

# THE STRING THEORY LANDSCAPE

The theory of strings  
predicts that the universe  
might occupy one  
random “valley” out  
of a virtually infinite  
selection of valleys  
in a vast landscape  
of possibilities

By **Raphael Bousso** and  
**Joseph Polchinski**

## OVERVIEW

- According to string theory, the laws of physics that we see operating in the world depend on how extra dimensions of space are curled up into a tiny bundle.
- A map of all possible configurations of the extra dimensions produces a “landscape” wherein each valley corresponds to a stable set of laws.
- The entire visible universe exists within a region of space that is associated with a valley of the landscape that happens to produce laws of physics suitable for the evolution of life.

THEORETICAL LANDSCAPE populated with an array of innumerable possible universes is predicted by string theory. The landscape has perhaps  $10^{500}$  valleys, each one of which corresponds to a set of laws of physics that may operate in vast bubbles of space. Our visible universe would be one relatively small region within one such bubble.



## According to Albert Einstein's theory of general relativity, gravity arises from

the geometry of space and time, which combine to form spacetime. Any massive body leaves an imprint on the shape of spacetime, governed by an equation Einstein formulated in 1915. The earth's mass, for example, makes time pass slightly more rapidly for an apple near the top of a tree than for a physicist working in its shade. When the apple falls, it is actually responding to this warping of time. The curvature of spacetime keeps the earth in its orbit around the sun and drives distant galaxies ever farther apart. This surprising and beautiful idea has been confirmed by many precision experiments.

Given the success of replacing the gravitational force with the dynamics of space and time, why not seek a geometric explanation for the other forces of nature and even for the spectrum of elementary particles? Indeed, this quest occupied Einstein for much of his life. He was particularly attracted to work by German Theodor Kaluza and Swede Oskar Klein, which proposed that whereas gravity reflects the shape of the four familiar spacetime dimensions, electromagnetism arises

Recent experimental and theoretical developments suggest a striking and controversial answer that greatly alters our picture of the universe.

### Kaluza-Klein Theory and Strings

KALUZA AND KLEIN put forth their concept of a fifth dimension in the early part of the 20th century, when scientists knew of two forces—electromagnetism and gravity. Both fall off inversely proportional to the square of the distance from their source, so it was tempting to speculate that they were connected in some way. Kaluza and Klein noticed that Einstein's geometric theory of gravity might provide this connection if an additional spatial dimension existed, making spacetime five-dimensional.

This idea is not as wild as it seems. If the extra spatial dimension is curled up into a small enough circle, it will have eluded our best microscopes—that is, the most powerful particle accelerators [see box on opposite page]. Moreover, we

# String theory's equations imply that **six extra dimensions exist** that are too small to have yet been detected.

from the geometry of an additional fifth dimension that is too small to see directly (at least so far). Einstein's search for a unified theory is often remembered as a failure. In fact, it was premature: physicists first had to understand the nuclear forces and the crucial role of quantum field theory in describing physics—an understanding that was only achieved in the 1970s.

The search for a unified theory is a central activity in theoretical physics today, and just as Einstein foresaw, geometric concepts play a key role. The Kaluza-Klein idea has been resurrected and extended as a feature of string theory, a promising framework for the unification of quantum mechanics, general relativity and particle physics. In both the Kaluza-Klein conjecture and string theory, the laws of physics that we see are controlled by the shape and size of additional microscopic dimensions. What determines this shape?

already know from general relativity that space is flexible. The three dimensions that we see are expanding and were once much smaller, so it is not such a stretch to imagine that there is another dimension that remains small today.

Although we cannot detect it directly, a small extra dimension would have important indirect effects that could be observed. General relativity would then describe the geometry of a five-dimensional spacetime. We can split this geometry into three elements: the shape of the four large spacetime dimensions, the angle between the small dimension and the others, and the circumference of the small dimension. The large spacetime behaves according to ordinary four-dimensional general relativity. At every location within it, the angle and circumference have some value, just like two fields permeating spacetime and taking on certain values at each location. Amazingly, the angle field turns out to mimic an electromagnetic field living in the four-dimensional world. That is, the equations governing its behavior are identical to those of electromagnetism. The circumference determines the relative strengths of the electromagnetic and gravitational forces. Thus, from a theory of gravity alone in five dimensions, we obtain a theory of both gravity and electromagnetism in four dimensions.

