quick study

The case for extra dimensions

Lisa Randall

Spaces with more than three dimensions are consistent with known physics, can help solve a vexing problem in the standard model, and may soon be indirectly observed at the Large Hadron Collider.

Lisa Randall is a professor of physics at Harvard University in Cambridge, Massachusetts, and author of *Warped Passages: Unraveling the Mysteries of the Universe's Hidden Dimensions* (Ecco, 2005).

The Large Hadron Collider will begin operation next year and will test some intriguing suggestions for what might lie beyond the standard model of particle physics. One of the most surprising ideas centers on the possible existence of extra dimensions of space.

Physicists speculate about such a possibility for several reasons. One is that we don't know any reason such dimensions cannot exist, whereas we do know how they might be hidden. No theory, not even Albert Einstein's general theory of relativity, stipulates a particular number of dimensions. People have often made the mistake of believing only in what they could see. We don't perceive extra dimensions, but that doesn't mean those dimensions aren't there.

String theory provides another reason to consider extra dimensions. The theory might consistently incorporate physicists' current conceptions of the very small and the very big in the universe—quantum mechanics and general relativity—a feat no earlier theory had accomplished. That doesn't prove string theory is right. Further research is critical. But because it promises to be a grander, more comprehensive theory—a theory of quantum gravity—string theory is worth investigating. However, it does not naturally describe a world with three dimensions of space. It more naturally suggests a world with more dimensions, perhaps 9 or 10. A string theorist doesn't ask whether extra dimensions exist; instead, two of the most important questions are, Where are they? and Why haven't physicists seen them?

But perhaps the most compelling reasons to believe in extra dimensions are that they permit new connections among physical properties of the observed universe and offer a real possibility for explaining some of its more mysterious features. Extra dimensions can have implications for the world we see, and they can explain phenomena that seem utterly mysterious when viewed from the perspective of a three-dimensional observer. Even if you're skeptical about string theory—after all, no one has yet proved it is right—recent research has provided perhaps the most compelling argument for extra dimensions: A universe with those dimensions might contain answers to physics puzzles that have no convincing solutions without them. That alone makes extra dimensions worthy of investigation.

Hiding extra dimensions

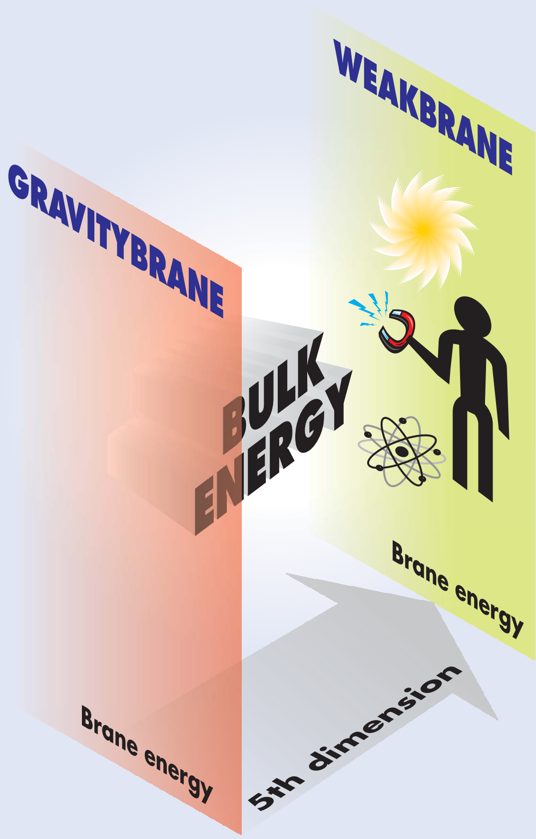
To see why extra dimensions are not ruled out by our observations of an apparently 3D world, we need to understand how dimensions can exist but be invisible. In 1919, almost immediately after Einstein completed his general theory of relativity, Theodor Kaluza suggested an extra dimension of space in a theory proposed to unify general relativity and electrodynamics. In 1926 Oskar Klein suggested a reason why the extra dimension would be hidden. An extra dimension could be rolled up to such a tiny size that it would have no visible effects. If you think of extra dimensions as being rolled like a garden hose, the width of the hose could be so small that you wouldn't notice it. Any variations over that tiny distance would be washed out, much as the atomic structure of this piece of paper is imperceptible.

One physical consequence of the extra dimensions could be that the number of generations of elementary particles—the number of particle types with the same charge—might be determined by the way dimensions are rolled up. But until the 1990s, extra dimensions were generally assumed to be so small that they would have no directly testable consequences.

But although physicists have known for years that extra dimensions could be invisibly small, it wasn't until 1999 that Raman Sundrum (now at Johns Hopkins University) and I discovered another reason that extra dimensions might be hidden. Einstein's theory of relativity says that energy and matter curve space and time. Sundrum and I found that spacetime with extra dimensions could be so extremely warped that even an infinite extra dimension could exist but escape detection.

Our idea exploits the so-called brane, which is an essential part of string theory. The word comes from "membrane," and indeed branes are membrane-like objects in a higher-dimensional space. You can think of branes as extended objects that do not necessarily extend in all the dimensions of the higher-dimensional space. One analogy is a 2D shower curtain in a 3D room. Water droplets travel on the shower curtain but not in the full higher-dimensional space. Similarly, particles and forces other than gravity can be confined to a brane that extends over fewer dimensions than the full higher-dimensional space.

