STRUCTURE

The visible universe could lie on a membrane floating within a higher-dimensional space

the Universe's unseen DIMENSIONS

BY NIMA ARKANI-HAMED, SAVAS DIMOPOULOS AND GEORGI DVALI

ILLUSTRATIONS BY BRYAN CHRISTIE DESIGN

THE CLASSIC 1884 story *Flatland: A Romance of Many Dimensions,* by Edwin A. Abbott, describes the adventures of "A. Square," a character who lives in a two-dimensional world populated by animated geometric figures—triangles, squares, pentagons and so on. Toward the end of the story, on the first day of 2000, a spherical creature from three-dimensional "Spaceland" passes through Flatland and carries A. Square up off his planar domain to show him the true three-dimensional nature of the larger world. As he comes to grasp what the sphere is showing him, A. Square speculates that Spaceland may itself exist as a small subspace of a still larger four-dimensional universe.

Amazingly, in the past four years physicists have begun seriously examining a very similar idea: that everything we can see in our universe is confined to a three-dimensional "membrane" that lies within a higher-dimensional realm. But unlike A. Square, who had to rely on divine intervention from Spaceland for his insights, physicists may soon be able to detect and verify the existence of reality's extra dimensions, which could extend over distances as large as a millimeter. Experiments are already looking for the extra dimensions' effect on the force of gravity. If the theory is correct, upcoming high-energy particle experiments in Europe could see unusual processes involving quantum gravity, such as the creation of transitory micro black holes. More than just an idle romance of many dimensions, the theory is based on some of the most recent developments in string theory and would solve some longstanding puzzles of particle physics and cosmology.

The exotic concepts of string theory and multidimensions actually arise from attempts to understand the most familiar of forces: gravity. More than three centuries after Isaac Newton proposed his law of gravitation, physics still does not explain why gravity is so much weaker than all the other forces. The feebleness of gravity is dramatic. A small magnet readily overcomes the gravitational pull of the entire mass of the earth when it lifts a nail off the ground. The gravitational attraction between two electrons is 10^{43} times weaker than the repulsive electric force between them. Gravity seems important to us—keeping our feet on the ground and the earth orbiting the sun—only because these large aggregates of matter are electrically neutral, making the electrical forces vanishingly small and leaving gravity, weak as it is, as the only noticeable force left over.

The Inexplicable Weakness of Gravity

ELECTRONS WOULD HAVE to be 10^{22} times more massive for the electric and gravitational forces between two of them to be equal. To produce such a heavy particle would take 10^{19} gigaelectron volts (GeV) of energy, a quantity known as the Planck energy (after German physicist Max Planck). A related quantity is the Planck length, a tiny 10^{-35} meter. By comparison, the nucleus of a hydrogen atom, a proton, is about 10^{19} times as large and has a mass of about 1 GeV. The Planck scale of energy and length is far out of reach of the most powerful accel-

MEMBRANE UNIVERSE in a higher-dimensional realm could be where we live. Experiments might detect signs of extra dimensions close to a millimeter in size in the near future.

erators. Even the Large Hadron Collider at CERN will probe distances only down to about 10^{-19} meter when it commences operations five years from now [see "The Large Hadron Collider," by Chris Llewellyn Smith; Scientific American, July 2000]. Because gravity becomes comparable in strength to electromagnetism and the other forces at the Planck scale, physicists have traditionally assumed that the theory unifying gravity with the other interactions would reveal itself only at these energies. The nature of the ultimate unified theory would then be hopelessly out of reach of direct experimental investigation in the foreseeable future [see "A Unified Physics by 2050?" by Steven Weinberg; Scientific American, December 1999].

Today's most powerful accelerators probe the energy realm between 100 and 1,000 GeV (one teraelectron volt, or TeV). In this range, experimenters have seen the electromagnetic force and the weak interaction (a force between subatomic particles responsible for certain types of radioactive decay) become unified. We would understand gravity's extraordinary weakness if we understood the factor of 10^{16} that separates the electroweak scale from the Planck scale.

Alas, physicists' extremely successful theory of particle physics, called the Standard Model, cannot explain the size of this huge gap, because the theory is carefully adjusted to fit the observed electroweak scale. The good news is that this adjustment (along with about 16 others) serves once and for all to fit myriad observations. The bad news is that we must fine-tune the underlying theory to an accuracy of about one part in 10^{32}; otherwise, quantum effects—instabilities—would drag the electroweak scale all the way back up to the Planck scale. The presence of such delicate balancing in the theory is like walking into a room and finding a pencil standing perfectly on its tip in the middle of a table. Though not impossible, the situation is highly unstable, and we are left wondering how it came about.

For 20 years, theorists have attacked this conundrum, called the hierarchy problem, by altering the nature of particle physics near 10^{-19} meter (or 1 TeV) to stabilize the electroweak scale. The most popular modification of the Standard Model that achieves this goal involves a new symmetry called supersymmetry. Going back to our pencil analogy, supersymmetry acts like an invisible thread holding up the pencil and preventing it from falling over. Although accelerators have not yet turned up any direct evidence for supersymmetry, some suggestive indirect evidence supports the theory. For example, when the measured strengths of the strong, weak and electromagnetic forces are theoretically extrapolated to shorter distances, they meet very accurately at a common value only if supersymmetric rules govern the extrapolation. This result hints at a supersymmetric unification of these three forces at about

10^{-32} meter, approximately 1,000 times larger than the Planck length but still far beyond the range of particle colliders.

