can nevertheless lead to a universe like the one we live in, in which the Second Law of Thermodynamics holds sway?

The second law of thermodynamics says that the entropy of a system will increase through time. Penrose's model of a universe that gives rise to human life has certain requirements, such as the maintaining of the second law as well as conditions of equilibrium of temperatures and other variables that are consistent with it. He writes:





> The argument would run roughly: "For sentient life to exist, we need a large universe with timescales long enough for evolution to take place, in conducive conditions, etc.; this requires some inflation, originating from our tiny smooth initial region, and once it starts, the inflation goes on to provide us with the wonderfully enormous observable universe that we know." Although it may seem that this picture is of such a marvelously romantic nature that it is completely immune from scientific attack, I do not believe that this is so. . . . The required precision in phase-space-volume terms is one part in $10^{10^{123}}$ at least. The exponent $10^{123}$ comes from the entropy of a black hole of mass equal to that in the observable universe.

Only a mathematical genius like Roger Penrose could come up with an argument for the existence of a life-giving universe based on the thermodynamic requirements of a black hole. Then Penrose refines his argument by asking: "But do we really need the conditions for life in the entire universe?" And his answer is that there is a minimum part of the universe that is forced to have benevolent conditions that could support life and intelligence. He can thus give up slightly on the requirements, leading him to conclude:

> Thus, the precision needed, on the part of our "Creator" . . . to construct this smaller region is now

> only about: one part in $10^{10^{117}}$ Our Creator now only requires a rather *smaller* "tiny smooth region" of the "initial manifold" than before. The Creator is much more likely to come across a smooth region. . . . There was indeed something very special about how the universe started off. . . . We might take the position that the initial choice was an "act of God" . . . or we might seek some scientific/mathematical theory to explain the extraordinarily special nature of the Big Bang. My own strong inclination is certainly to try to see how far we can get with the second possibility.

Penrose draws a picture of "The Creator," a man with a long white beard pointing to an infinitesimally small point, within the entire "space of parameters" possible for the entropy of the universe, in order to have created the universe that we actually have. Not at all a religious man, Penrose nevertheless understands that something like a miracle might have created our world to the precise amount of entropy required for its existence. In seeking alternative reasons for this amazing cosmic "coincidence" of infinitesimally small probability, Penrose also admits that an ultimate theory of quantum gravity might someday lead us to another answer.

**PENROSE'S MOST FAMOUS** former student and scientific collaborator is Stephen Hawking. As we've seen, Hawking himself has hedged somewhat on the issue of the creation of the uni-





verse, sometimes choosing a more atheistic point of view than at other times. Throughout his life, it appears that Hawking, too, has been deeply concerned with anthropic arguments.

In September 1981, Hawking attended a conference at the Vatican. Addressing Hawking among a group of top scientists, Pope John Paul II said that it was probably futile for human beings to inquire into the actual moment of the creation of the universe. According to the pope, such knowledge comes "from the revelation of God." The pope was correct in pointing out that physics and cosmology are unable to bring us to the actual moment of creation, let alone take us beyond it to see what caused the Big Bang. So whether it was God or not, we are unable to explain the Big Bang. Sometime afterward, Hawking discussed this issue with author John Boslough, offering a telling glimpse of his view of the universe and how it might have come about:

> The odds against a universe like ours emerging out of something like the Big Bang are enormous. I think there are clearly religious implications whenever you start to discuss the origins of the universe.

Hawking has wondered about the parameters of the universe throughout his life and has pointed out that if the electric charge of the electron had been slightly different from what it is, stars would either not burn at all or would not have exploded in supernovas to spew into space many of the elements we need for life. If the force of gravity had been even slightly weaker, matter would not have come together to make stars and planets.

We have no theory that can predict why the forces and charges and masses are the way they are. These parameters seem arbitrary from a theoretical point of view. But without their values being precisely what they are, we wouldn't be here. Hawking also said the following: "If one considers the possible constants and laws that could have emerged, the odds against a universe that has produced life like ours are immense."

