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Science's crisis of faith

By Alan P. Lightman

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In the fifth century B.C., 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. The atoms themselves were taken as givens. In the nineteenth century, scientists discovered that the chemical properties of atoms repeat periodically (and created the periodic table to reflect this fact), 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 determined by the number and placement of its electrons, the subatomic particles that orbit its nucleus. And we now know that all atoms heavier than helium were created in the nuclear furnaces of stars.

The history of science can be viewed as the recasting of phenomena that were once thought to be accidents as phenomena that can 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 these phenomena and many more, once thought to have been fixed at the beginning of time or to be the result of random events thereafter, have been explained as *necessary* consequences of the fundamental laws of nature—laws discovered by human beings.

This long and appealing trend 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 indeed mere *accidents*—a random throw of the cosmic dice. In which case, there is no hope of ever explaining our universe's features in terms of fundamental causes and principles.

It is perhaps impossible to say how far apart the different universes may be, or whether they exist simultaneously in time. Some may have stars and galaxies like ours. Some may not. Some may be finite in size. Some may be infinite. Physicists call the totality of universes the "multiverse." Alan Guth, a pioneer in cosmological thought, says that "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 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 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 past few years, they agreed that the entire universe, the one universe, is generated from a few mathematical truths and principles of symmetry, 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, eternal inflation and string theory, now suggest that the *same* fundamental principles from which the laws of nature derive may 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 atomic nuclei together, the weak force that is responsible for some forms of radioactive decay, and the electromagnetic force between electrically charged particles. And there were prospects for merging the theory known as quantum physics with Einstein’s theory of the fourth force, gravity, and thus pulling all of them into the fold of what physicists called the Theory of Everything, or 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 step would then have been to derive most of the elementary particle masses in terms of one or two fundamental masses and define 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, 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 derived using the theory of quantum electrodynamics. More than any other science, physics brims with 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, something 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 14 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 the stacks of paper and empty Diet Coke bottles on his desk. More piles of paper 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 was the services 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.” He wears aviator-style eyeglasses, keeps his hair long, 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 percentage points stronger than it actually is, then all the hydrogen atoms in the infant universe would have fused with other hydrogen atoms to make helium, and there would be 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 any stars that explode and spew out life-supporting chemical elements into space or any other stars that form planets. Both kinds of stars are required for the emergence of life. 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 finetuning led British physicist Brandon Carter to articulate what he called the anthropic principle, which states that the universe must have the parameters it does because we are here to observe it. Actually, the word *anthropic*, from the Greek for "man," is a misnomer: if these fundamental parameters were much different from what they are, it is not only 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* 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 fair number of theologians, philosophers, and even some scientists have used fine-tuning and the anthropic principle as evidence of the existence of God. For example, at the 2011 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.... [Y]ou 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, however, is an answer to fine-tuning that does not appeal to most scientists. The multiverse offers another explanation. If there are countless 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 others 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 ask 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, and Venus, where it rains sulfuric acid.

The multiverse offers an explanation to the fine-tuning conundrum that does not require the presence of a Designer. As Steven 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 because we are here. The situation could be likened to a school of intelligent fish who one day began wondering why their world is completely filled with water. Many of the fish, the theorists, hope to prove that the entire 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 there are, they suggest, many other worlds, some of them completely dry, 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 Arizona, Chile, Hawaii, 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; it’s a central feature of the Big Bang model. Orthodox cosmological thought held that the expansion is slowing down. After all, gravity is an attractive force; it pulls masses closer together. So it was quite a surprise in 1998 when two teams of astronomers announced that some unknown force appears to be jamming its foot down on the cosmic accelerator pedal. The expansion is speeding up. Galaxies are flying away from each other as if repelled by antigravity. Says Robert Kirshner, one of the team members who made the discovery: “This is not your father’s universe.” (In October, members of both teams were awarded the Nobel Prize in Physics.)

Physicists have named the energy associated with this 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 constitutes a whopping three quarters of the total energy of the universe. It 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 calculated 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 three hundred thousand—that is, 3×10^5—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 in the universe.

Theoretical physicists have several hypotheses about the identity of dark energy. It may be the energy of ghostly subatomic particles that can briefly appear out of nothing before selfannihilating 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 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.) And in the models proposed by 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 would mean 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 either very, very small or very, very large compared with what it could be. This fact alone is surprising. If the theoretically possible positive values for dark energy were marked out on a ruler stretching from here to the sun, with zero at one end of the ruler and 10^{115} ergs per cubic centimeter at the other end, 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 more and the universe would accelerate so rapidly that the matter in the young cosmos could never pull itself together to form stars and thence form the complex atoms made in stars. And, going into negative values of dark energy, a little less and the universe would decelerate so rapidly that it would recollapse 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. 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 Andrei Linde, Paul Steinhardt, and Alex Vilenkin in the early and mid-1980s. In regular 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. Moreover, as space expands rapidly, the number of marbles increases. 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, 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 be the ultimate realization of the Platonic ideal of a fully explicable cosmos. In the past few years, however, physicists have discovered that string theory predicts not a unique universe but a huge number of possible 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 special relativity or quantum electrodynamics, mentioned earlier. 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 same uncertainty 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. All we can do is hope that the same theories that predict the multiverse also produce many other predictions that we can test here in our own 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 young Alan Guth, considering a career in science today, would choose theoretical physics.

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