Gravity and Large Spatial Dimensions

FOR TWO DECADES, the only viable framework for tackling the hierarchy problem has been to change particle physics near 10^{-19} meter by introducing new processes such as supersymmetry. But in the past four years, theorists have proposed a radically different approach, modifying spacetime, gravity and the Planck scale itself. The key insight is that the extraordinary size of the Planck scale, accepted for a century since Planck first introduced it, is based on an untested assumption about how gravity behaves over short distances.

Newton's inverse square law of gravity—which says the force between two masses falls as the square of the distance between them—works extremely well over macroscopic distances, explaining the earth's orbit around the sun, and so on. But because gravity is so weak, the law has been experimentally tested down to distances of only about a millimeter, and we must extrapolate across 32 orders of magnitude to conclude that gravity becomes strong only at a Planck scale of 10^{-35} meter.

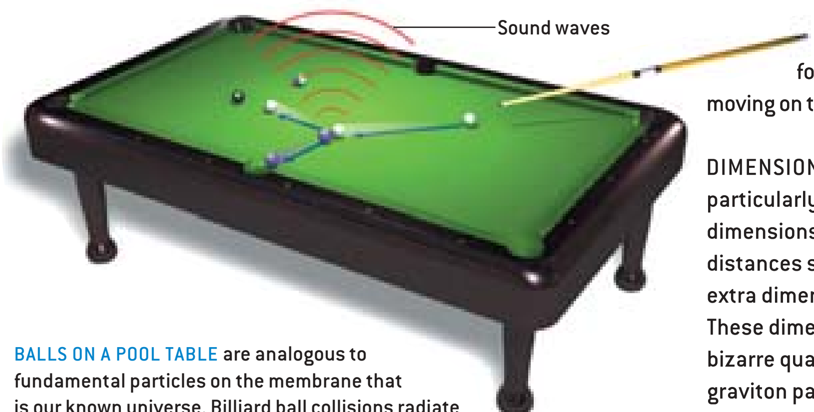
The inverse square law is natural in three-dimensional space [*see upper illustration on opposite page*]. Consider lines of gravitational force emanating uniformly from the earth. Farther from the earth, the lines are spread over a spherical shell of greater area. The surface area increases as the square of the distance, and so the force is diluted at that rate. Suppose there were one more dimension, making space four-dimensional. Then the field lines emanating from a point would get spread over a four-dimensional shell whose surface would increase as the cube of the distance, and gravity would follow an inverse cube law.

The inverse cube law certainly doesn't describe our universe, but now imagine that the extra dimension is curled up into a small circle of radius R and that we're looking at field lines coming from a tiny point mass [*see lower illustration on opposite page*]. When the field lines are much closer to the mass than the distance R, they can spread uniformly in all four dimensions, and so the force of gravity falls as the inverse cube of distance. Once the lines have spread fully around the circle, however, only three dimensions remain for them to continue spreading

IN A NUTSHELL by Graham P. Collins

DIMENSIONS. Our universe seems to have four dimensions: three of space (up-down, left-right, forward-backward) and one of time. Although we can barely imagine additional dimensions, mathematicians and physicists have long analyzed the properties of theoretical spaces that have any number.

SIZE OF DIMENSIONS. The four known spacetime dimensions of our universe are vast. The dimension of time extends back at least 13 billion years into the past and may extend infinitely into the future. The three spatial dimensions may be infinite; our telescopes have detected objects more than 12 billion light-years away. Dimensions can also be finite. For example, the two dimensions of the surface of the earth extend only about 40,000 kilometers—the length of a great circle.



BALLS ON A POOL TABLE are analogous to fundamental particles on the membrane that is our known universe. Billiard ball collisions radiate energy into three dimensions as sound waves (*red*), analogous to gravitons. Precise studies of the balls' motions could detect the missing energy and thus the higher dimensions.

SMALL EXTRA DIMENSIONS. Some modern physics theories postulate additional real dimensions that are wrapped up in circles so small (perhaps 10^{-35}-meter radius) that we have not detected them. Think of a thread of cotton: to a good approximation, it is one-dimensional. A single number can specify where an ant stands on the thread. But using a microscope, we see dust mites crawling on the thread's two-dimensional surface: along the large length dimension and around the short circumference dimension.

LARGE EXTRA DIMENSIONS. Recently physicists realized that extra dimensions as big as a millimeter could exist and remain invisible to us. Surprisingly, no known experimental data rule out the theory, and it could explain several mysteries of particle physics and cosmology. We and all the contents of our known three-dimensional universe (except for gravity) would be stuck on a membrane, like balls moving on the two-dimensional green baize of a pool table.

DIMENSIONS AND GRAVITY. The behavior of gravity—particularly its strength—is intimately related to how many dimensions it pervades. Studies of gravity acting over distances smaller than a millimeter could thus reveal large extra dimensions to us. Such experiments are under way. These dimensions would also enhance the production of bizarre quantum gravity objects such as micro black holes, graviton particles and superstrings, all of which could be detected sometime this decade at high-energy particle accelerators.

