

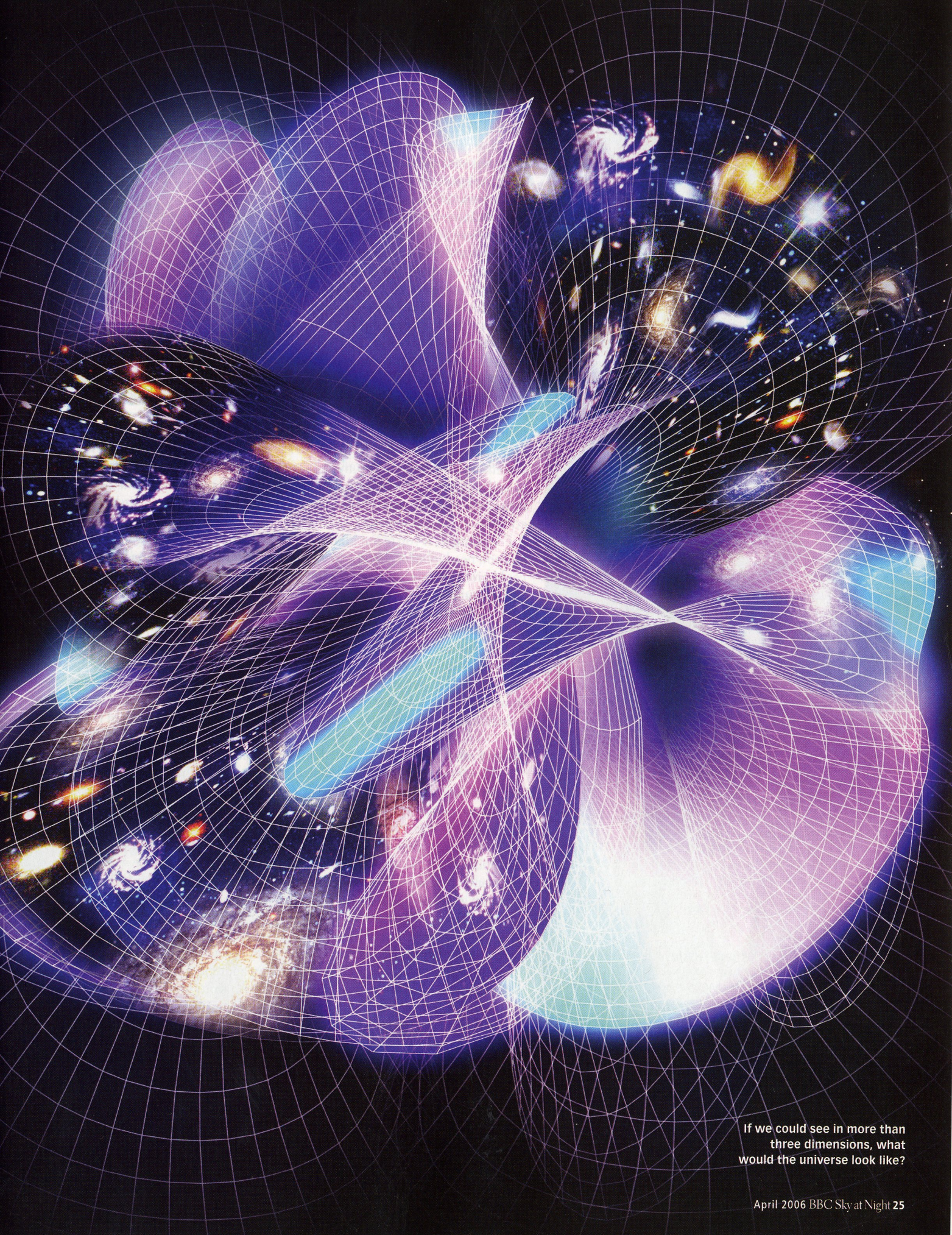
Search for the universe's hidden dimensions

[sarah reed discovers that there's more to the cosmos than the
three dimensions that humans are accustomed to]

Six years ago, as she crossed the Charles River in Cambridge, Massachusetts, the Harvard physicist Lisa Randall had an epiphany. Perhaps it was the river winding its way through this famous university city that led her to ponder our place in the universe. Perhaps it was the clear blue sky on this sunny day – she can't say for sure. What is certain

is that in that moment she had the striking thought that the universe could contain even more dimensions of space than the three in which we live out our lives on Earth.

