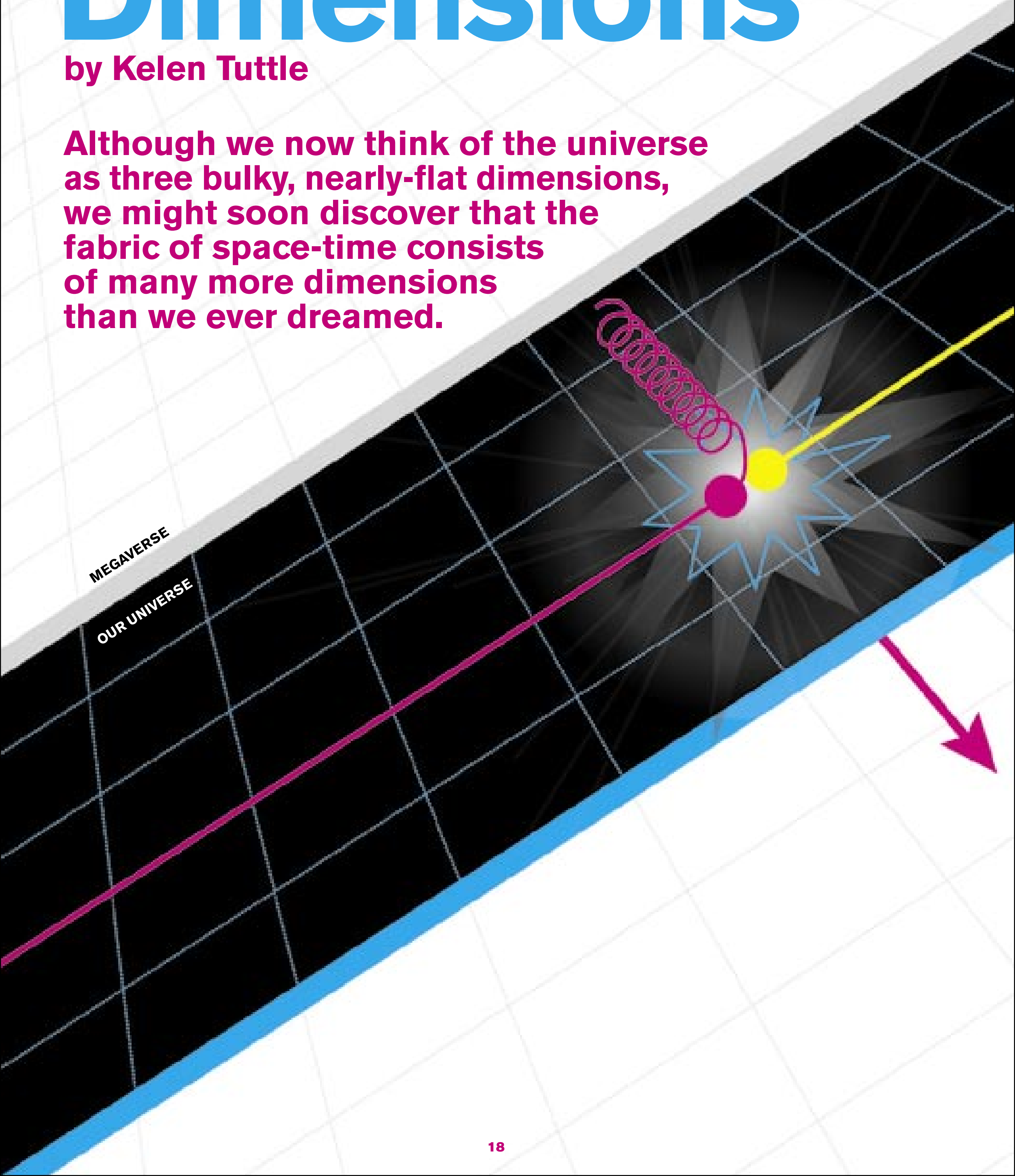
The Search for Extra Dimensions

by Kelen Tuttle

Although we now think of the universe as three bulky, nearly-flat dimensions, we might soon discover that the fabric of space-time consists of many more dimensions than we ever dreamed.



