CHAPTER 8

A GRAND ACCIDENT?

Once you assume a creator and a plan, it makes humans objects in a cruel experiment whereby we are created to be sick and commanded to be well.

—CHRISTOPHER HITCHENS

We are hardwired to think that everything that happens to us is significant and meaningful. We have a dream that a friend is going to break her arm, and the next day we find out that she sprained her ankle. Wow! Cosmic! Clairvoyant?

The physicist Richard Feynman used to like to go up to people and say: "You won't believe what happened to me today! You just won't believe it!" And when they would inquire what happened, he would say, "Absolutely nothing!" By this he was suggesting that when something like the dream I described above happens, people ascribe significance to it. But they forget the myriad nonsense dreams they had that predicted absolutely nothing. By forgetting that most of the time nothing of note occurs during the day, we then misread the nature of probability when something unusual does occur: among any sufficiently large number of events, something unusual is bound to happen just by accident.

How does this apply to our universe?

Until the discovery that, inexplicably, the energy of empty space is not only not zero, but takes a value that is 120 orders of magnitude smaller than the estimate I described based on ideas from particle physics suggests, the conventional wisdom among physicists was that every fundamental parameter we measured in nature *is* significant. By this I mean that, somehow, on the basis of fundamental principles, we would eventually be able to understand things such as why gravity is so much weaker than the other forces of nature, why the proton is 2,000 times heavier than the electron, and why there are three families of elementary particles. Put another way, once we understood the fundamental laws that govern the forces of nature at its smallest scales, all of these current mysteries would be revealed as natural consequences of these laws.

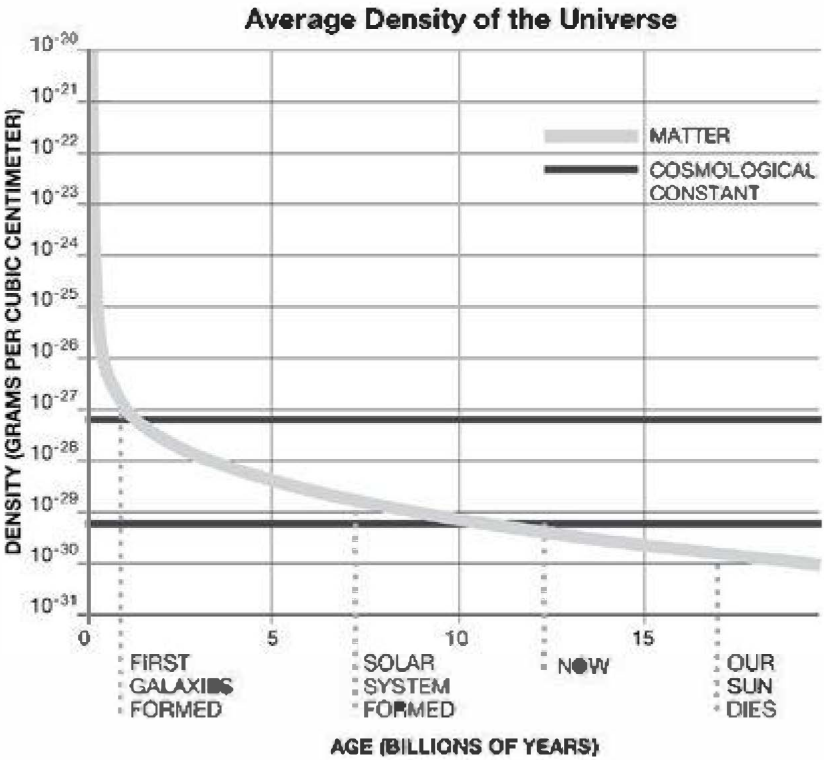
(A purely religious argument, on the other hand, could take significance to an extreme by suggesting that each fundamental constant is significant because God presumably chose each one to have the value it does as part of a divine plan for our universe. In this case, nothing is an accident, but by the same token, nothing is predicted or actually explained. It is an argument by fiat that goes nowhere and yields nothing useful about the physical laws governing the universe, other than perhaps providing consolation for the believer.)