Physicists are used to thinking strange thoughts. The complex mathematics that describes the Universe on the largest scales often throws up ideas that are so beyond the normal realm of possibilities that they're almost impossible to grasp. For ►



If we could see in more than
three dimensions, what
would the universe look like?

[Key words]

Reading about physics can be like studying a new language, so here's a vocabulary list to help you along

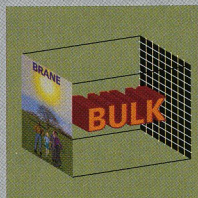


◀ BRANE

This is a slice of space-time that has fewer dimensions than the full, higher dimensional, space-time it exists in. All the particles and forces in our Universe, except gravity, may be trapped on a brane.

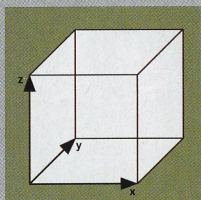
BULK ▶

The full, higher-dimensional space-time between branes. We experience four dimensions, including time. If space-time had an extra dimension, then the bulk would have five dimensions.



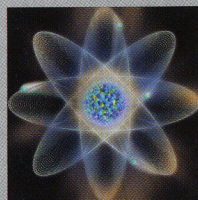
◀ DIMENSION

A direction in space-time. The number of dimensions tells you how many pieces of information are needed to uniquely specify an object's position in space-time.



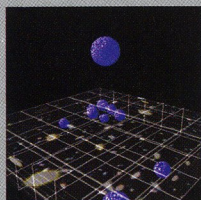
FUNDAMENTAL FORCES ▶

These are the weak nuclear force (radioactivity), strong nuclear force (confines quarks in subatomic particles), electromagnetic force and gravity. All processes involve one of these forces.



◀ GRAVITON

The particle that carries the gravitational force. In string theory, the graviton is produced by a closed string and so it isn't trapped on a brane like all other particles are.



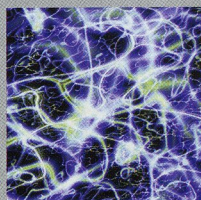
KALUZA-KLEIN (KK) PARTICLES ▶

The manifestation in our world of particles that travel in a higher-dimensional space. Originally, the idea came from Theodor Kaluza, pictured right, and Oskar Klein.



◀ STRING THEORY

This theory proposes all matter at the smallest level is made of tiny, vibrating filaments of energy, called strings. The frequency with which the string vibrates determines the type of particle.



THE STANDARD MODEL ▶

A theoretical model which says that at the smallest level, matter is composed of elementary particles. Every other particle in the Universe is made up of these elementary particles.



▶ Randall, though, the idea that extra dimensions might not be just a product of arcane maths, but a real working part of the universe, merely spurred her on to look deeper into the idea.

The crowning achievement of this research came late last year. With University of Washington physicist Andreas Karch, Randall suggested that our Universe is merely an island in a sea of universes with even higher dimensions and, moreover, that the number of these dimensions is far from random. According to their research, universes with three and seven dimensions will come to dominate.

But what exactly is a dimension anyway? Well, that's the easy part. By itself, a dimension is a piece of information that identifies where something is in space-time – the so-called 'fabric of the Universe' that consists of three dimensions of space and one dimension of time.

For example, if you're out hiking and you need to meet friends, you could give them the longitude, latitude and altitude for a spot, as well as the appointed time, and trust that they'll find you. Correspondingly, in a universe with more than three dimensions, you need more information to describe an event. In other words, the number of dimensions tells you how many bits of information you need.

Playing with strings

The idea that there might be more dimensions than the ones we directly experience comes from physics research known as 'string theory'. String theory proposes that everything that exists in nature, such as the electrons, neutrons and protons that make up atoms, is made of tiny strings – objects that are too small to detect in present-day experiments. Crucially, string theory requires extra dimensions in order to work.