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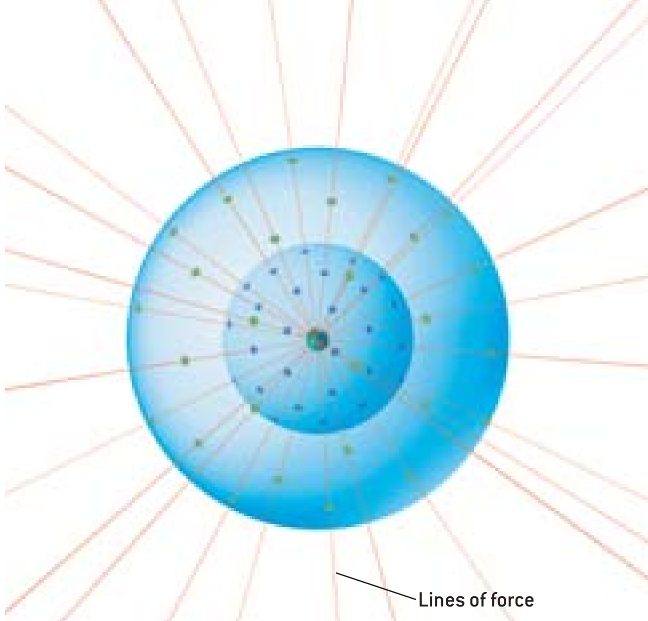
through, and so for distances much greater than R the force varies as the inverse square of the distance.

The same effect occurs if there are many extra dimensions, all curled up into circles of radius R. For n extra spatial dimensions at distances smaller than R, the force of gravity will follow an inverse $2 + n$ power law. Because we have measured gravity only down to about a millimeter, we would be oblivious to changes in gravity caused by extra dimensions for which R was smaller than a millimeter. Furthermore, the $2 + n$ power law would cause gravity to reach Planck-scale strength well above 10^{-35} meter. That is, the Planck length (defined by where gravity becomes strong) would not be that small, and the hierarchy problem would be reduced.

One can solve the hierarchy problem completely by postulating enough extra dimensions to move the Planck scale very close to the electroweak scale. The ultimate unification of gravity with the other forces would then take place near 10^{-19} meter rather than 10^{-35} meter as traditionally assumed. How many dimensions are needed depends on how large they are. Conversely, for a given number of extra dimensions we can compute how large they must be to make gravity strong near 10^{-19} meter. If there is only one extra dimension, its radius R must be roughly the distance between the earth and the sun. Therefore, this case is already excluded by observation. Two extra dimensions, however, can solve the hierarchy problem if they are about a millimeter in size—precisely where our direct knowledge of gravity ends. The dimensions are smaller still if we add more of them, and for seven extra dimensions we need them to be around 10^{-14} meter big, about the size of a uranium nucleus. This is tiny by everyday standards but huge by the yardstick of particle physics.

Postulating extra dimensions may seem bizarre and ad hoc, but to physicists it is an old, familiar idea that dates back to the 1920s, when Polish mathematician Theodor Kaluza and Swedish physicist Oskar Klein developed a remarkable unified theory of gravity and electromagnetism that required one extra dimension. The idea has been revived in modern string theories, which require a total of 10 spatial dimensions for internal mathematical consistency. In the past, physicists have assumed that the extra dimensions are curled up into tiny circles with a size near the traditional Planck length of 10^{-35} meter, making them undetectable but also leaving the conundrum of the hierarchy problem. In contrast, in the new theory that we are discussing, the extra dimensions are wrapped into big circles of at least 10^{-14} meter radius and perhaps as enormous as a millimeter.

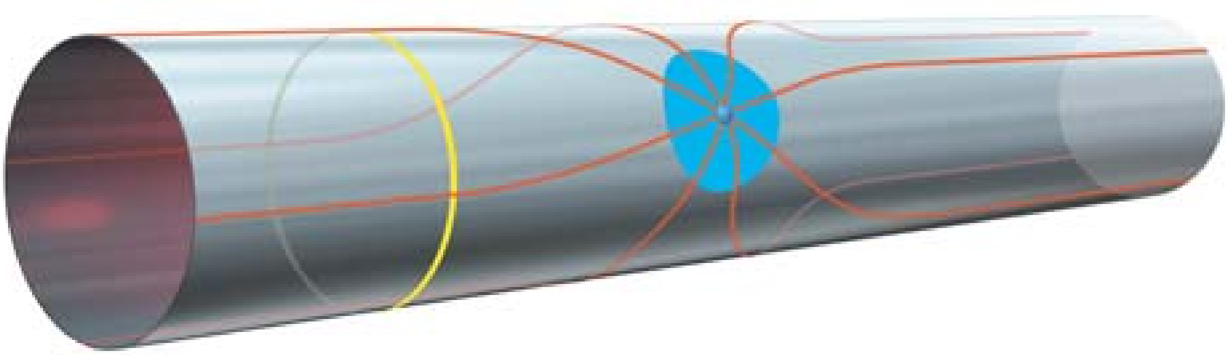


GRAVITATIONAL LINES OF FORCE spread out from the earth in three dimensions. As distance from the earth increases, the force becomes diluted by being spread across a larger surface area (*spheres*). The surface area of each sphere increases as the square of its radius, so gravity falls as the inverse square of distance in three dimensions.