But the discovery that empty space has energy started a revision in thinking among many physicists about what is required in nature and what may be accidental.

The catalyst for this new gestalt originates from the argument I gave in the last chapter: dark energy is measurable today because "now" is the only time in the history of the universe when the energy in empty space is comparable to the energy density in matter.

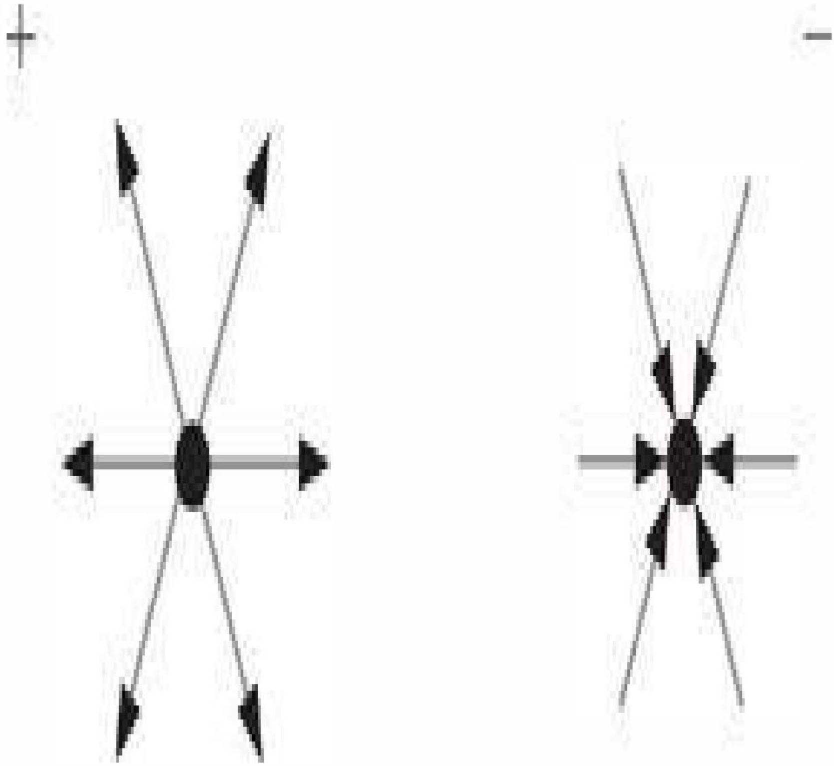
Why should we be living at such a "special" time in the history of the universe? Indeed, this flies in the face of everything that has characterized science since Copernicus. We have learned that the Earth is not the center of the solar system and that the Sun is a star on the lonely outer edges of a galaxy that is merely one out of 400 billion galaxies in the observable universe. We have come to accept the "Copernican principle" that there is nothing special about our place and time in the universe.

But with the energy of empty space being what it is, we *do* appear to live at a special time. This is shown best by the following illustration of a "brief history of time."



The two curves represent the energy density of all matter in the universe, and the energy density of empty space (presuming it is a cosmological constant) as a function of time. As you can see, the density of matter falls, as the universe expands (as the distance between galaxies becomes ever greater and matter therefore gets "diluted"), just as you would expect. However, the energy density in empty space remains constant, because, one might argue, with empty space there is nothing to dilute! (Or, as I have somewhat less facetiously described, the universe does work on empty space as it expands.) The two curves cross relatively close to the present time, which is the source of the strange coincidence I have described.

Now consider what would happen if the energy in empty space were, say, 50 times greater than the value we estimate today. Then the two curves would cross at a different, earlier time, as shown in the figure below.



The time that the two curves cross for the upper, enlarged value of the energy of empty space is the time when galaxies first formed, about a billion years after the Big Bang. But remember that the energy of empty space is gravitationally repulsive. If it had come to dominate the energy of the universe before the time of galaxy formation, the repulsive force due to this energy would have outweighed (literally) the normal attractive gravitational force that caused matter to clump together. And galaxies would never have formed!