String theory isn't new. The idea was first introduced in the 1960s, and since then it has received many makeovers. It wasn't until the 1980s, and a new incarnation known as 'superstrings', that it really started to split scientists. Until then, most physicists worked on the so-called 'standard model', which maintains that the building blocks of matter include various kinds of particles. But superstring theory is



simplicity itself. Everything is made of the same stuff – strings – even those fundamental particles. It's the frequency with which the strings vibrate that determines what kind of particle you get.

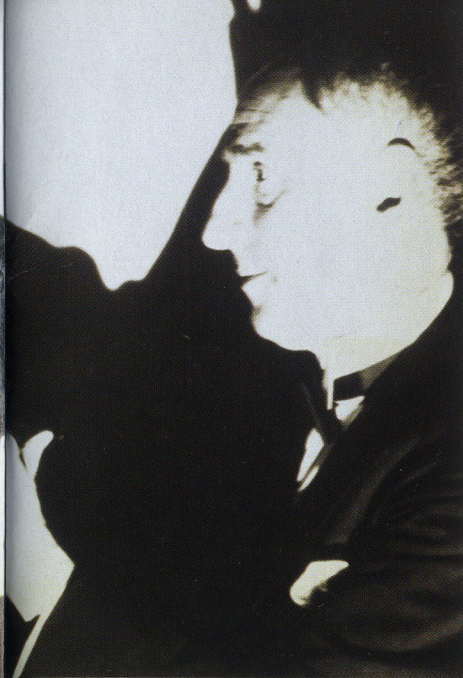
Some physicists stayed true to the standard model that had been the accepted framework for the past 30 years. Others saw strings as a better theory and jumped ship. One of those who jumped was the Japanese-American Michio Kaku, the renowned physicist who helped to come up with an elegant, inch-long, mathematical equation to describe string theory. Kaku believes the standard model is too "ugly" to be true. "It's like getting an aardvark, a giraffe and a platypus, then taping them all together, and then calling it nature's highest evolutionary achievement. Nature must be simpler than that," he insists.

Simplicity came at a price though, and that price was to change the dimensions we thought the universe had. Our familiar four-dimensional space-time was too cramped for string theory – it needed an additional six spatial dimensions in order to work. The trouble was that these extra dimensions, if they existed, would affect the laws of gravity unless they were extremely small.

The reason for this is that gravity would be dispersed along the extra

▶ String Theory proposes that everything is made up of tiny strings of energy





◀ Lose dimensions and you lose detail, much like these hands become a man

be noticeable. A three-dimensional particle simply couldn't pass through these curled-up regions that have extra dimensions, in the same way that a 2D painting like the Mona Lisa can never be truly three-dimensional no matter how lifelike it is. Instead, every particle would have a partner that could travel in extra dimensions – a Kaluza-Klein (KK) particle. Scientists have been looking for KK particles already, in giant machines called colliders that accelerate particles to enormous speeds and crash them into one another. So far, though, the mysterious KK particles have eluded discovery. This meant that either the extra dimensions were even smaller than one-billionth the size of an atom – and therefore beyond the reach of current particle colliders – or they didn't exist at all.

directions of these higher dimensions. According to Isaac Newton, the strength of gravity exerted by, say, a planet decreases inversely with the square of the distance away from it. So with extra dimensions, gravity would be diluted even more rapidly with distance. Clearly, that just doesn't happen on Earth or anywhere near it.