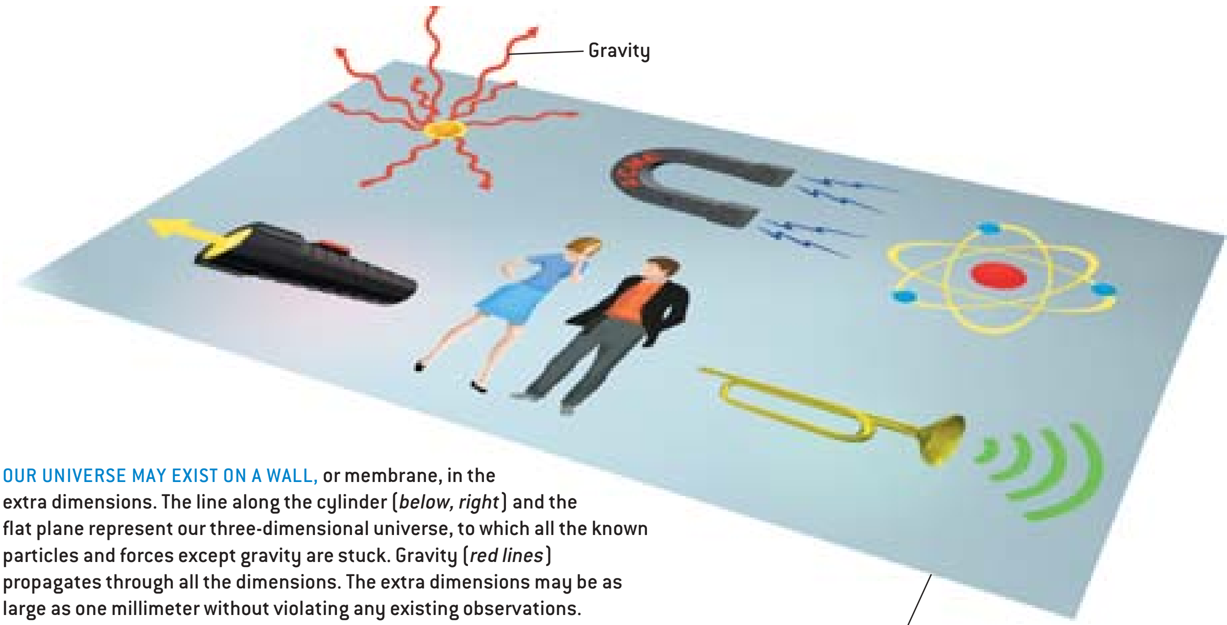
Our Universe on a Wall

IF THESE DIMENSIONS are that large, why haven't we seen them yet? Extra dimensions a millimeter big would be discernible to the naked eye and obvious through a microscope. And although we have not measured gravity much below about a millimeter, we have a wealth of experimental knowledge concerning all the other forces at far shorter distances, approaching 10^{-19} meter, all of it consistent only with three-dimensional space. How could there possibly be large extra dimensions?

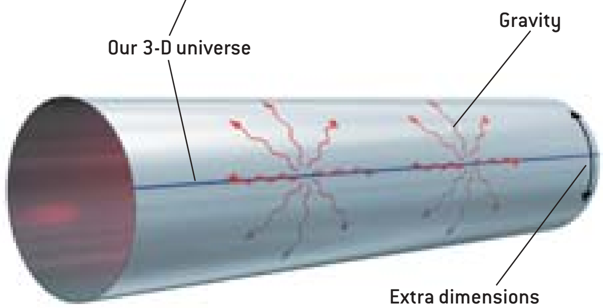
The answer is at once simple and peculiar: all the matter and forces we know of—with the sole exception of gravity—are stuck to a "wall" in the space of the extra dimensions [*see illustration on next page*]. Electrons, protons, photons and all the other particles in the Standard Model cannot move in the extra



SMALL EXTRA DIMENSION wrapped in a circle (*circumference of tube*) modifies how gravity (*red lines*) spreads in space. At distances smaller than the circle radius (*blue patch*), the lines of force spread apart rapidly through all the dimensions. At much larger distances (*yellow circle*), the lines have filled the extra dimension, which has no further effect on the lines of force.



OUR UNIVERSE MAY EXIST ON A WALL, or membrane, in the extra dimensions. The line along the cylinder (*below, right*) and the flat plane represent our three-dimensional universe, to which all the known particles and forces except gravity are stuck. Gravity (*red lines*) propagates through all the dimensions. The extra dimensions may be as large as one millimeter without violating any existing observations.



dimensions; electric and magnetic field lines cannot spread into the higher-dimensional space. The wall has only three dimensions, and as far as these particles are concerned, the universe might as well be three-dimensional. Only gravitational field lines can extend into the higher-dimensional space, and only the particle that transmits gravity, the graviton, can travel freely into the extra dimensions. The presence of the extra dimensions can be felt only through gravity.