Hawking was also led to the anthropic principle in his attempts to explain how a universe supporting life, which a priori had such an incredibly small probability of emerging, ever came about. According to science biographer Kitty Ferguson,

> Hawking explains the anthropic principle as follows: picture a lot of different, separate universes, or different regions of the same universe. The conditions in most of these universes, or in these regions of the same universe, do not allow the development of intelligent life. However, in a very few of them, the conditions are just right for stars and galaxies and solar systems to form and for intelligent beings to develop and study the universe and ask the question, why is the universe as we observe it? According to the anthropic principle, the only answer to their question may be that, if it were otherwise, we wouldn't be around to ask the question.





Many physicists dislike the anthropic principle because it has no explanatory power, except for the trivial one that things are the way they are because they couldn't be any other way. And the anthropic principle is not a good replacement for God. You could say that there is one universe and that God made it this way—the parameters and forces all fitting perfectly well—so as to create intelligent life. Positing infinitely many universes and an anthropic principle to "choose" among them the one in which we must live is an unparsimonious way of building a model of life, and not a highly scientific one. Hawking and many other physicists hope that a "theory of everything" will some day *explain* the values of all the parameters of the universe so that the anthropic principle could be retired.

**ALTHOUGH THE ANTHROPIC** principle does not have the usual scientific validity or the power to truly explain things, the New Atheists embrace this theory because it is a substitute for God. Richard Dawkins devotes almost thirty pages of *The God Delusion* to this principle, curiously even linking it to natural selection: "Natural selection works because it is a cumulative one-way street to improvement. It needs some luck to get started, and the 'billions of planets' anthropic principle grants it that luck." Noting that the anthropic principle is "hated by most physicists," Dawkins says, "I can't understand why. I think it's beautiful—perhaps because my consciousness has been raised by Darwin."

Roger Penrose, in fact, sidesteps the anthropic principle.

For him, the origin of the universe is either an "act of God" or something that we may find when we have the "final theory" of physics. Like the multiverse, to which it is often linked, the anthropic principle is a kind of forcing argument that lacks a profound theoretical justification.

There are some variants of the anthropic idea. The *weak* anthropic principle guides variables such as why we are on Earth and not on Venus: Venus is too hot, so we must be here and not there. We must be within the "habitable zone" around our sun, a zone that satisfies the Goldilocks Quest—not too hot and not too cold; it is the region of space where water can exist in liquid form so it can support life as we know it.

The *strong* anthropic principle applies to everything: the masses and charges of all elementary particles, the cosmological constant, the entropy of our part of the universe, the strengths of all the forces of nature, and everything else. It says that all the parameters of nature are the way they are simply because if any of them had different values we simply wouldn't be here.

The anthropic principle has an interesting history. In the early 1960s, Princeton physicist Robert Dicke invoked what are essentially anthropic arguments to explain the age of the universe. He stated that the age must be compatible with the evolution of life, and, for that matter, with sentient, conscious beings who now wonder about the age of the universe. In a universe too young for life to have evolved, there were no such beings. But the term *anthropic principle* seems to have been coined in 1973 by the Australian physicist Brandon Carter, in a lecture





he gave at a congress in Kraków celebrating Copernicus's five hundredth birthday.

Over the decades, Dicke's argument has been extended to other numerical measurements of the universe we observe around us, and thus to questions such as: Why is the mass of the proton 1,836.153 times that of the electron? Why are the electric charges of the up and down quarks exactly 2/3 and –1/3, respectively, on a scale in which the electron's charge is –1? Why is Newton's gravitational constant, *G*, equal to $6.67384 \times 10^{-11}$?

And there is also the question that has deeply puzzled so many physicists since 1916: Why is the *fine structure constant*, which measures the strength of electromagnetic interactions, so tantalizingly close to 1/137—the inverse of a prime number? (We now know it to far greater accuracy: about 1/137.035999.)