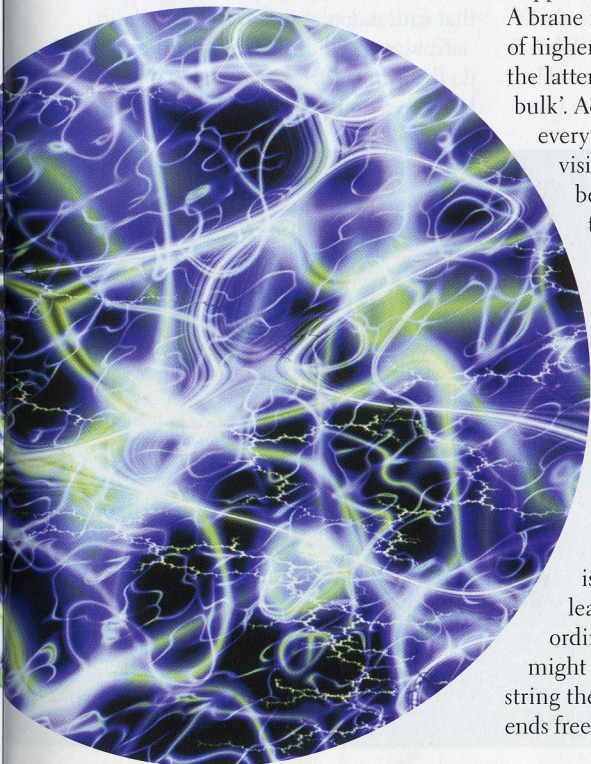
To get around this problem it was thought that the dimensions might be tiny and curled up – at their largest they'd be just one billionth the size of an atom. In other words, so small that they'd disperse gravity over such small distances that the effects wouldn't

The brane and the bulk

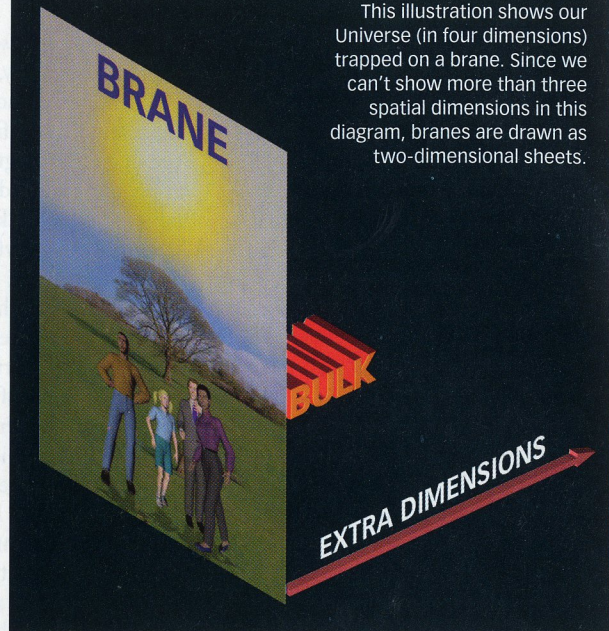
In time, though, another theory came along that might mean extra dimensions don't have to be tiny after all. It came in 1995, when another American physicist, Joe Polchinski of the Kavli Institute for Theoretical Physics in Santa Barbara, showed that both particles and forces could be trapped on something called a brane. A brane is a lower-dimensional slice of higher-dimensional space-time, the latter being referred to as 'the bulk'. According to Polchinski's idea,

everything we experience in our visible Universe, bar gravity, could be trapped on a single 3-brane, the number '3' referring to the number of dimensions of space. "You can think of a brane as us living on a piece of paper, a bit like an Egyptian frieze, but obviously we're not two-dimensional," explains Ruth Gregory, a physicist from Durham University.

One thing that can't be restrained on a brane, though, is gravity, and this is what leads us back to strings. Just like ordinary bits of string that you might use to tie a parcel, a string in string theory can be 'open' with both its ends free, or 'closed' in a loop that goes ▶



EXPLAINING THE BRANE



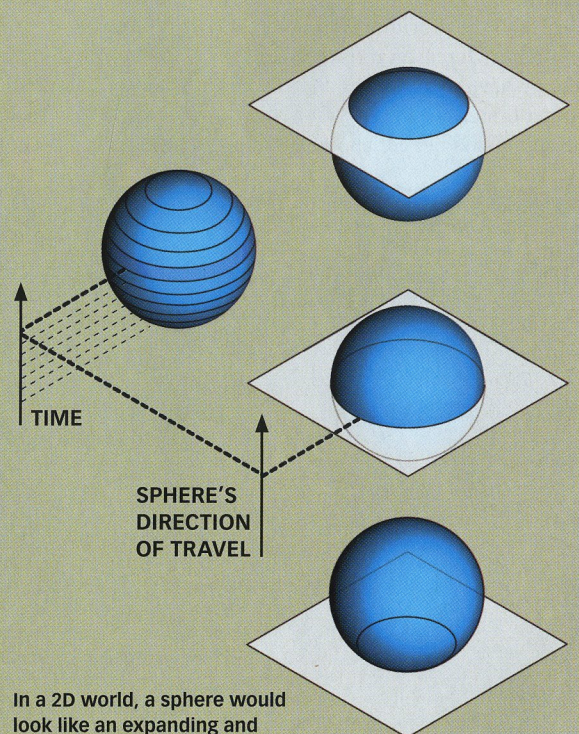
This illustration shows our Universe (in four dimensions) trapped on a brane. Since we can't show more than three spatial dimensions in this diagram, branes are drawn as two-dimensional sheets.