To make an analogy, imagine that all the particles in the Standard Model, like electrons and protons, are billiard balls moving on the surface of a vast pool table. As far as they are concerned, the universe is two-dimensional. Nevertheless, pool-table inhabitants made out of billiard balls could still detect the higher-dimensional world: when two balls hit each other sufficiently hard, they produce sound waves, which travel in all three dimensions, carrying some energy away from the table surface [*see illustration on page 68*]. The sound waves are analogous to gravitons, which can travel in the full higher-dimensional space. In high-energy particle collisions, we expect to observe missing energy, the result of gravitons escaping into the extra dimensions.

Although it may seem strange that some particles should be confined to a wall, similar phenomena are quite familiar. For instance, electrons in a copper wire can move only along the one-dimensional space of the wire and do not travel into the surrounding three-dimensional space. Likewise, water waves travel primarily on the surface of the ocean, not throughout its depth. The specific scenario we are describing, in which all particles except gravity are stuck to a wall, can arise naturally in string theory. In fact, one of the major insights triggering recent breakthroughs in string theory has been the recognition that the theory contains such walls, known as D-branes ("brane" comes from the word "membrane," and "D" stands for "Dirichlet," which indicates a mathematical property of the branes). D-branes have precisely the required features: particles such as electrons and photons are represented by tiny lengths of string that each have two end points that must be stuck to a D-brane. Gravitons, on the other hand, are tiny closed loops of string that can wander into all the dimensions because they have no end points anchoring them to a D-brane.

Is It Alive?

ONE OF THE FIRST THINGS good theorists do when they have a new theory is to try to kill it by finding an inconsistency with experimental results. The theory of large extra dimensions changes gravity at macroscopic distances and alters other physics at high energies, so surely it is easy to kill. Remarkably, however, it does not contradict any known experiment. A few examples show how surprising this conclusion is.

One might initially worry that changing gravity would affect objects held together by gravity, such as stars and galaxies. But they are not affected. Gravity changes only at distances shorter than a millimeter, whereas in a star, for example, gravity acts across thousands of kilometers to hold distant parts of the star together.

A much more serious concern relates to gravitons, the hypothetical particles that transmit gravity in a quantum theory. In the theory with extra dimensions, gravitons interact much more strongly with matter, so many more of them should be produced in high-energy particle collisions. In addition, they propagate in all the dimensions, thus taking energy away from the wall, or membrane, that is the universe where we live.

When a star collapses and explodes as a supernova, the high temperatures can readily boil off gravitons into extra dimensions [*see upper illustration on next page*]. From observations of the famous supernova 1987A, however, we know that the explosion emits most of its energy as neutrinos, leaving little room for any energy leakage by gravitons. Our understanding of supernovae therefore limits how strongly gravitons can couple to matter. This constraint could easily have killed the idea of large extra dimensions, but detailed calculations show that the theory survives. The most severe limit is for only two extra dimensions, in which case gravitons cool supernovae too much.

Theorists have examined many other possible constraints based on unacceptable changes. The theory passes all these experimental checks, which turn out to be less stringent than the supernova constraint. Perhaps surprisingly, the constraints become less severe as more dimensions are added to the theory. We saw this right from the start: the case of one extra dimension was excluded immediately because gravity would be altered at solar system distances. This indicates why more dimensions are safer: the dramatic strengthening of gravity begins at shorter distances and therefore has a smaller impact on the larger-distance processes.

Answers by 2010

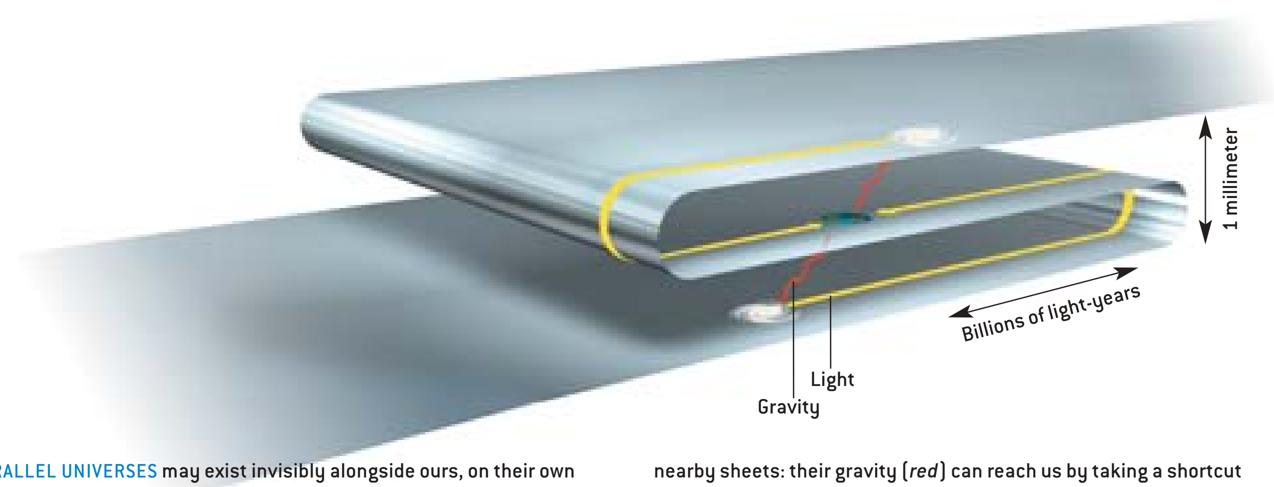
THE THEORY SOLVES the hierarchy problem by making gravity a strong force near TeV energies, precisely the energy scale to be probed using upcoming particle accelerators. Experiments at the Large Hadron Collider (LHC), due to begin around 2007, should therefore uncover the nature of quantum gravity! For instance, if string theory is the correct description of quantum gravity, particles are like tiny loops of string that can vibrate like a violin string. The known fundamental particles correspond to a string that is not vibrating, much like an unbowed violin string. Each different "musical note" that a string can carry by vibrating would appear as a different, exotic new particle. In conventional string theories, the strings have been thought of as only 10^{-35} meter long, and the new particles would have masses on the order of the traditional Planck energy—the "music" of such strings would be too high-pitched for us to "hear" at particle colliders. But with large extra dimensions, the strings are much longer, near 10^{-19} meter, and the new particles would appear at TeV energies—low enough to hear at the LHC.