Richard Feynman once wrote: "It's one of the *greatest* damn mysteries of physics: a *magic number* that comes to us with no understanding by man. You might say the 'hand of God' wrote that number, and 'we don't know how he pushed his pencil.'" The astronomer Arthur Eddington (who proved Einstein's hypothesis that space-time curves around massive objects) built entire numerological theories around this number—all of them false. (He assumed that the constant was 1/136). There is even a joke that the Austrian physicist and quantum pioneer Wolfgang Pauli, who throughout his life was obsessed with the number 137, asked God about it when he died (in fact in a hospital room numbered 137) and went up to heaven; God handed him a thick packet and said: "Read my preprint, I explain it all there."

Stories and jokes aside, the values of all the physical constants described above have persistently defied all analysis or rational explanation. One physicist who made a strong attempt to understand them is Steven Weinberg, who seems to have always been ahead of his time. In 1998, just a few months before the announcement of the stunning astronomical discovery that the universe is accelerating its expansion—leading to the conclusion that "dark energy" permeates space, pushing the universe ever outward—Weinberg and colleagues at the University of Texas published a paper about that then-hypothetical dark energy. They argued that if it exists, its numerical measurement *must* fall within a very narrow range of values, which they specified in their paper; for otherwise, the energy would be too high for galaxies to coalesce through the gravitational force, or it would be too low and the gravitational force affecting all matter would win out, leading to a gravitational collapse before galaxies and life would have had time to evolve.

Weinberg and his colleagues thus derived what the value of the cosmological constant would have to be (within bounds) based purely on the anthropic principle. The anthropic principle helped predict the value of an unknown parameter, but the methodology used was not satisfying since it did not reveal any underlying reasons for the value of the cosmological constant other than "if we are here to observe it, it has to be within this given range."

Of course this argument would also apply to Newton's constant, the masses and charges of the quarks and the electron,





the fine structure constant, the parameters governing the strong and weak nuclear forces, and so on. The forces of nature are *extremely* fine-tuned to accommodate a universe such as the one we see around us. Anthropically speaking, if we are here, the parameters have to be what they are.

The force of gravity, even though it is the one we feel the most, is in fact the weakest of the four forces of nature. Gravity is *forty orders of magnitude weaker* than the electromagnetic force. You can perform an experiment to prove it: Place a small paper clip on a table. The force of gravity, exerted on the paper clip by the entire planet underneath the table, is keeping it in place. Now take a small bar magnet and lower it down toward the paper clip. When you get close enough to it, the paper clip will jump up and stick to the magnet. This shows you that a very small magnet can *overcome,* using the electromagnetic force it generates, the gravitational pull on the paper clip that is exerted on it by the entire Earth.

Why is the gravitational force forty orders of magnitude weaker than electromagnetism? Why are the strengths of the four forces of nature exactly what they are? Without the highly fine-tuned values of the forces, we simply would not be here: gravitation would crush us before we had a chance to exist if it were any stronger, and if the electromagnetic force had a different strength, chemistry as we know it would not work because the electrical forces in atoms could not maintain the electrons in their orbits around the nuclei. If the strong nuclear force had a different value, quarks would be crushed or fly out of protons and neutrons, and atomic nuclei and therefore matter would not endure. And if the weak nuclear force had a different value, possibly almost everything would be radioactive, or stars would not shine and produce heat, so there would be no life.

When I interviewed Weinberg about his work and about the anthropic principle, he told me, "The universe could well be like a giant Schrödinger's cat. There are parts of the universe where the cat is alive, where the cosmological constant is just the right level and there are scientists there observing it and asking questions. And there are parts of the universe where the cat is dead—where the cosmological constant is too small or too large and therefore there is no life and no scientists asking questions about the universe." This is certainly one interesting view of the universe.

But the anthropic principle is used by some cosmologists simply because we do not know why parameters such as the masses and charges of the electron and the quarks, the entropy of the universe, and the strength of the cosmological constant are so immensely fine-tuned as to assure the existence of our universe.

If you wanted to test which hypothesis is true, a universe *created* to specific requirements, or a universe that just happens to satisfy the requirements because we observe them, you would find that there is no scientific way to determine the answer.