But if galaxies hadn't formed, then stars wouldn't have formed. And if stars hadn't formed, planets wouldn't have formed. And if planets hadn't formed, then astronomers wouldn't have formed!

So, in a universe with an energy of empty space merely 50 times bigger than that we observe, apparently no one would have been around today to try to measure the energy.

Could this be telling us something? Shortly after the discovery of our accelerating universe, physicist Steven Weinberg proposed, based on an argument he had developed more than a decade earlier—before the discovery of dark energy—that the "Coincidence Problem" could therefore be solved if perhaps the value of the cosmological constant that we measure today were somehow "anthropically" selected. That is, if somehow there were many universes, and in each universe the value of the energy of empty space took a randomly chosen value based on some probability distribution among all possible energies, then only in those universes in which the value is not that different from what we measure would life as we know it be able to evolve. So maybe we find ourselves in a universe with a tiny energy in empty space because we couldn't find ourselves in one with a much larger value. Put another way, it is not too surprising to find that we live in a universe in which we can live!

This argument, however, makes mathematical sense only if there is a possibility that many different universes have arisen. Talking about many different universes can sound like an oxymoron. After all, traditionally the notion of universe has become synonymous with "everything that exists."

More recently, however, *universe* has come to have a simpler, arguably more sensible meaning. It is now traditional to think of "our" universe as comprising simply the totality of all that we can now see and all that we could ever see. Physically, therefore, our universe comprises everything that either once could have had an impact upon us or that ever will.

The minute one chooses this definition for a universe, the possibility of other "universes"—regions that have always been and always will be causally disconnected from ours, like islands separated from any communication with one another by an ocean of space—becomes possible, at least in principle.

Our universe is so vast that, as I have emphasized, something that is not impossible is virtually guaranteed to occur somewhere within it. Rare events happen all the time. You might wonder whether the same principle applies to the possibility of many universes, or a *multiverse,* as the idea is now known. It turns out that the theoretical situation is actually stronger than simply a possibility. A number of central ideas that drive much of the current activity in particle theory today appear to require a multiverse.

I want to stress this because, in discussions with those who feel the need for a creator, the existence of a multiverse is viewed as a cop-out conceived by physicists who have run out of answers—or perhaps questions. This may eventually be the case, but it is not so now. Almost every logical possibility we can imagine regarding extending laws of physics as we know them, on small scales, into a more complete theory, suggests that, on large scales, our universe is not unique.

The phenomenon of inflation provides perhaps the first, and perhaps best, rationale. In the inflationary picture, during the phase when a huge energy temporarily dominates some region of the universe, this region begins to expand exponentially. At some point, a small region within this "false vacuum" may exit inflation as a phase transition occurs within the region and the field within it relaxes to its true, lower energy value; the expansion within this region will then cease to be exponential. But the space *between* such regions will continue to expand exponentially. At any one time, unless the phase transition completes through all of space, then almost all of space lies within an inflating region. And the inflating region will separate those regions that first exit inflation by almost unfathomable distances. It is like lava pouring out of a volcano. Some of the rock will cool and solidify, but those rocks will be carried far apart from one another as they float on a sea of liquid magma.

The situation can be even more dramatic. In 1986, Andrei Linde, who along with Alan Guth has been one of the chief architects of modern inflationary theory, promoted and explored a possibly even more general scenario. This was also anticipated in some sense by another inventive Russian cosmologist in the

United States, Alex Vilenkin. Both Linde and Vilenkin have the inner confidence that one finds in great Russian physicists, but their history is quite different. Linde thrived in the old Soviet physics establishment before immigrating to the United States after the fall of the Soviet Union. Brash, brilliant, and funny, he has continued to dominate much of theoretical particle cosmology in the interim. Vilenkin emigrated far earlier, before he was a physicist, and worked in the United States in various jobs, including as a night watchman, while he studied. And while he was always interested in cosmology, he accidentally applied to the wrong school for graduate work and ended up doing a thesis in condensed matter physics—the physics of materials. He then got a job as a postdoctoral researcher at Case Western Reserve University, where I later became Chair. During this period, he asked his supervisor, Philip Taylor, if he could spend several days a week working on cosmology in addition to his assigned projects. Philip later told me that, even with this part-time labor, Alex was the most productive postdoc he had ever had.