Similarly, the energies needed to create micro black holes in particle collisions would fall within experimental range [*see lower illustration on next page*].

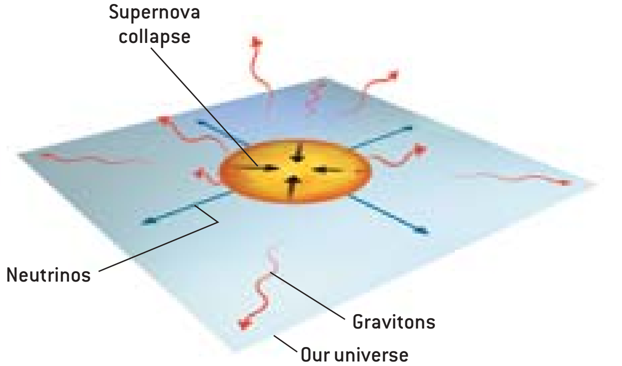
Even at energies too low to produce vibrating strings or black holes, particle collisions would produce large numbers of gravitons, a process that is negligible in conventional theories. The experiments could not directly detect the emitted gravitons, but the energy they carry off would show up as energy missing from the collision debris. The theory predicts specific properties of the missing energy—how it should vary with collision energy and so on—so evidence of graviton production can be distinguished from other processes that can carry off energy in unseen particles. Current data from the highest-energy accelerators already mildly constrain the large-dimensions scenario. Experiments at the LHC should either see evidence of gravitons or begin to exclude the theory by their absence.

A completely different type of experiment could also substantiate the theory, perhaps much sooner than the particle colliders. Recall that for two extra dimensions to solve the hierarchy problem, they must be as large as a millimeter. Measurements of gravity would then detect a change from Newton's inverse square law to an inverse fourth power law at distances near a millimeter. Extensions of the basic theoretical framework lead to a whole host of other possible deviations from Newtonian gravity, the most interesting of which is *repulsive* forces more than a million times stronger than gravity occurring between masses separated by less than a millimeter. Tabletop experiments using exquisitely built detectors are now under way, testing Newton's law from the centimeter range down to tens of microns [*see illustration on page 73*].

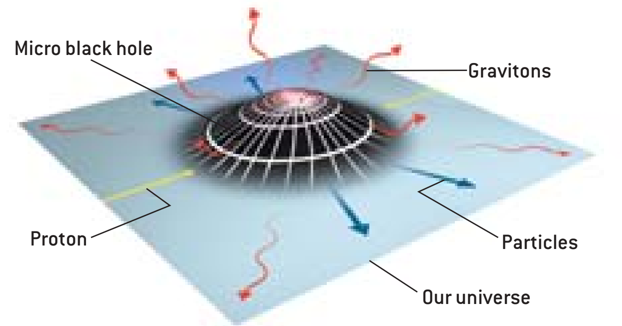
To probe the gravitational force at submillimeter distances, one must use objects not much larger than a millimeter, which therefore have very small masses. One must carefully screen out numerous effects, such as residual electrostatic forces, that could



PARALLEL UNIVERSES may exist invisibly alongside ours, on their own membranes less than a millimeter away from ours. Such parallel universes could also be different sheets of our own universe folded back on itself. So-called dark matter could be explained by ordinary stars and galaxies on nearby sheets: their gravity (*red*) can reach us by taking a shortcut through the extra dimensions, but we cannot see them because light (*yellow*) must travel billions of light-years to the folds and back before it reaches the earth.



SUPERNOVA occurs when the collapse of a massive star produces an explosive shock wave. Most of the energy is emitted as neutrinos (*blue*). If extra dimensions exist, radiated gravitons (*red*) carry away more energy than they would in three dimensions. Theorists constrain the properties of the extra dimensions by requiring that energy leakage by gravitons not cause supernovae to fizzle.