The possibility of extra dimensions has also come to play a vital role in unifying general relativity and quantum mechanics. In string theory, a leading approach to that unification, particles are in actuality one-dimensional objects, small vibrating loops or strands. The typical size of a string is near

**RAPHAEL BOUSSO** and **JOSEPH POLCHINSKI**'s work together began at a workshop on string duality in Santa Barbara. It grew out of the synergy between Bousso's background in quantum gravity and inflationary cosmology and Polchinski's background in string theory. Bousso is assistant professor of physics at the University of California, Berkeley. His research includes a general formulation of the holographic principle, which relates spacetime geometry to its information content. Polchinski is a professor at the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara. His contributions to string theory include the seminal idea that branes constitute a significant feature of the theory.

the Planck length, or  $10^{-33}$  centimeter (less than a billionth of a billionth of the size of an atomic nucleus). Consequently, a string looks like a point under anything less than Planckian magnification.

For the theory's equations to be mathematically consistent, a string has to vibrate in 10 spacetime dimensions, which implies that six extra dimensions exist that are too small to have yet been detected. Along with the strings, sheets known as "branes" (derived from "membranes") of various dimensions can be immersed in spacetime. In the original Kaluza-Klein idea, the quantum wave functions of ordinary particles would fill the extra dimension—in effect, the particles themselves would be smeared across the extra dimension. Strings, in contrast, can be confined to lie on a brane. String theory also contains fluxes, or forces that can be represented by field lines, much as forces are represented in classical (nonquantum) electromagnetism.

Altogether the string picture looks more complicated than Kaluza-Klein theory, but the underlying mathematical structure is actually more unified and complete. The central theme of Kaluza-Klein theory remains: the physical laws that we see depend on the geometry of hidden extra dimensions.

## Too Many Solutions?

THE KEY QUESTION IS, What determines this geometry? The answer from general relativity is that spacetime must satisfy Einstein's equations—in the words of John Wheeler of Princeton University, matter tells spacetime how to curve, and spacetime tells matter how to move. But the solution to the equations is not unique, so many different geometries are allowed. The case of five-dimensional Kaluza-Klein geometry provides a simple example of this nonuniqueness. The circumference of the small dimension can take any size at all: in the absence of matter, four large flat dimensions, plus a circle of any size, solve Einstein's equations. (Similar multiple solutions also exist when matter is present.)

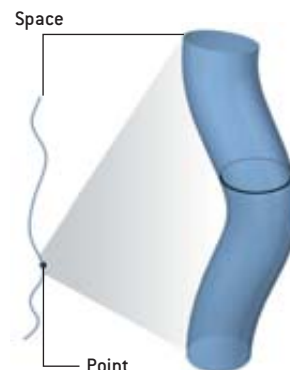
In string theory we have several extra dimensions, which results in many more adjustable parameters. One extra dimension can be wrapped up only in a circle. When more than one extra dimension exists, the bundle of extra dimensions can have many different shapes (technically, "topologies"), such as a sphere, a doughnut, two doughnuts joined together and so on. Each doughnut loop (a "handle") has a length and a circumference, resulting in a huge assortment of possible geometries for the small dimensions. In addition to the handles, further parameters correspond to the locations of branes and the different amounts of flux wound around each loop [see box on page 83].

Yet the vast collection of solutions are not all equal: each configuration has a potential energy, contributed by fluxes, branes and the curvature itself of the curled-up dimensions. This energy is called the vacuum energy, because it is the energy of the spacetime when the large four dimensions are completely devoid of matter or fields. The geometry of the small dimensions will try to adjust to minimize this energy, just as a ball

## EXTRA DIMENSIONS

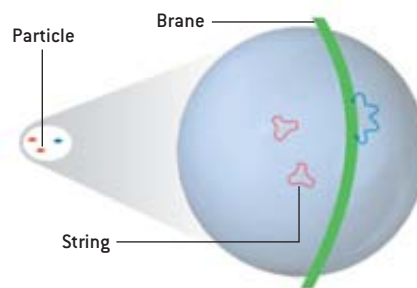
### Strings and Tubes

Extra spatial dimensions beyond the three we perceive are postulated by Kaluza-Klein theory and string theory. To imagine those dimensions, which are tiny, consider a space that consists of a long, very thin tube. Viewed from a distance, the tube looks like a one-dimensional line, but under high magnification, its cylindrical shape becomes apparent. Each zero-dimensional point on the line is revealed to be a one-dimensional circle of the tube. In the original Kaluza-Klein theory, every point in our familiar three-dimensional space is actually a tiny circle.