**AS WE HAVE** seen, physics is unable to escape the conundrum of the incredibly fine-tuned nature of many of its parameters. The best and simplest example of this mystery is that of the





interplay of the proton, neutron, electron, and quarks. Every student of physics knows that matter is made of protons and neutrons inside the nucleus, orbited by electrons to complete the picture of the atom. Now, the dance of electrons around nuclei is achieved because the electric charge of the electron is equal in magnitude but opposite in sign to that of the proton: without this equality of charges, there would be no life-giving universe.

But while the electron is an elementary particle (it has no internal structure), the proton and neutron are not. Each proton is made out of three quarks—two "up" quarks and a "down" quark. So the electric charges of the quarks *must add up precisely* so that the charge of the proton will equal +1 (the electron's charge is defined as –1), or else the balance won't hold.

We know that this indeed happens: the charge of the "up" quark is exactly 2/3, and the charge of the "down" quark is exactly –1/3. When we add up the charges of the two "up" quarks and the single "down" quark that make up the proton we get $2/3 + 2/3 - 1/3 = 1$. How could this happen so precisely? To further compound the mystery, the neutron (present in the nuclei of all elements heavier than hydrogen) must have an electric charge of zero, and it is composed of two "down" quarks and an "up" quark. And yet the mathematical magic works again. If you add the charges of the quarks that make up the neutron, you get $2/3 - 1/3 - 1/3 = 0$.

Why would the charges of the quarks work out so perfectly? In the beginning, a fraction of a second after the Big Bang, the universe is believed to have consisted of a *quark-gluon* *plasma*, commonly referred to as a "quark soup." Then these quarks swimming in the dense and extremely hot soup created by the Big Bang suddenly bunched in *threes* to make protons and neutrons. This alone seems mysterious: generally in nature things pair up—not form threesomes. Why and how did all this happen, and how did the charges and masses and strengths of interactions for bunching up together to create stable composite particles all work out as needed to make a universe? Science has no good answers for these mysteries.

In fact, the standard model of particle physics was devised, using powerful mathematical ideas, to try to answer some of these very riddles—but it has absolutely failed to address the questions about the masses of the elementary particles and about the strengths of interactions of the forces, such as the infamous "1/137" governing all electromagnetic interactions. These numbers do not come out as results of the formulation of the equations of the model and have to be "put in by hand." Just how the "free parameters" in our models of the universe obtained the precise values they require so that our universe would exist remains a deep unsolved mystery—among the greatest riddles of science.

One way out of the problem is to say, "If the parameter values weren't what they are, we wouldn't be here to ask the question"—the anthropic principle. But one cannot use such a statement to scientifically falsify the competing hypothesis: "The parameters were created the way they are in order to make a universe." So is it God, or is it the anthropic principle?





**PERHAPS THE BEST** example of how inadequate the anthropic principle is in providing good, valid explanations for phenomena has to do with an event mentioned earlier, the crash into Earth of a large solar-system object 65 million years ago, which resulted in the atmosphere being filled with dust for years, causing freezing that killed much of life, including the dinosaurs. It is widely believed that had this event not taken place, dinosaurs would have continued to rule the Earth and primates would never have had the opportunity to evolve and eventually take over the planet as humans.

If a strict advocate of the anthropic principle were to be asked why an asteroid or meteorite hit the Earth 65 million years ago, his or her answer would have to be: "Because otherwise we wouldn't be here to ask this question." This answer is exactly in line with those to similar questions, seen throughout this chapter. But in this example we can clearly see why the anthropic answer is not science. A solar-system object hit the Earth 65 million years ago because its orbit happened to intersect that of our planet at that point in time. This is the correct *scientific*, non-anthropic explanation. It is immensely important to note, however, that no such explanation exists for the masses and strengths of interaction constants of the universe. And since the anthropic principle, as we see, is so unsatisfactory, one must consider other explanations. These may include divine intention, or at least something that resides well outside our present powers of understanding.