IDEAS FROM THE EDGE

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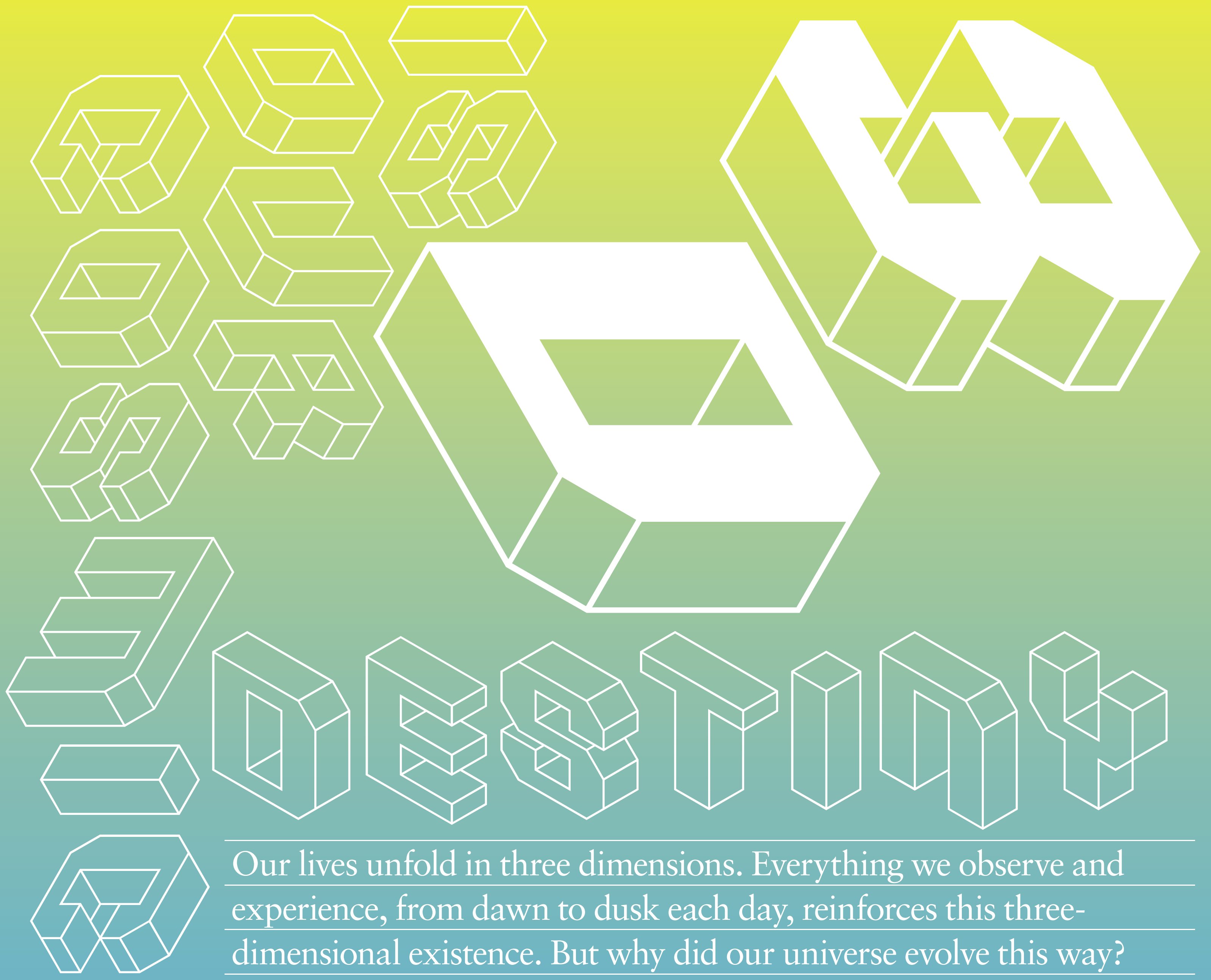

Our lives unfold in three dimensions. Everything we observe and experience, from dawn to dusk each day, reinforces this three-dimensional existence. But why did our universe evolve this way? Is there anything special about 3-D? By Lisa Randall

Why do we only experience three dimensions of space—the familiar up-down, left-right, and forward-backward? Their existence is so deeply ingrained in our consciousness that most of us don't even bother to ask. But for physicists, the mystery of why we experience just three dimensions, when we know there could be many more, presents an enormous challenge—so much so that at a conference at the turn of the millennium, it was singled out as one of the top five most important unsolved problems in physics. Is it merely a cosmological accident, or is there a natural preference in the universe for three dimensions? My work on extra dimensions recently led me to a potential answer.

String theory, which proposes that the fundamental units of matter are minuscule oscillating strings, consistently combines our theories of the very small and the very big—quantum mechanics and general relativity. But despite showing great promise, physicists have yet to determine the connection between string theory and our physical world. For example, string theory doesn't manifestly describe a universe with three dimensions of space; it naturally suggests more: perhaps as many as nine or 10. Although it might be difficult for us to fathom so many additional dimensions, string theorists have no choice but to accept them and ask: Where are these extra dimesions? Why haven't we seen them? and Why are three large dimensions singled out in our universe? Although physicists have thought about how to address the first two questions for some time, we have had only tentative ideas about the third.