All about KK particles

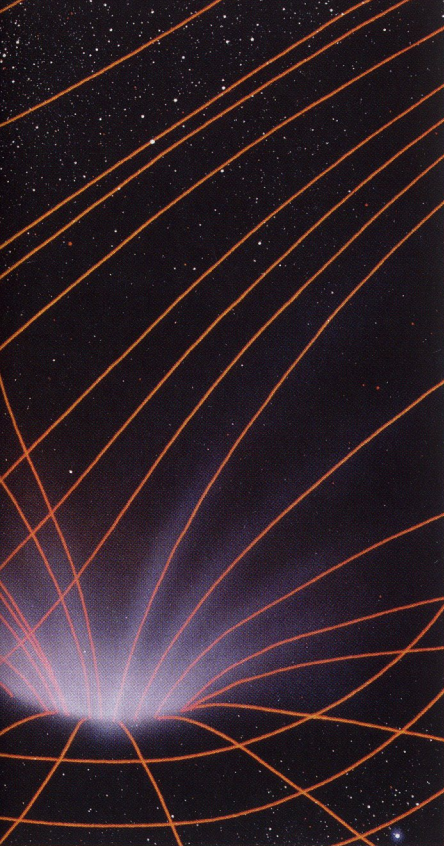
Kaluza-Klein particles may appear ordinary, but there's more to them than meets the eye

In our Universe, no object can have more than four dimensions, even if they are really higher dimensional. So KK particles manifest themselves as 4D objects instead. To imagine what this

might be like, consider Edwin Abbott's novel *Flatland*, in which a 3D sphere enters a 2D world. What the inhabitants of *Flatland* see are a sequence of circles increasing in size, and not the whole 3D sphere.



In a 2D world, a sphere would look like an expanding and contracting set of circles



graviton is free to move throughout the entire bulk, it is so unlikely to be found far from the brane that it may as well be restricted. Progress on these ideas was rapid. This extension to their work on warped geometry was released at the end of 1999 – only a couple of months after they published their first work on the subject.

Lisa Randall didn't stop there, however. The following year she collaborated with Andreas Karch, a physicist who had initially thought that Randall was wrong. He wasn't alone. At least Randall did have one famous

name on her side. "It was a radical new hypothesis, but some people knew the implications right away. Stephen Hawking was one of the first," she says.

Eventually, Karch warmed to her ideas and, together, the pair further investigated the geometry of branes. Previously, only flat branes had been considered. The argument went that energy tries to warp a brane, but energy in the higher-dimensional bulk fights back. The result: a flat brane. But Randall and Karch decided to give curved branes a try. They found that curved branes in a warped bulk would make it not just extremely unlikely to find a graviton far from the brane, but impossible. Gravity was safe.

Copernicus comes again

The idea was revolutionary. Gravity would only permeate an area close to the brane on which we live. Just as the famous astronomer Nicolaus Copernicus discovered that the Sun did not revolve around the Earth, so there'd be no reason to suppose that gravity, as we know it, existed elsewhere. "The history of physics has been discovering time and time again that we don't live at the centre of the Universe, and what we see isn't all there is. Now it seems we might not even see the same number of dimensions that the rest of the universe sees – it's the new Copernican revolution," Randall says.

This mind-boggling twist could mean that there's a collection of ►

[An expert answers]

Lisa Randall is professor of physics at Harvard University in Cambridge, Massachusetts, USA.



▲ Lisa Randall, rethinking the dimensions we live in

Who was the first scientist to suggest that extra dimensions exist?