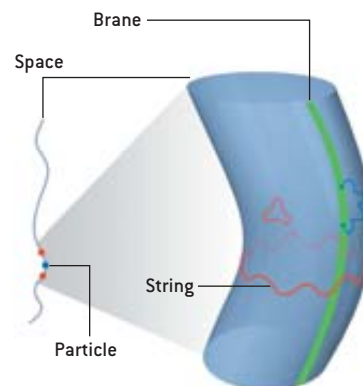
String theory predicts that what appear to be pointlike particles are actually tiny strings. In addition, it predicts the existence of membranelike objects called branes (green), which can come in a variety of dimensionalities.

Strings that have end points (blue) always have their ends on a brane. Those that are closed loops (red) are free from that restriction.



String theory also incorporates Kaluza-Klein theory, which we again represent by showing a line of space that is actually a tube. This tube has a one-dimensional brane running through it and is populated by strings,

some of which loop around the circumference of the tube one or more times. At lower magnification, the strings look like point particles, and the extra dimension, including its brane, is not apparent.



placed on a slope will start to roll downhill to a lower position.

To understand what consequences follow from this minimization, focus first on a single parameter: the overall size of the hidden space. We can plot a curve showing how the vacuum energy changes as this parameter varies. An example is shown in the top illustration on page 85. At very small sizes, the energy is high, so the curve starts out high at the left. Then, from left to right, it dips down into three valleys, each one lower than the previous one. Finally, at the right, after climbing out of the last valley, the curve trails off down a shallow slope to a constant value. The bottom of the leftmost valley is above zero energy; the middle one is at exactly zero; and the right-hand one is below zero.

How the hidden space behaves depends on the initial conditions—where the “ball” that represents it starts on the curve. If the configuration starts out to the right of the last peak, the ball will roll off to infinity, and the size of the hidden space will increase without bound (it will cease to be hidden). Otherwise it will settle down at the bottom of one of the troughs—the size of the hidden space adjusts to minimize the energy. These three local minima differ by virtue of whether the resulting vacuum energy is positive, negative or zero. In our universe the size

of the hidden space adjusts to minimize the energy. These three local minima differ by virtue of whether the resulting vacuum energy is positive, negative or zero. In our universe the size

of the hidden space adjusts to minimize the energy. These three local minima differ by virtue of whether the resulting vacuum energy is positive, negative or zero. In our universe the size

of the hidden space adjusts to minimize the energy. These three local minima differ by virtue of whether the resulting vacuum energy is positive, negative or zero. In our universe the size

## Each solution will conjure up different phenomena in the macroscopic world by defining which kinds of particles and forces are present.

of the hidden dimensions is not changing with time: if it were, we would see the constants of nature changing. Thus, we must be sitting at a minimum. In particular, we seem to be sitting at a minimum with a slightly positive vacuum energy.

Because there is more than one parameter, we should actually think of this vacuum energy curve as one slice through a complex, multidimensional mountain range, which Leonard Susskind of Stanford University has described as the landscape of string theory [see middle illustration on page 85]. The minima of this multidimensional landscape—the bottoms of depressions where a ball could come to rest—correspond to the stable configurations of spacetime (including branes and fluxes), which are called stable vacua.

A real landscape allows only two independent directions (north-south and east-west), and this is all we can draw. But the landscape of string theory is much more complicated, with hundreds of independent directions. The landscape dimensions should not be confused with the actual spatial dimensions of the world; each axis measures not some position in physical space but some aspect of the geometry, such as the size of a handle or the position of a brane.

The landscape of string theory is far from being fully mapped out. Calculating the energy of a vacuum state is a difficult problem and usually depends on finding suitable ap-

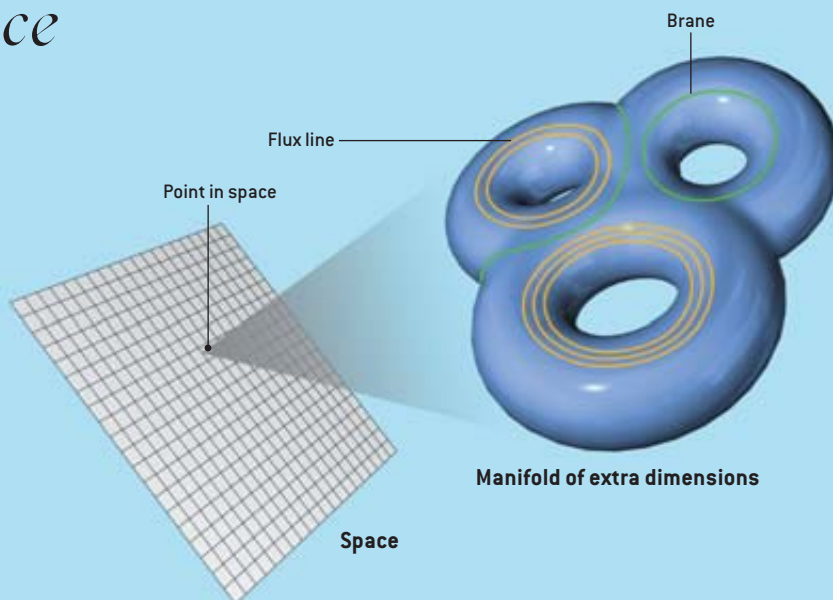
proximations. Researchers have made steady progress recently, most notably in 2003, when Shamit Kachru, Renata Kallosh and Andrei Linde, all at Stanford, and Sandip Trivedi of the Tata Institute of Fundamental Research in Mumbai, India, found strong evidence that the landscape does have minima where a universe can get stuck.