Right now, a central and contentious issue in string theory (indeed, in all of physics) is which of the known properties of our universe, such as particle masses or the dark energy of the universe, can be predicted. Although it was initially advertised as a "theory of everything," many physicists are now considering the possibility that we may not be able to calculate some of the physical properties of the universe—via string theory or any other means. These physicists accept the "anthropic principle," which says that we live in our particular universe because it's the only one that can support galaxies and hence life. Widespread acceptance of the anthropic principle would mark a revolution in physics because it gives up on predictability for some questions.

But before we dramatically abandon the goal of a deeper understanding of nature, physicists need to explore all the physical scenarios that string theory presents. These alternate scenarios, what string theorists call "the landscape," are universes with distinct physical properties. The challenge for physicists, and the problem I tackle in my new work, is to find all possible qualitatively different universes—and to search for principles that determine which of these universes is most likely to exist. One route to resolving this question is to try to understand why we experience three spatial dimensions.

Physicists have considered the possibility of additional dimensions for a long time. In 1919, on the heels of Einstein's theory of general relativity, which didn't specify three dimensions, Theodor Kaluza suggested an extra dimension of space. Then in 1926, Oskar Klein offered an answer to the question of why we wouldn't see it—an answer that seemed to be the only possibility until the late 1990s. He proposed that an extra dimension could be rolled up into such a tiny size that it would have no visible effects. For example, if you imagine an extra dimension rolled up like a tube, the width of the "tube" could be so tiny that you'd never notice it. Any structure at this tiny size would be washed out, much as the atomic structure of this piece of paper is imperceptible.

This view held until 1999, when my colleague Raman Sundrum and I discovered a completely different reason why extra dimensions might be hidden. Einstein's theory of relativity tells us that energy and matter curve space and time. Raman and I found that spacetime could be so extremely warped that even an extra dimension that is infinite in size would escape our detection. Because of the warping of spacetime, gravity wouldn't spread as efficiently in an extra dimension as it does in the three dimensions we experience. The result is that the gravitational force we feel would be almost identical to that of a purely three-dimensional world, making it extremely difficult for us to detect an extra dimension. This idea was so unusual and had such startling implications that it took a while for other physicists to accept.

A key element in our work on extra dimensions is an object called a "brane," another basic ingredient of string theory. Branes are membrane-like objects in higher-dimensional space that can confine particles and forces (except for gravity, which is very different from the other known forces). These particles and forces can travel along the dimensions of the brane but can't venture into dimensions that run perpendicular to it. You might imagine a two-dimensional brane (a two-brane) as the surface of a pond, and the particles and forces as ducks that can only swim along the surface.

The notion of branes naturally leads to the idea of "braneworlds," in which our universe exists on the surface of a brane. In a braneworld scenario, gravity spreads throughout all dimensions of space, but the stuff that composes our universe—atoms, stars, electromagnetism—is confined to the brane. Braneworlds tell us that there can be radically new blueprints for the surrounding universe, such as multiverses, in which there are different universes stuck to different branes.

Although these schemes may seem far-fetched, the year after my work with Raman, Andreas Karch and I found that space can be more spectacular still: The universe can appear to have three spatial dimensions in some regions and more in others. We might live on a three-brane and experience three dimensions of space, but that may not be true for regions beyond what we can perceive. Put another way, our universe might be a tiny, isolated pocket that experiences three spatial dimensions inside an even larger world that experiences many more—an idea that extends the Copernican revolution beyond anything we could have imagined.

Nevertheless, this and other work on extra dimensions still raises the question of why there should be a three-brane in the first place. My current work with Andreas attempts an answer. We show how string theory might single out three-dimensional branes, and hence three dimensions of space, as special. We imagined that the universe really has 10 space-time dimensions, as suggested by string theory, and assumed that it is initially filled with branes of all possible dimensions. Then we asked how the universe would evolve with time if all nine spatial dimensions were large and none were rolled up to a tiny size.

The result of this thought experiment was remarkable. It turns out that even if the universe starts off with branes of all dimensions, most of them will not survive the evolution of the universe. As time goes on, the volume of space they occupy is diluted relative to the space occupied by three-branes and seven-branes. So, three-branes and seven-branes come to predominate. This result suggests that three (and seven) dimensions really are special; that the evolution of the universe appears to inevitably single them out.

This work involved a new way of thinking about how the current state of our universe came to be. Unlike anthropic arguments, we did not invoke arbitrary criteria involving galaxies or life. Instead, we proposed that the branes that occupy the most volume of space are also the ones most relevant to our universe, and that the universe naturally selects which branes those will be as it evolves over time, according to Einstein's theory of gravity. The favored branes are those that naturally survive. We call this alternative view "the relaxation principle," and from it we can conclude that the universe favors "relaxing to three dimensions." Tying this result in with my previous work leads me to a scenario in which we live on a three-dimensional brane, even though the universe is, in reality, higher-dimensional.

> Acceptance of the anthropic principle, which says that we live in our particular universe because it's the only one that can support galaxies and hence life, would mark a revolution in physics.

Clearly, there is still much to be understood about the universe. But those of us who no longer straitjacket ourselves to theories with just three dimensions have discovered amazing consequences of Einstein's equations that had escaped physicists for years. I'm confident extra dimensions are out there and I believe that our biggest challenge is to determine their consequences and how to find them. Given how much extra dimensions will tell us about the fundamental nature of our universe, do we have any choice but to explore?