Extra dimensions promise to solve many of current particle theory's nagging problems. They can explain the abundance of matter over antimatter, the surprisingly large number of elementary particles, and even dark matter—all phenomena that the Standard Model of particle physics fails to predict. This makes the concept of extra dimensions enticing. Yet in the empirical discipline of physics, extra dimensions face an embarrassing dilemma: so far, not a single shred of experimental evidence has been found to support their existence.

According to Greg Landsberg of Brown University, this stumbling block may vanish in the next few years. Landsberg, along with about a dozen others at the Fermi National Accelerator Laboratory, is searching for experimental evidence of extra dimensions. Similar searches for extra dimensions are going on at DESY's electron-proton collider in Germany and in various tabletop experiments. "We need a new lens through which to view the universe," Landsberg says. "And this one offers the type of mathematical beauty that the current understanding of gravity lacks."

Gravity's mystery

Gravity is unlike the other three fundamental forces. While the strong, weak, and electromagnetic forces offer both a full quantum theory and straightforward mathematical models on both macro- and micro-scales, gravity is a hodgepodge of Newton's and Einstein's models that does not seem to fit our quantum view of the universe at small scales. Since the early 20th century, theorists have sought a mathematical description that connects gravity with the electromagnetic force, introducing the idea of extra dimensions.

One of the greatest discrepancies is gravity's surprising weakness. Although gravity is unquestionably the force we feel most often, it is extraordinarily weak compared to the three other fundamental forces. For example, even a small magnet can overcome gravity to pick up paperclips and other small objects.

Today's understanding of the big bang suggests that for a few moments after the beginning of our universe, all four fundamental forces were part of a single force. As the universe evolved and cooled, the strong, weak, and electromagnetic forces retained similar strengths while gravity became significantly more feeble. At the atomic scale, gravity is one trillion trillion trillion times weaker than the electromagnetic force.

It seems unreasonable that this extreme variation would occur arbitrarily; something unexplained by current theory must have caused gravity to become weak. "Nature is simple," says physicist Beate Heinemann of the University of Liverpool. "And as a result, theory requires elegance and simplicity, an elegance and simplicity that the current model lacks with regard to gravity."

Heinemann, an experimenter at the Collider Detector at Fermilab (CDF), goes on to suggest that gravity could be just as simple and elegant as the other three forces if people could, for some reason, only feel a small percentage of its strength. It is this very idea that has led theorists to predict the existence of extra dimensions. Gravity, they postulate, exists in more dimensions than we do, and most of its strength resides in space not visible to us.

Branes: compact and warped

According to most theories of extra dimensions, gravitons—the minuscule particles that are believed to carry gravity's force between objects—travel not only in our three spatial dimensions, called a "brane," but also in additional dimensions that extend beyond this brane. Gravity could then be equally strong as the other three forces, but thinly spread throughout many dimensions.

"We don't see these extra dimensions because we don't live in them," says Landsberg, who works on Fermilab's DZero experiment. "Our world could be just a tiny speck in this ultimate volume of space."

As first suggested by Nima Arkani-Hamed, Savas Dimopoulos, and Georgi Dvali in 1998, any extra dimensions extending beyond our brane are not flat like the three we are familiar with, but rather curled tightly in a loop: if a graviton were to move in one direction far enough, it would circumnavigate the dimension and end up right back where it started, like circling a thin tube.

Another description of extra dimensions, proposed by Lisa Randall and Raman Sundrum in 1999, predicts that the geometry of dimensions beyond our brane could be warped. Like a bead of water distorting an image, warped extra dimensions could affect our measurements of gravity's strength, making gravity appear weaker than it really is.