In the 1990s Joseph Polchinski and others developed the theory of branes and demonstrated that they are essential to string theory—that is, string theory cannot be consistently formulated without them. The notion of branes significantly changed the way particle physicists imagine higher-dimensional worlds. Theorists now think that we might live in a "braneworld," where some of the stuff of which we and our universe are made is confined to a brane even though gravity can travel throughout higher dimensions. A braneworld is like a higher-dimensional version of Edwin A. Abbott's Flatland, which was a 2D world in 3D space. Our braneworld might span three spatial dimensions but be embedded in a universe with more. The figure illustrates the idea and relates braneworlds to an important question that has puzzled particle physicists since the 1970s: Why is gravity so weak?



In higher-dimensional spacetimes the gravitational force can be strong in one region—the Gravitybrane—and become orders of magnitude weaker as it approaches a Weakbrane that confines the other fundamental forces. Thus, extra dimensions may allow for a natural solution of the hierarchy problem described in the text. Because the branes and the bulk spacetime they bound have energy, spacetime can be highly curved. As a result, two branes can be separated by a very small distance and still allow for a solution of the hierarchy problem. (Figure adapted from L. Randall, *Warped Passages*, Ecco, 2005, originally created by Greg Elliott.)

The hierarchy problem

Gravity might not appear to be all that weak when you're hiking up a mountain, but bear in mind that the gravitational force of the entire Earth is acting on you. Think how feeble gravity must be if you can counter the force of the much larger Earth whenever you pick up a ball. The force of gravity acting between two electrons is roughly 42 orders of magnitude smaller than the electrostatic force between them. For more than 30 years, physicists (including me) have tried to understand that huge discrepancy, but they've found no completely compelling solution.

The orders-of-magnitude discrepancy is known as the hierarchy problem of particle physics. The force of gravity is proportional to Newton's constant, which is inversely proportional to two powers of a mass scale called the Planck mass. So we can also state the problem in terms of masses. The spontaneous symmetry breaking that gives elementary particles their mass occurs at the weak scale, about 1000 times the mass of the proton, which is 16 orders of magnitude smaller than the Planck scale.

The discrepancy between the Planck and weak scales might just be taken to be a big unexplained parameter. The problem for particle physics, though, is in fact much worse. If you use quantum field theory, which combines quantum mechanics and special relativity, you would expect that the two scales are about the same. It is only by an enormous fudge, or what theorists call a fine-tuning, that the standard model of particle physics manages to be the successful theory that it is. For years physicists have been trying to understand the underlying physics that keeps the weak scale so much lower than the Planck scale.

But with one additional *small* warped dimension, it is natural for gravity to be weak. In a warped spacetime geometry, gravity can be very strong in one region of a fourth dimension of space (a fifth dimension of spacetime) but very weak everywhere else. So, extra dimensions could naturally explain the mass hierarchy of particle physics through an exponential relation between the size of the masses, which is what particle physicists have been searching for since the 1970s. The weakness of gravity is the biggest gaping hole in our understanding of the physics of elementary particles, and extra dimensions might naturally provide an answer.

Another idea for accommodating the hierarchy is very large extra dimensions, in which case gravity would be diluted because it is dispersed over a large region of extra-dimensional space (see the article by Nima Arkani-Hamed, Savas Dimopoulos, and Georgi Dvali in PHYSICS TODAY, February 2002, page 35). However, to truly explain the hierarchy in that model, one needs to explain the large dimension and contend with dangerous cosmological implications. In the warped case, the dimensions are small, only one or two orders of magnitude larger than the minuscule Planck length of 10^{-35} m.

Even if scientists believe extra dimensions might exist in nature, we don't have blind faith. Physicists don't yet know how to experimentally test all extra-dimensional theories, but the fabulous thing is that if extra dimensions are responsible for the weakness of gravity, experimental evidence will present itself within the next five years. The tests that high-energy experimenters will perform will be critical to confirming or ruling out theorists' ideas.

The experimental evidence will take the form of Kaluza–Klein particles—particles that travel in extra dimensions but would register in experiments as new heavy particles in a spatially 3D world. If warped extra dimensions explain the weakness of gravity, the Large Hadron Collider, scheduled to begin operation at CERN in 2008, will have enough energy to make such particles. Other even more speculative possibilities for what might be found at the collider include higher-dimensional black holes that decay right away or string states that, due to warping, are much lighter than conventionally expected.

Other interesting possibilities with extra dimensions include particles that are separated by the additional dimensions. Our three visible dimensions seem to be homogeneous and isotropic, but that is presumably not true with additional dimensions, or we would have seen them too. Particles might be confined to various branes that have different locations in the extra dimensions. That mechanism might prevent or suppress dangerous interactions that quantum gravity indicates would otherwise occur. It might also help explain particle masses in more detail.

The history of physics is a story of discovering different, more basic elements of matter as scientists develop the tools to explore expanded length and energy scales. Once physicists could observe matter on smaller scales, they discovered atoms and quarks, and after physicists and astronomers could study the universe on larger scales, they discovered galaxies and dark matter. Extra dimensions might be hidden for now but nonetheless be part of reality. Detailed observations at higher energies and shorter distances might eventually reveal their existence. ■