We cannot be sure how many stable vacua there are—that is, how many points where a ball could rest. But the number could very well be enormous. Some research suggests that there are solutions with up to about 500 handles, but not many more. We can wrap different numbers of flux lines around each handle, but not too many, because they would make the space unstable, like the right part of the curve in the figure. If we suppose that each handle can have from zero to nine flux lines (10 possible values), then there would be  $10^{500}$  possible configurations. Even if each handle could have only zero or one flux unit, there are  $2^{500}$ , or about  $10^{150}$ , possibilities.

As well as affecting the vacuum energy, each of the many solutions will conjure up different phenomena in the four-dimensional macroscopic world by defining which kinds of particles and forces are present and what masses and interaction strengths they have. String theory may provide us with

## The Hidden Space

Any given solution to the equations of string theory represents a specific configuration of space and time. In particular, it specifies the arrangement of the small dimensions, along with their associated branes (green) and lines of force known as flux lines (orange). Our world has six extra dimensions, so every point of our familiar three-dimensional space hides an associated tiny six-dimensional space, or manifold—a six-dimensional analogue of the circle in the top illustration on page 81. The physics that is observed in the three large dimensions depends on the size and the structure of the manifold: how many doughnutlike “handles” it has, the length and circumference of each handle, the number and locations of its branes, and the number of flux lines wrapped around each doughnut.



tery of why our particular vacuum should be the only one to exist is eliminated. Moreover, we proposed that our idea resolves one of the greatest puzzles in nature.

### A Trail through the Landscape

AS OUTLINED BEFORE, each stable vacuum is characterized by its numbers of handles, branes and flux quanta. But now we take into account that each of these elements can be created and destroyed, so that after periods of stability, the world can snap into a different configuration. In the landscape picture, the disappearance of a flux line or other change of topology is a quantum jump over a mountain ridge into a lower valley.

Consequently, as time goes on, different vacua can come into existence. Suppose that each of the 500 handles in our earlier example starts out with nine units of flux. One by one, the 4,500 flux units will decay in some sequence governed by the probabilistic predictions of quantum theory until all the energy stored in fluxes is used up. We start in a high mountain valley and leap randomly over the adjoining ridges, visiting 4,500 successively lower valleys. We are led through some varied scenery, but we pass by only a minuscule fraction of the  $10^{500}$  possible solutions. It would seem that most vacua never get their 15 minutes of fame.

Yet we are overlooking a key part of the story: the effect of the vacuum energy on how the universe evolves. Ordinary objects such as stars and galaxies tend to slow down an expanding universe and can even cause it to recollapse. Positive vacuum energy, however, acts like antigravity: according to Einstein's equation, it causes the three dimensions that we see to grow more and more rapidly. This rapid expansion has an

important and surprising effect when the hidden dimensions tunnel to a new configuration.

Remember that at every point in our three-dimensional space there sits a small six-dimensional space, which lives at some point on the landscape. When this small space jumps to a new configuration, the jump does not happen at the same instant everywhere. The tunneling first happens at one place in the three-dimensional universe, and then a bubble of the new low-energy configuration expands rapidly [see box on page 86]. If the three large dimensions were not expanding, this growing bubble would eventually overrun every point in the universe. But the old region is also expanding, and this expansion can easily be faster than that of the new bubble.

Everybody wins: both the old and the new regions increase in size. The new never completely obliterates the old. What makes this outcome possible is Einstein's dynamical geometry. General relativity is not a zero-sum game—the stretching of the spatial fabric allows new volume to be created for both the old and the new vacua. This trick will work as the new vacuum ages as well. When its turn comes to decay, it will not disappear altogether; rather it will sprout a growing bubble, occupied by a vacuum with yet lower energy.