In any case, what Linde recognized is that, while quantum fluctuations during inflation may often push the field that drives inflation toward its lowest energy state, and thus provide a graceful exit, there is always the possibility that, in some regions, quantum fluctuations will drive the field toward yet higher energies, and hence away from values where inflation will end, so that inflation will continue unabated. Because such regions will expand for longer periods of time, there will be far more space that is inflating than that which is not. Within these regions, quantum fluctuations again will drive some subregions to exit inflation and thus stop expanding exponentially, but again there will be regions where quantum fluctuations will cause inflation to persist even longer. And so on.

This picture, which Linde dubbed “chaotic inflation,” indeed resembles more familiar chaotic systems on Earth. Take boiling oatmeal, for example. At any point a bubble of gas may burst from the surface, reflecting regions where liquid at high temperature completes a phase transition to form a vapor. But between the bubbles the oatmeal is roiling and flowing. On large scales there is regularity—there are always bubbles popping somewhere. But locally, things are quite different depending upon where one looks. So it would be in a chaotically inflating universe. If one happened to be located in a “bubble” of true ground state that had stopped inflating, one’s universe would appear very different from the vast bulk of space around it, which would still be inflating.

In this picture, inflation is eternal. Some regions, indeed most of space, will go on inflating forever. Those regions that exit inflation will become separate, causally disconnected universes. I want to stress that a multiverse is *inevitable* if inflation is eternal, and eternal inflation is by far the most likely possibility in most, if not all, inflationary scenarios. As Linde put it in his 1986 paper:

> The old question why our universe is the only possible one is now replaced by the question in which theories [of] the existence of mini-universes of our type [are] possible. This question is still very difficult, but it is much easier than the previous one. In our opinion, the modification of the point of view on the global structure of the universe and on our place in the world is one of the most important consequences of the development of the inflationary universe scenario.

As Linde emphasized, and has since become clear, this picture also provides another new possibility for physics. It could easily be that there are many possible low-energy quantum states of the universe present in nature that an inflating universe might ultimately decay into. Because the configuration of the quantum states of these fields will be different in each such region, the character of the fundamental laws of physics in each region/universe can then appear different.

Here arose the first “landscape” in which the anthropic argument, provided earlier, could play itself out. If there are many different states in which our universe could end up in after inflation, perhaps the one we live in, one in which there is non-zero vacuum energy that is small enough so galaxies could form, is just one of a potentially infinite family and the one that is selected for inquisitive scientists because it supports galaxies, stars, planets, and life.

The term "landscape" did not, however, first arise in this context. It was promoted by a much more effective marketing machine associated with the juggernaut that has been driving particle theory for much of the past quarter century—string theory. String theory posits that elementary particles are made up of more fundamental constituents, not particles, but objects that behave like vibrating strings. Just as string vibrations on a violin can create different notes, so too in this theory different sorts of vibrations produce objects that might, in principle, behave like all the different elementary particles we find in nature. The catch, however, is that the theory is not mathematically consistent when defined in merely four dimensions, but appears to require many more to make sense. What happens to the other dimensions is not immediately obvious, nor is the issue of what other objects besides strings may be important to define the theory—just some of the many unsolved challenges that have presented themselves and dulled some of the early enthusiasm for this idea.

Here is not the place to thoroughly review string theory, and in fact a thorough review is probably not possible, because if one thing has become clear in the past twenty-five years, it is that what was formerly called string theory is clearly something much more elaborate and complicated, and something whose fundamental nature and makeup is still a mystery.

We still have no idea if this remarkable theoretical edifice actually has anything to do with the real world. Nevertheless, perhaps no theoretical picture has ever so successfully permeated the consciousness of the physics community without having yet demonstrated its ability to successfully resolve a single experimental mystery about nature.