Both explanations offer a relatively simple solution to gravity's weakness, but neither is supported by experimental evidence. According to the mathematical equations that govern extra dimensions, if there were one extra dimension it would be roughly the size of our universe. Surely such a monstrous extra dimension would have appeared in a previous experiment. However, if there were two extra dimensions, this size shrinks drastically to less than one millimeter, and at three extra dimensions it drops to less than one nanometer, about the diameter of an atom. These are scales at which researchers can currently conduct experiments. To probe a size range of one millimeter and less, researchers need very precise tabletop experiments (see sidebar) or very large "microscopes" in the form of particle accelerators.

Microscopes for gravity

The world's most powerful accelerator, Fermilab's Tevatron, operates at nearly two teraelectronvolts. With this much energy, it's possible to explore the interaction of particles in our brane at distances smaller than one millionth of a nanometer, about the diameter of a proton. Researchers suspect that these distances are similar to the radii of the curled dimensions.

By producing scores of new particles in high-energy collisions, researchers at Fermilab search for indirect evidence that gravitons are entering and exiting our brane. Needless to say, detecting and sifting through the hundreds of particles created in such a collision is rather difficult. "It's an experimental challenge," Fermilab theorist Joe Lykken says with a wry grin.

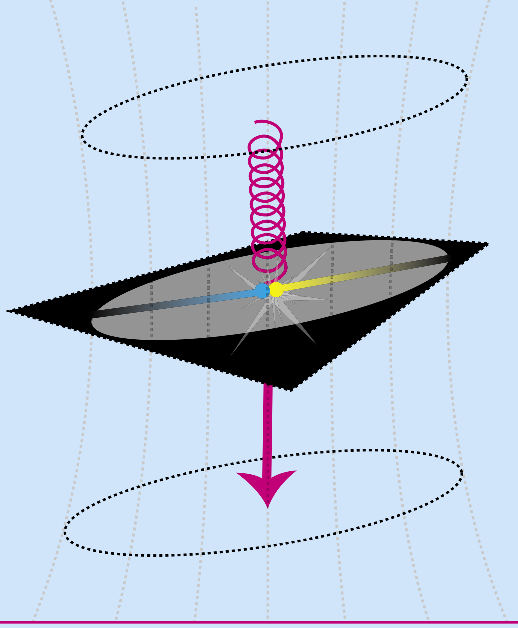
One way Fermilab experimentalists including Heinemann and Landsberg hope to detect extra dimensions is to catch a graviton in the act of disappearing into another dimension. Collisions create a symmetrical ball of energy and, like fireworks, particles should spray in all directions. A tell-tale sign of extra dimensions would be a collision in which visible particles sprayed only in one direction, suggesting that an invisible particle traveled in the other direction. This particle could be the key to extra dimensions—a graviton, leaving our visible universe and disappearing into a fourth spatial dimension. Unfortunately, gravitons are not the only invisible particles. Lightweight particles called neutrinos, which very rarely interact with matter, can also travel right through a detector without a trace.

The ability to search for extra dimensions hinges on a researcher's ability to track neutrinos. "If you don't know your neutrinos, you don't know anything about extra dimensions," says Lykken. By calculating the probability of creating a neutrino and comparing that to the number of asymmetrical events observed in the Tevatron, Fermilab researchers hope to discover an excess of events unaccounted for by neutrinos. Such a discrepancy could be the first experimental evidence of gravitons disappearing into extra dimensions.

It might also be possible to detect extra dimensions by observing a graviton's return from an extra dimension. Landsberg describes this search as a quest for the echoes of gravitons. "We're using the Tevatron as a 'radio receiver,' scanning the universe for the 'graviton station,'" he says. To do this, researchers search for signals of gravitons decaying into detectable pairs of photons, electrons, or muons. An excess of these particles at specific energy and mass levels would indirectly provide evidence for the existence of dimensions beyond our own. What's more, quantum theory relates energy and mass to the size of that curled dimension's loop, offering the researchers a glimpse of the extra dimension's geometry.