MICRO BLACK HOLES could be created in particle accelerators such as the Large Hadron Collider by smashing together protons (*yellow*) at high energies. The holes would evaporate rapidly by emitting Hawking radiation of Standard Model particles (*blue*) and gravitons (*red*).

mask or fake the tiny gravitational attraction. Such experiments are difficult and subtle, but it is exciting that they might uncover dramatic new physics. Even apart from the search for extra dimensions, it is important to extend our direct knowledge of gravity to these short distances. Researchers at the University of Washington have performed a measurement of gravity down to one fifth of a millimeter and have found no deviations from Newtonian gravity. Therefore, any large new dimensions must be less than a fifth of a millimeter in size. Several groups are now looking to improve on this measurement.

The idea of extra dimensions in effect continues the Copernican tradition in understanding our place in the world: The earth is not the center of the solar system, the sun is not the center of our galaxy, our galaxy is just one of billions in a universe that has no center, and now our entire three-dimensional universe would be just a thin membrane in the full space of dimensions. If we consider slices across the extra dimensions, our universe would occupy a single infinitesimal point in each slice, surrounded by a void.

Perhaps this is not the full story. Just as the Milky Way is not the only galaxy in the universe, might our universe not be alone in the extra dimensions? The membranes of other three-dimensional universes could lie parallel to our own, only a millimeter removed from us in the extra dimensions [*see illustration on preceding page*]. Similarly, although all the particles of the Standard Model must stick to our own membrane universe, other particles beyond the Standard Model might propagate through the extra dimensions. Far from being empty, the extra dimensions could have a multitude of interesting structures.

The effects of new particles and universes in the extra dimensions may provide answers to many outstanding mysteries of particle physics and cosmology. For example, they may account for the masses of the ghostly elementary particles called neutrinos. Impressive evidence from the Super Kamiokande experiment in Japan indicates that neutrinos, long assumed to be massless, have a minuscule but nonzero mass. The neutrino can gain its mass by interacting with a partner field living in the extra dimensions. As with gravity, the interaction is greatly diluted by the partner's being spread throughout the extra dimensions, and so the neutrino acquires only a tiny mass.

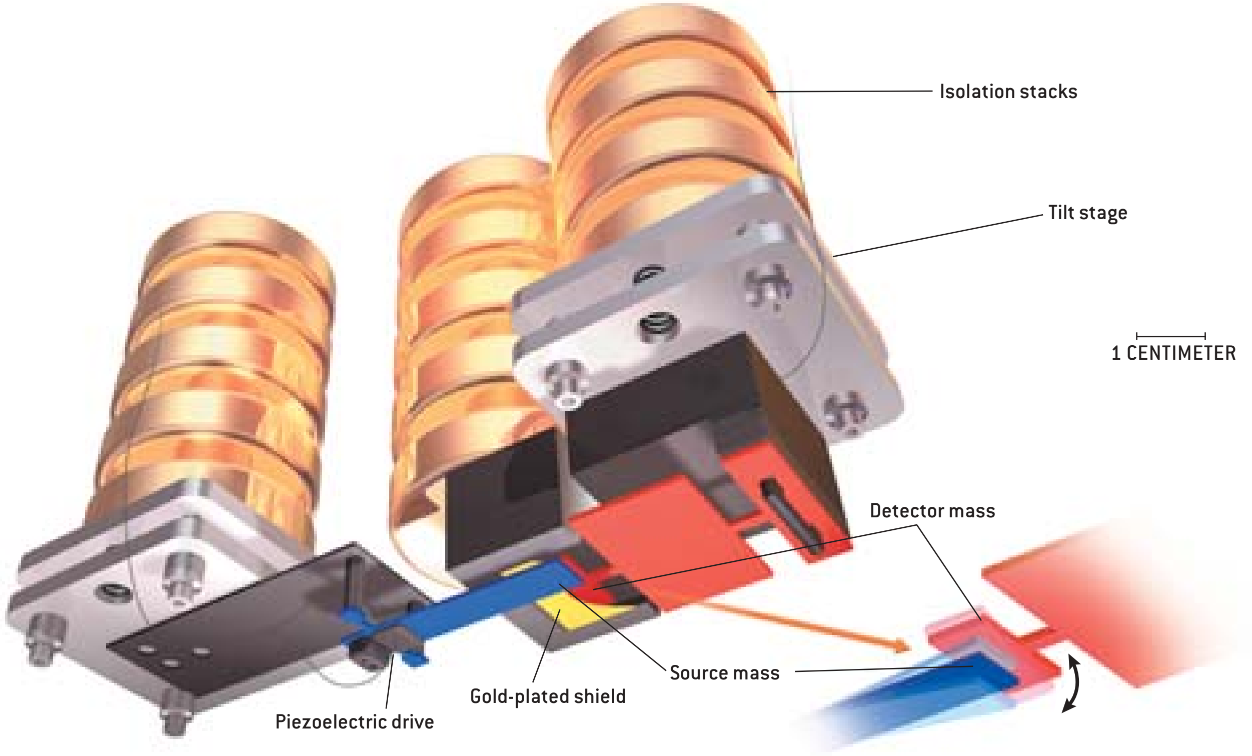
Parallel Universes

ANOTHER EXAMPLE is the mystery in cosmology of what constitutes dark matter, the invisible gravitating substance that seems to make up more than 90 percent of the mass of the universe. Dark matter may reside in parallel universes. Such matter would affect our universe through gravity and is necessarily "dark" because our species of photon is stuck to our membrane, so photons cannot travel across the void from the parallel matter to our eyes.