Because the original configuration keeps growing, eventually it will decay again at another location, to another nearby minimum in the landscape. The process will continue infinitely many times, decays happening in all possible ways, with far separated regions losing fluxes from different handles. In this manner, every bubble will be host to many new solutions. Instead of a single sequence of flux decay, the universe thus experiences all possible sequences, resulting in a hi-



erarchy of nested bubbles, or subuniverses. The result is very similar to the eternal inflation scenario proposed by Alan Guth of the Massachusetts Institute of Technology, Alexander Vilenkin of Tufts University, and Linde [see “The Self-Reproducing Inflationary Universe,” by Andrei Linde; SCIENTIFIC AMERICAN, November 1994].

Our scenario is analogous to an infinite number of explorers embarking on all possible paths through every minimum in the landscape. Each explorer represents some location in the universe far away from all the others. The path taken by that explorer is the sequence of vacua experienced at his location in the universe. As long as the explorers’ starting point in the landscape is high up in the glaciers, practically all the minima will be visited. In fact, each one will be reached infinitely many times by every possible path downhill from the higher minima. The cascade comes to a halt only where it drops below sea level—into negative energy. The characteristic geometry associated with negative vacuum energy does not allow the game of perpetual expansion and bubble formation to continue. Instead a localized “big crunch” occurs, much like in the interior of a black hole.

In each bubble, an observer conducting experiments at

nundrum,” by Lawrence M. Krauss and Michael S. Turner, on page 70]. To obtain a static universe, he proposed that this constant takes a positive value, but he abandoned the idea after observations proved the universe to be expanding.

With the advent of quantum field theory, empty space—the vacuum—became a busy place, full of virtual particles and fields popping in and out of existence, and each particle and field carries some positive or negative energy. According to the simplest computations based on this theory, these energies should add up to a tremendous density of about  $10^{94}$  grams per cubic centimeter, or one Planck mass per cubic Planck length. We denote that value by  $\Lambda_P$ . This result has been called the most famous wrong prediction in physics because experiments have long shown that the vacuum energy is definitely no greater than  $10^{-120}\Lambda_P$ . Theoretical physics thus stumbled into a major crisis.

Understanding the origin of this great discrepancy has been one of the central goals of theoretical physics for more than three decades, but none of the numerous proposals for a resolution has gained wide acceptance. It was frequently assumed that the vacuum energy is exactly zero—a reasonable guess for a number that is known to have at least 120 zeros

## Think of the landscape of string theory as a complex, **multidimensional mountain range**, with hundreds of independent directions.

low energies (like we do) will see a specific four-dimensional universe with its own characteristic laws of physics. Information from outside our bubble cannot reach us, because the intermediate space is expanding too rapidly for light to outrun it. We see only one set of laws, those corresponding to our local vacuum, simply because we do not see very far. In our scenario, what we think of as the big bang that began our universe was no more than the most recent jump to a new string configuration in this location, which has now spread across many billions of light-years. One day (probably too far off to worry about) this part of the world may experience another such transition.

### The Vacuum Energy Crisis

THE PICTURE WE HAVE DESCRIBED explains how all the different stable vacua of the string landscape come into existence at various locations in the universe, thus forming innumerable subuniverses. This result may solve one of the most important and long-standing problems in theoretical physics—one related to the vacuum energy. To Einstein, what we now think of as vacuum energy was an arbitrary mathematical term—a “cosmological constant”—that could be added to his equation of general relativity to make it consistent with his conviction that the universe was static [see “A Cosmic Co-

after the decimal point. So the apparent task was to explain how physics could produce the value zero. Many attempts centered on the idea that the vacuum energy can adjust itself to zero, but there were no convincing explanations of how this adjustment would take place or why the end result should be anywhere near zero.