In 1919, Theodor Kaluza introduced the idea of extra dimensions in his unsuccessful attempt to unify the forces of gravity and electromagnetism. Then in 1926, Oskar Klein suggested that extra dimensions could be very small and curled-up. That idea held until 1999, when Raman Sundrum's work and mine showed there is a radically different possibility.

How has the attitude of scientists towards extra dimensions changed?

Extra dimensions are definitely taken more seriously nowadays. Although scientists have been thinking about them for a while, extra dimensions now play a big role in experimental physics. Even some more conventional theories have been elevated to include extra dimensions.

What do you mean when you refer to yourself as a model builder?

As a model builder, I'm not restricted to the rules we think we have from string theory. I don't think we understand string theory well enough to know what it's going to tell us at the end of the day anyway.

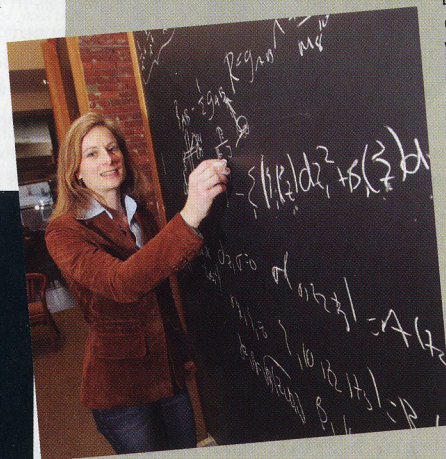
If we are on one of many branes, do we live in a multiverse?

The term 'universe' should technically encompass all branes and the higher dimensional bulk as well. However, each of the branes is often considered to be a separate universe and so the term 'multiverse' is often used instead.

Do you think we will ever have evidence for extra dimensions?

Gravitons interact so weakly that they haven't yet been detected in particle colliders. But in my models, the warping

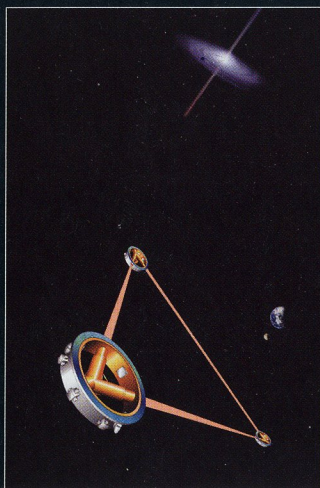
of space-time means the partners of the graviton that travel in the bulk will interact much more strongly than the graviton does. This means that if higher dimensional partners of the graviton do actually exist, the Kaluza-Klein representation of them will be detected in the new particle accelerator, the Large Hadron Collider.



▲ Lisa Randall needs a big blackboard to do her sums

Why does string theory require 10 dimensions?

Basically the theory wouldn't make sense if it didn't include extra dimensions. Without them, it would make nonsensical predictions like probabilities greater than one, or negative probabilities.



[Laser Interferometer Space Antenna]

NASA's gravitational wave detector spacecraft, the Laser Interferometer Space Antenna (LISA) is due for launch in 2015. It is actually three craft arranged in a giant equilateral triangle.

LISA will help to look for evidence of extra dimensions by trying to prove that strings exist. This evidence could come from ripples in the fabric of space-time, called gravitational waves. According to string theory, gravitational waves with particular frequencies will have been formed in the early Universe. Detecting waves with these frequencies would be indirect evidence for string theory, which relies on extra dimensions to work.

Cosmology

► branes with different dimensions out there: 5D, 7D or 9D for example, each with its own type of gravity. We can only imagine what worlds like these would be like. "I think it would be hard for life to form in a world with higher dimensional gravity. Gravity's strength would diminish rapidly with distance, so planets with stable orbits around a star couldn't form. But it is certainly possible," Karch says.

So what kind of branes might be out there? Well, they may not be so different after all. Randall and Karch have recently shown that the universe might select certain branes as its favourites, like a child picking out her favourite-coloured sweets from a tube of Smarties.