A Graviton Escapes

Collision experiments carefully reconstruct all particles emerging from a collision. A possible sign of extra dimensions would be a collision in which a particle—and hence energy—"disappeared," perhaps indicating a graviton leaving our visible universe and entering extra spatial dimensions—the megaverse.



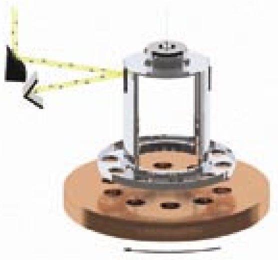
The tabletop approach

The chances of making a discovery are highest when many people work on the same problem in diverse ways. A few researchers scattered across the country search for extra dimensions not with colossal high-powered accelerators, but with small tabletop experiments. These researchers hope to discover deviations from Newton's laws of gravity—a sign indicative of extra dimensions. If two objects are closer together than the size of the extra dimension, the gravitational interaction between them should be significantly stronger than regular Newtonian gravity predicts.

With remarkably meticulous precision, Eric Adelberger of the University of Washington's Eöt-Wash group searches for extra dimensions by suspending a molybdenum disc above an identical plate with a thin tungsten wire. Each disc has two rows of 21 carefully placed holes. As the bottom disc rotates on a precision motor, the top disc reacts to the changing gravitational pull. Adelberger and his colleagues search for deviations that cause an exceptionally small twist—on the order of one ten-millionth of a degree—to the upper disc. To date, the Eöt-Wash group has excluded the existence of extra dimensions larger than 0.08 millimeters, regardless of how many dimensions exist.

Other physicists, including Aharon Kapitulnik of Stanford University and Joshua Long of Indiana University, attempt to detect gravitational deviations with experiments that measure the bending of thin strips of material.

"We work in tandem with particle accelerators," says Adelberger. "Particle accelerators can't see really weak interactions, but they can measure particles that are very, very close together. We can measure very weak interactions at relatively large distances." Working together, particle accelerators and tabletop experiments should be able to detect extra dimensions, whatever their scale—assuming, of course, that they exist at all.



Schematic drawing of the Eöt-Wash group's search for deviations from Newton's Law of Gravitation.

Image: Eöt-Wash group, University of Washington

Constraining the brane

Experimentalists at both DZero and CDF have yet to conclusively record a graviton's disappearance or reappearance. But as they scan the universe for signs of extra dimensions, researchers progressively constrain the size of the extra dimension's loop. So far, Fermilab's findings suggest that if there are two extra dimensions, they can be no larger than a third of a millimeter, about the width of the period at the end of this sentence. If there are as many as six, they all must be at least 10 million times smaller than that dot.

"If there are as many as six, they must all be at most one ten-millionth of that size," says Landsberg. "But there's still much left to probe."

Fermilab's results build on the work of CERN's LEP collider, which collided electrons and positrons—in contrast to the protons and antiprotons used at Fermilab—until it closed in late 2000 to make way for the Large Hadron Collider. According to CERN research fellow Stefan Ask, LEP's results remain the most stringent at low numbers of dimensions, constraining two extra dimensions to radii of 0.19 millimeters or less. For higher numbers of extra dimensions, Fermilab has improved on LEP's figures, and the lab is the first to search for warped extra dimensions. Meanwhile, experiments at DESY's HERA collider, which currently conduct a similar search using protons and electrons, continue to collect more data and may soon match Fermilab's results for curled extra dimensions, says researcher Hans-Ulrich Martyn of the H1 experiment at DESY.

With the Tevatron running strong, both the CDF and DZero searches will continue scanning the universe for extra dimensions. Over the next few years, Fermilab has an exciting opportunity to catch a first glimpse of dimensions beyond our own. But even if the Tevatron fails to find evidence of extra dimensions, CERN's LHC will continue the search in 2007. With significantly more energy, the LHC will be able to probe ever smaller radii.

"If we haven't found extra dimensions with the Tevatron by then, the LHC may still do it," says Lykken. "This is the type of discovery we should be able to make in the next five years."