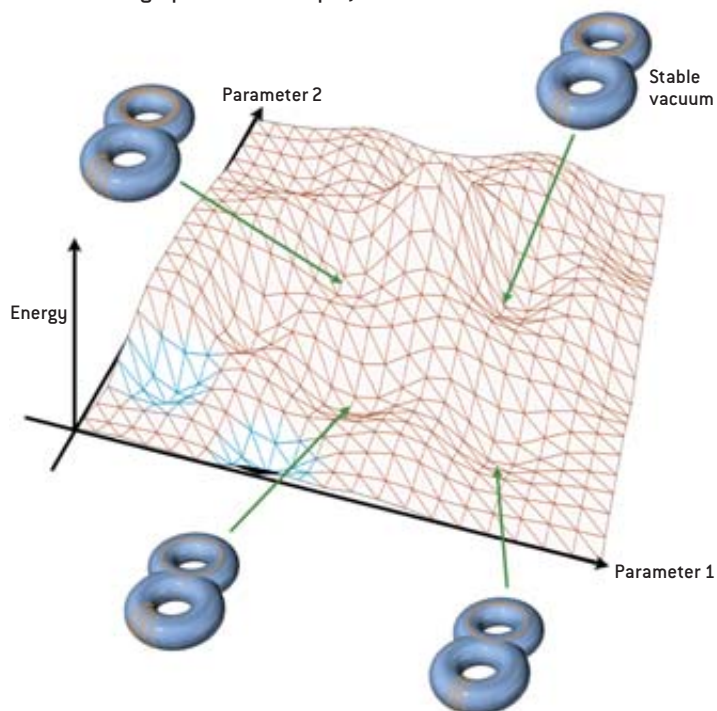
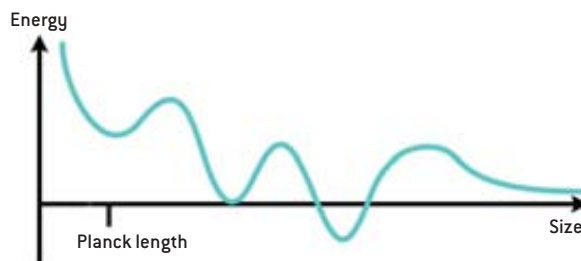
In our 2000 paper, we combined the wealth of string theory solutions and their cosmological dynamics with a 1987 insight of Steven Weinberg of the University of Texas at Austin to provide both a how and a why.

First consider the wealth of solutions. The vacuum energy is just the vertical elevation of a point in the landscape. This elevation ranges from around  $+\Lambda_P$  at the glacial peaks to  $-\Lambda_P$  at the bottom of the ocean. Supposing that there are  $10^{500}$  minima, their elevations will lie randomly between these two values. If we plot all these elevations on the vertical axis, the average spacing between them will be  $10^{-500}\Lambda_P$ . Many, albeit a very small fraction of the total, will therefore have values between zero and  $10^{-120}\Lambda_P$ . This result explains *how* such small values come about.

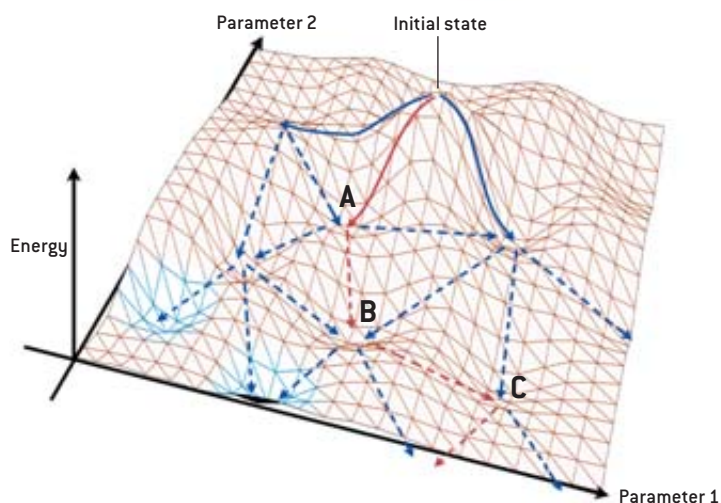
The general idea is not new. Andrei Sakharov, the late Soviet physicist and dissident, suggested as early as 1984 that the complicated geometries of hidden dimensions might produce a spectrum for vacuum energy that includes values in the ex-

# Topography of Energy

A landscape emerges when the energy of each possible string solution is plotted as a function of the parameters that define the six-dimensional manifold associated with that solution. If only one parameter is varied—say, the overall size of that manifold—the landscape forms a simple line graph. Here three particular sizes (all close to the Planck scale) have energies in the troughs, or minima, of the curve. The manifold will naturally tend to adjust its size to end up at one of the three minima, like a ball rolling around on the slope (it might also “roll off” to infinity at the right-hand end of the graph in this example).



The true string theory landscape reflects all parameters and thus would form a topography with a vast number of dimensions. We represent it by a landscape showing the variation of the energy contained in empty space when only two features change. The manifold of extra dimensions tends to end up at the bottom of a valley, which is a stable string solution, or a stable vacuum—that is, a manifold in a valley tends to stay in that state for a long while. Blue regions are below zero energy.