"The universe might have started off with higher dimensions, say a 10-dimensional universe, and the first stage of evolution might be when the 3-brane sort of gets singled out – we realised that branes with three spatial dimension are special. You might start off with a whole bunch of branes of many different dimensions and they dilute as the universe expands. And what we found is that 3-branes and 7-branes are special and, at the end of the day, they will come to dominate," explains Randall.

A special part of the cosmos

The point about 3-branes is the key one for us. The research shows that there is a good reason why 3-branes, like the one we live on, exist. It seems, then, that our part of the cosmos is indeed special after all, even if the rest of the universe doesn't consist of exactly the same number of dimensions.

In the space of only seven years, Lisa Randall has come up with some truly extraordinary ideas about what the universe is and how it is all joined together. This spurt of research has happened at just the right time. Next

year, the most powerful particle collider ever built, the Large Hadron Collider, will be switched on. The Large Hadron Collider may well have the high energies that scientists require in order to find the first direct evidence of those elusive extra dimensions.

Randall is excited by the prospect. "If these extra dimensions do play a role in particle physics there will be evidence, and that would take the form of Kaluza-Klein particles.

These are particles that travel in the extra dimensions.

So what I'm hoping they find when they turn on the Large Hadron Collider at CERN are the Kaluza-Klein partners of the graviton."

And that's just the beginning; other Earth-bound experiments are already being prepared to test these theories,

including the neutrino detector at the South Pole, as well as in space aboard NASA's LISA spacecraft. "The study of extra dimensions has found an arena, whereas before it was just playing around with exotic ideas," says Ruth Gregory.

Although the theories are already in place, it will be the next few years that are the most crucial. If those experiments don't produce the hoped-for answers, Lisa Randall acknowledges that she may have to go back to the drawing board. If the worst happens, she could be taking another stroll across the Charles River, on another sunny day, waiting for inspiration to strike once more. ✪

[FIND OUT MORE]

Warped Passages, Lisa Randall, Penguin, 2005

Parallel Worlds, Michio Kaku, Penguin, 2006

CERN: <http://public.web.cern.ch/Public/Welcome.html>

LISA: <http://lisa.jpl.nasa.gov/>

IceCube: <http://icecube.wisc.edu/>



▲ Randall's theories could have the impact of Copernicus's, above

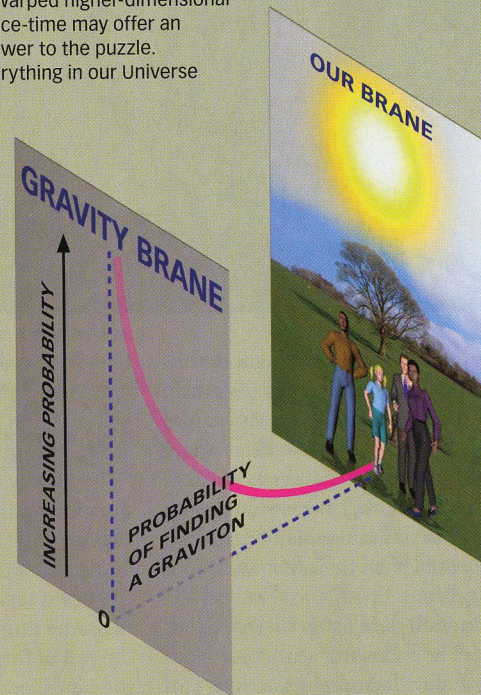
[Why is gravity weak?]

Extra dimensions could provide the answer to the perennial puzzle of why it is so easy to beat gravity

It may surprise you at first that the weakness of gravity is a big unanswered problem in physics. But consider a small magnet lifting a pin off a table – that small magnet has defeated gravity.

Warped higher-dimensional space-time may offer an answer to the puzzle. Everything in our Universe

could be trapped on a brane, with gravity on another brane. Therefore, gravity could actually be as powerful as the other fundamental forces – we simply wouldn't experience its full strength.



[THE HOLOGRAPHIC UNIVERSE]

Forget for a moment the idea of extra dimensions. Some scientists think we live in a world with just two dimensions of space, the third being a kind of illusion. The idea takes its name from the familiar optical hologram – a hologram is actually two-dimensional, but if you look at it at the right angle, a three-dimensional objects appears to leap out at you.