Many people will take the last sentence as a criticism of string theory, but although I have been branded in the past as a detractor, that is not really my intent here, nor has it been my intent in the numerous lectures and well-intentioned public debates I have had with my friend Brian Greene, one of string theory's main proponents, on the subject. Rather, I think it is simply important to cut through the popular hype for a reality check. String theory involves fascinating ideas and mathematics that might shed light on one of the most fundamental inconsistencies in theoretical physics—our inability to cast Einstein's general relativity in a form that can be combined with the laws of quantum mechanics to result in sensible predictions about how the universe behaves on its very smallest scales.

I have written a whole book about how string theory has attempted to circumvent this problem, but for our purposes here, only a very brief summary is necessary. The central proposal is simple to state, if difficult to implement. On very small scales, appropriate to the scale where the problems between gravity and quantum mechanics might first be encountered, elementary strings may curl up into closed loops. Amidst the set of excitations of such closed loops there always exists one such excitation that has the properties of the particle that, in quantum theory, conveys the force of gravity—the graviton. Thus, the quantum theory of such strings provides, in principle, the playing field on which a true quantum theory of gravity might be built.

Sure enough, it was discovered that such a theory might avoid the embarrassing infinite predictions of the standard quantum approaches to gravity. There was one hitch, however. In the simplest version of the theory, such infinite predictions can be obviated only if the strings that make up elementary particles are vibrating, not merely in the three dimensions of space and one of time that we are all familiar with, but rather in twenty-six dimensions!

You might expect that such a leap of complexity (and, perhaps, faith) would be enough to turn off most physicists about the theory, but in the mid-1980s some beautiful mathematical work by a host of individuals, most notably Edward Witten at the Institute for Advanced Study, demonstrated that the theory could in principle do far more than just provide a quantum theory of gravity. By introducing new mathematical symmetries, most notably a remarkably powerful mathematical framework called "supersymmetry," it became possible to reduce the number of dimensions required for consistency of the theory from twenty-six to merely ten.

More important, however, it looked like it might be possible, within the context of string theory, to unify gravity with the other forces in nature in a single theory, and moreover possible to explain the existence of every single elementary particle known in nature! Finally, it appeared as if there might be a single unique theory in ten dimensions that would reproduce everything we see in our four-dimensional world.

Claims of a "Theory of Everything" began to propagate, not just in the scientific literature, but in popular literature as well. As a result, perhaps more people are familiar with "superstrings" than are familiar with "superconductivity"—the latter being the remarkable fact that when some materials are cooled to extremely low temperatures, they can conduct electricity without any resistance whatsoever. This is not only one of the most remarkable properties of matter ever observed, but it has already transformed our understanding of the quantum makeup of materials.

Alas, the intervening twenty-five years or so have not been kind to string theory. Even as the best theoretical minds in the world began to focus their attention on it, producing volumes of new results and a great deal of new mathematics in the process (Witten went on to win the highest prize in mathematics, for example), it became clear that the "strings" in string theory are probably not the fundamental objects at all. Other, more complicated structures, called "branes," named after membranes in cells, which exist in higher dimensions, probably control the behavior of the theory.

What is worse, the uniqueness of the theory began to disappear. After all, the world of our experience is not ten-dimensional, but rather four-dimensional. Something has to happen to the remaining six spatial dimensions, and the canonical explanation of their invisibility is that they are somehow "compactified"—that is, they are curled up on such small scales that we cannot resolve them on our scales or even on the tiny scales that are probed by our highest energy particle accelerators today.

There is a difference between these proposed hidden domains and the domains of spirituality and religion, even though they may not appear so different on the surface. In the first place, they are accessible in principle if one could build a sufficiently energetic accelerator—beyond the bounds of practicality perhaps, but not beyond the bounds of possibility. Second, one might hope, as one does for virtual particles, to find some indirect evidence of their existence via the objects we can measure in our four-dimensional universe. In short, because these dimensions were proposed as part of a theory developed to actually attempt to explain the universe, rather than justify it, they might ultimately be accessible to empirical testing, even if the likelihood is small.