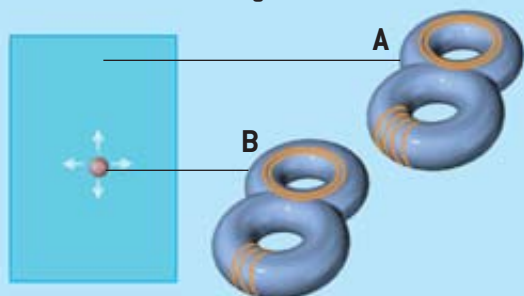


Quantum effects, however, allow a manifold to change state abruptly at some point—to tunnel through the intervening ridge to a nearby lower valley. The red arrows show how one region of the universe might evolve: starting out at a high mountaintop, rolling down into a nearby valley (*vacuum A*), eventually tunneling through to another, lower valley (*vacuum B*), and so on. Different regions of the universe will randomly follow different paths. The effect is like an infinite number of explorers traversing the landscape, passing through all possible valleys (*blue arrows*).

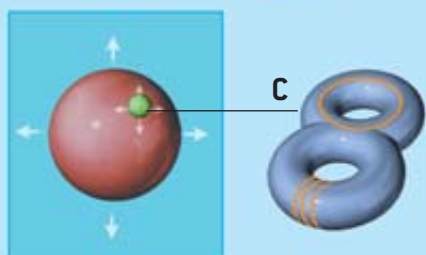


# Bubbles of Reality

The possibility of decay from one stable vacuum to another suggests a radical new picture of our universe at the largest scales.



Tunneling from one stable vacuum to another would not occur everywhere in the universe at once. Instead it would occur at one random location, producing an expanding bubble of space (arrows) having the new vacuum. In this example, the blue region of space has vacuum A, whose manifold of small extra dimensions consists of a two-handled doughnut with groups of two and four flux lines wrapped around the handles. The red region, which has vacuum B, emerges when one of the four flux lines decays. Corresponding to their different manifolds, the two regions will have different kinds of particles and forces and thus different laws of physics.



The red region grows rapidly, potentially becoming billions of light-years in diameter. Eventually another transition occurs within the red region, this time a decay of one of the two flux lines. This decay generates the green region, which has vacuum C and still another set of particles and forces.

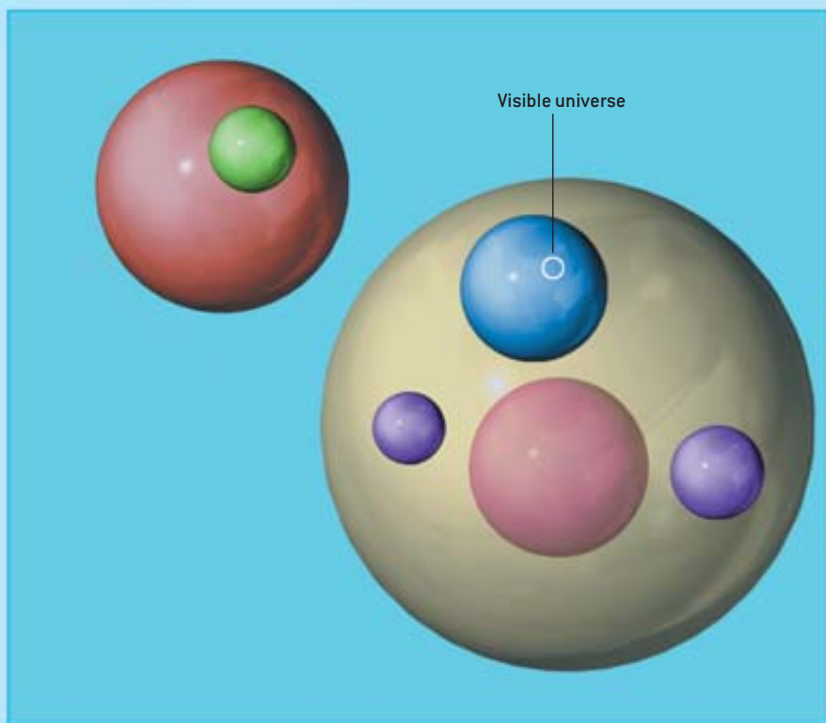


The green region also grows rapidly, but it never catches up with the red region. Similarly, the red region never completely replaces the original blue vacuum.

Because the quantum tunneling is a random process, widely separated locations in the universe will decay through different sequences of vacua.

In this way, the entire landscape is explored; every stable vacuum occurs in many different places in the universe.

The whole universe is therefore a foam of expanding bubbles within bubbles, each with its own laws of physics. Extremely few of the bubbles are suitable for the formation of complex structures such as galaxies and life. Our entire visible universe (more than 20 billion light-years in diameter) is a relatively small region within one of these bubbles.



perimental window. Other researchers have made alternative proposals that do not seem to be realized in string theory.