Such parallel universes might be utterly unlike our own, having different particles and forces and perhaps even being confined to membranes with fewer or more dimensions. In one intriguing scenario, however, they have identical properties to our own world. Imagine that the wall where we live is folded a number of times in the extra dimensions [*see illustration on preceding page*]. Objects on the other side of a fold will appear to be very distant even if they are less than a millimeter from us in the extra dimensions: the light they emit must travel to the crease and back to reach us. If the crease is tens of billions of light-years away, no light from the other side could have reached us since the universe began.

THE AUTHORS

NIMA ARKANI-HAMED, SAVAS DIMOPOULOS and *GEORGI DVALI* conceived the extra-dimension theory at Stanford University in February 1998. Arkani-Hamed was born in Houston and in 1997 received a Ph.D. in physics at the University of California, Berkeley, where he has been assistant professor since 1999. When he's not exploring theoretical possibilities beyond the Standard Model of particle physics, he enjoys hiking in the High Sierra and the California desert. Dimopoulos grew up in Athens, received a Ph.D. from the University of Chicago and has been professor of physics at Stanford since 1979. His research has mostly been driven by the quest for what lies beyond the Standard Model. In 1981, together with Howard Georgi of Harvard University, he proposed the supersymmetric Standard Model. "Gia" Dvali was raised in what is now the Republic of Georgia and in 1992 received his Ph.D. in high-energy physics and cosmology from Tbilisi State University. In 1998 he became associate professor of physics at New York University. He enjoys overcoming gravity by high mountaineering and rock and ice climbing.



TORSION OSCILLATOR at the University of Colorado looks for changes in gravity from 0.05 to 1.0 millimeter. Piezoelectrics vibrate the tungsten source mass (*blue*) like a diving board. Any forces acting between the source mass and the tungsten detector (*red*) produce twisting oscillations of the detector (*inset; oscillations are exaggerated*), which are sensed by electronics. A gold-plated shield (*yellow*) suppresses electrostatic forces, and suspension from brass isolation stacks stops vibrations from traveling from the source to the detector. Electrostatic shields enclosing the apparatus are not shown. For maximum sensitivity, liquid helium cools the apparatus to four kelvins.

Dark matter could be composed of ordinary matter, perhaps even ordinary stars and galaxies, shining brightly on their own folds. Such stars would produce interesting observable effects, such as gravitational waves from supernovae. Gravitational-wave detectors scheduled for completion soon could find evidence for folds by observing large sources of gravitational radiation that cannot be accounted for by matter visible in our own universe.

Our theory is not the first proposal involving extra dimensions larger than 10^{-35} meter. In 1990 Ignatios Antoniadis of the École Polytechnique in France suggested that some of string theory's dimensions might be as large as 10^{-19} meter. In 1996 Petr Hořava of the California Institute of Technology and Edward Witten of the Institute for Advanced Study in Princeton, N.J., pointed out that a single extra dimension of 10^{-30} meter would neatly unify forces. Following this idea, Joseph Lykken of Fermi National Accelerator Laboratory in Batavia, Ill., attempted to lower the unification scale to near 10^{-19} meter. Keith Dienes of the University of Arizona, Emilian Dudas of the University of Paris–South and Tony Gherghetta, now at the University of Minnesota, observed in 1998 that extra dimensions smaller than 10^{-19} meter could allow the forces to unify at distances much larger than 10^{-32} meter.

Since our proposal in 1998 a number of interesting variations have appeared, using the same basic ingredients of extra dimensions and our universe-on-a-wall. In an intriguing model, Lisa Randall of Harvard University and Raman Sundrum of Johns Hopkins University proposed that gravity itself may be concentrated on a membrane in a five-dimensional spacetime that is infinite in all directions. Gravity appears very weak in our universe in a natural way if we are on a different membrane.

For 20 years, the conventional approach to tackling the hierarchy problem, and therefore understanding why gravity is so weak, had been to assume that the Planck scale near 10^{-35} meter is fundamental and that particle physics must change near 10^{-19} meter. Quantum gravity would remain in the realm of speculation, hopelessly out of the reach of experiment. We now realize this does not have to be the case. If there are large new dimensions, in the next several years we could discover deviations from Newton's law near 6×10^{-5} meter, say, and we would detect stringy vibrations or black holes at the LHC. Quantum gravity and string theory would become testable science. Whatever happens, experiment will point the way to answering a 300-year-old question. By 2010 we will have made decisive progress toward understanding why gravity is so weak. And we may find that we live in a strange Flatland, a membrane universe where quantum gravity is just around the corner. SA

MORE TO EXPLORE

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An introduction to tabletop gravity experiments is available at **http://mist.npl.washington.edu/eotwash/**

An introduction to string theory is available at **http://superstringtheory.com/**