But beyond this, the possible existence of these extra dimensions provides a huge challenge to the hope that our universe is unique. Even if one starts with a unique theory in ten dimensions (which, I repeat, we do not yet know exist), then every different way of compactifying the invisible six dimensions can result in a different type of four-dimensional universe, with different laws of physics, different forces, different particles, and governed by differing symmetries. Some theorists have estimated that there are perhaps 10^{500} different possible consistent four-dimensional universes that could result from a single ten-dimensional string theory. A "Theory of Everything" had suddenly become a "Theory of Anything"!

This situation was exemplified sarcastically in a cartoon from one of my favorite scientific comic strips, called *xkcd*. In this strip one person says to another: "I just had an awesome idea. What if all matter and energy is made of tiny vibrating strings." The second person then says, "Okay. What would that imply?" To which the first person responds: "I dunno."

On a slightly less facetious note, the Nobel Prize–winning physicist Frank Wilczek has suggested that string theorists have invented a new way of doing physics, reminiscent of a novel way of playing darts. First, one throws the dart against a blank wall, and then one goes to the wall and draws a bull's-eye around where the dart landed.

While Frank's comment is an accurate reflection of much of the hype that has been generated, it should be stressed that at the same time those working on the theory are honestly trying to uncover principles that might govern the world in which we live. Nevertheless, the plethora of possible four-dimensional universes, which used to be such an embarrassment for string theorists, has now become a virtue of the theory. One can imagine that, in a ten-dimensional "multiverse" one can embed a host of different four-dimensional universes (or five-dimensional ones, or six-dimensional ones, or so on . . .), and each one can have different laws of physics, and moreover, in each one the energy of empty space can be different.

While it sounds like a convenient fabrication, it appears to be an automatic consequence of the theory, and it does create a true multiverse "landscape" that might provide a natural framework for developing an anthropic understanding of the energy of empty space. In this case, we do not need an infinite number of possible universes separated in three-dimensional space. Rather, we can imagine an infinite number of universes stacked up above a single point in our space, invisible to us, but each of which could exhibit remarkably different properties.

I want to emphasize that this theory is not as trivial as the theological musing of Saint Thomas Aquinas about whether several angels could occupy the same place, an idea that was derided by later theologians as fruitless speculations on how many angels could fit on the point of a needle—or most popularly, on the head of a pin. Aquinas actually answered this question himself by saying that more than one angel could not occupy the same space—of course, without any theoretical or experimental justification! (And if they were bosonic quantum angels, he would have been wrong in any case.)

Presented with such a picture, and adequate mathematics, one might hope, in principle, to actually make physical predictions. For example, one might derive a probability distribution describing the likelihood of finding different types of four-dimensional universes embedded in a larger dimensional multiverse. One might find, for example, that the bulk of such universes that have small vacuum energy also have three families of elementary particles and four different forces. Or one might find that only in universes with small vacuum energy could there exist a long-range force of electromagnetism. Any such result might provide reasonably compelling evidence that a probabilistic anthropic explanation of the energy of empty space—in other words, finding that a universe that looks like ours with small vacuum energy is not improbable—makes solid physical sense.

Yet the mathematics has not yet brought us this far, and it may never do so. But in spite of our current theoretical impotence, this does not mean that this possibility is not actually realized by nature.

Nevertheless, in the meantime, particle physics has taken anthropic reasoning a step further.

Particle physicists are way ahead of cosmologists. Cosmology has produced one totally mysterious quantity: the energy of empty space, about which we understand virtually nothing. However, particle physics has not understood many more quantities for far longer!

For example: Why are there three generations of elementary particles—the electron, and its heavier cousins the muon and tauon, for example, or the three different sets of quarks, of which the lowest energy set makes up the bulk of matter we find on Earth? Why is gravity so much weaker than the other forces in nature, such as electromagnetism? Why is the proton 2,000 times heavier than the electron?