We have explained how cosmology populates most of the minima, resulting in a complicated universe that contains bubbles with every imaginable value of the vacuum energy. In which of these bubbles will we find ourselves? Why should our vacuum energy be so close to zero? Here Weinberg's insight comes into play. Certainly an element of chance is involved. But many places are so inhospitable, it is no wonder we do not live there. This logic is familiar on smaller scale—you were not born in Antarctica, at the bottom of the Marianas Trench or on the airless wastes of the moon. Rather you find yourself in the tiny fraction of the solar system that is hospitable to life. Similarly, only a small fraction of the stable vacua are hospitable to life. Regions of the universe with large positive vacuum energy experience expansions so virulent that a supernova explosion would seem peaceful in comparison. Regions with large negative vacuum energy rapidly disappear in a cosmic crunch. If the vacuum energy in our bubble had been greater than  $+10^{-118}\Lambda_P$  or less than  $-10^{-120}\Lambda_P$ , we could

made or whether its laws are completely fixed by some fundamental principle. As physicists, we might hope for the latter. The underlying laws of string theory, although they are still not completely known, appear to be completely fixed and inevitable: the mathematics does not allow any choices. But the laws that we see most directly are not the underlying laws. Rather our laws depend on the shape of the hidden dimensions, and for this the choices are many. The details of what we see in nature are not inevitable but are a consequence of the particular bubble that we find ourselves in.

Does the string landscape picture make other predictions, beyond the small but nonzero value of the vacuum energy? Answering this question will require a much greater understanding of the spectrum of vacua and is the subject of active research on several fronts. In particular, we have not yet located a specific stable vacuum that reproduces the known laws of physics in our four-dimensional spacetime. The string landscape is largely uncharted territory. Experiments could help. We might someday see the higher-dimensional physical laws directly, via strings, black holes or Kaluza-Klein particles using accelerators.

## In each bubble, an observer will see a specific four-dimensional universe with its own characteristic laws of physics.

not have lived here, just as we do not find ourselves roasting on Venus or crushed on Jupiter. This type of reasoning is called anthropic.

Plenty of minima will be in the sweet spot, a hair's breadth above or below the water line. We live where we can, so we should not be surprised that the vacuum energy in our bubble is tiny. But neither should we expect it to be exactly zero! About  $10^{380}$  vacua lie in the sweet spot, but at most only a tiny fraction of them will be exactly zero. If the vacua are distributed completely randomly, 90 percent of them will be somewhere in the range of  $0.1$  to  $1.0 \times 10^{-118}\Lambda_P$ . So if the landscape picture is right, a nonzero vacuum energy should be observed, most likely not much smaller than  $10^{-118}\Lambda_P$ .

In one of the most stunning developments in the history of experimental physics, recent observations of distant supernovae have shown that the visible universe's expansion is accelerating—the telltale sign of positive vacuum energy [see “Surveying Space-time with Supernovae,” by Craig J. Hogan, Robert P. Kirshner and Nicholas B. Suntzeff; *SCIENTIFIC AMERICAN*, January 1999]. From the rate of acceleration, the value of the energy was determined to be about  $10^{-120}\Lambda_P$ , just small enough to have evaded detection in other experiments and large enough for the anthropic explanation to be plausible.

The landscape picture seems to resolve the vacuum energy crisis, but with some unsettling consequences. Einstein asked whether God had a choice in how the universe was

Or we might even make direct astronomical observations of strings of cosmic size, which could have been produced in the big bang and then expanded along with the rest of the universe.

The picture that we have presented is far from certain. We still do not know the precise formulation of string theory—unlike general relativity, where we have a precise equation based on a well-understood underlying physical principle, the exact equations of string theory are unclear, and important physical concepts probably remain to be discovered. These may completely change or do away with the landscape of string vacua or with the cascade of bubbles that populate the landscape. On the experimental side, the existence of nonzero vacuum energy now seems an almost inevitable conclusion from observations, but cosmological data are notoriously fickle and surprises are still possible.

It is far too early to stop seeking competing explanations for the existence of vacuum energy and its very small size. But it would be equally foolish to dismiss the possibility that we have emerged in one of the gentler corners of a universe more varied than all the landscapes of planet Earth. ■

### MORE TO EXPLORE

**The Elegant Universe.** Brian Greene. W. W. Norton, 1999.

**A First Course in String Theory.** Barton Zwiebach. Cambridge University Press, 2004.

**The Cosmological Constant Problem.** Thomas Banks in *Physics Today*, Vol. 57, No. 3, pages 46–51; March 2004.

The official string theory Web site is at [www.superstringtheory.com/](http://www.superstringtheory.com/)