Some particle physicists have now jumped on the anthropic bandwagon in the extreme, perhaps because their efforts to explain these mysteries according to physical causes have not yet been successful. After all, if one fundamental quantity in nature is actually an environmental accident, why aren't most or all of the other fundamental parameters? Maybe all of the mysteries of particle theory can be solved by invoking the same mantra: if the universe were any other way, we could not live in it.

One might wonder if such a solution of the mysteries of nature is any solution at all or, more important, whether it describes science as we understand it. After all, the goal of science, and in particular physics, over the past 450 years has been to explain why the universe must be the way we measure it to be, rather than why in general the laws of nature would produce universes that are quite different.

I have tried to explain why this is not quite the case, namely why many respectable scientists have turned to the anthropic principle and why a number have worked quite hard to see if we might learn something new about our universe based on it.

Let me now go further and try to explain how the existence of forever undetectable universes—either removed from us by virtually infinite distances in space or, right beyond the tip of our noses, removed from us by microscopic distances in possible extra dimensions—might nevertheless be subject to some kind of empirical testing.

Imagine, for example, that we devised a theory based on unifying at least three of the four forces of nature in some Grand Unified Theory, a subject of continued intense interest in particle physics (among those who have not given up looking for fundamental theories in four dimensions). Such a theory would make predictions about the forces of nature that we measure and about the spectrum of elementary particles that we probe at our accelerators. Should such a theory make a host of predictions that are subsequently verified in our experiments, we would have very good reason to suspect that it contains a germ of truth.

Now, suppose this theory also predicts a period of inflation in the early universe, and in fact predicts that our inflationary epoch is merely one of a host of such episodes in an eternally inflating multiverse. Even if we could not explore the existences of such regions beyond our horizon directly, then, as I have said earlier, if it walks like a duck and quacks like a duck . . . Well, you know.

Finding possible empirical support for the ideas surrounding extra dimensions is more far-fetched but not impossible. Many bright young theorists are devoting their professional careers to the hope of developing the theory to the point where there might be some evidence, even indirect, that it is correct. Their hopes might be misplaced, but they have voted with their feet. Perhaps some evidence from the new Large Hadron Collider near Geneva will reveal some otherwise hidden window into this new physics.

So, after a century of remarkable, truly unprecedented progress in our understanding of nature, we have found ourselves able to probe the universe on scales that were previously unimaginable. We have understood the nature of the Big Bang expansion back to its earliest microseconds and have discovered the existence of hundreds of billions of new galaxies, with hundreds of billions of new stars. We have discovered that 99 percent of the universe is actually invisible to us, comprising dark matter that is most likely some new form of elementary particle, and even more dark energy, whose origin remains a complete mystery at the present time.

And after all of this, it may be that physics will become an "environmental science." The fundamental constants of nature, so long assumed to take on special importance, may just be environmental accidents. If we scientists tend to take ourselves and our science too seriously, maybe we also have taken our universe too seriously. Maybe literally, as well as metaphorically, we are making much ado about nothing. At least we may be making too much of the nothing that dominates our universe! Maybe our universe is rather like a tear buried in a vast multiversal ocean of possibilities. Maybe we will never find a theory that describes why the universe has to be the way it is.

Or maybe we will.

That, finally, is the most accurate picture I can paint of reality as we now understand it. It is based on the work of tens of thousands of dedicated minds over the past century, building some of the most complex machines ever devised and developing some of the most beautiful and also the most complex ideas with which humanity has ever had to grapple. It is a picture whose creation emphasizes the best about what it is to be human—our ability to imagine the vast possibilities of existence and the adventurousness to bravely explore them—without passing the buck to a vague creative force or to a creator who is, by definition, forever unfathomable. We owe it to ourselves to draw wisdom from this experience. To do otherwise would do a disservice to all the brilliant and brave individuals who helped us reach our current state of knowledge.

If we wish to draw philosophical conclusions about our own existence, our significance, and the significance of the universe itself, our conclusions should be based on empirical knowledge. A truly open mind means forcing our imaginations to conform to the evidence of reality, and not vice versa, whether or not we like the implications.