Lisa Randall, one of the world's most influential physicists, explains why we need more than three dimensions to understand the cosmos

Why I believe in higher dimensions

Scientific progress always entails an almost contradictory set of beliefs. You need to make assumptions to build a mathematical picture of reality. But while you want to be sufficiently excited about your assumptions to think they merit investigation, you need to remain sceptical enough to subject the consequences of those premises to rigorous analysis.

Although I've always combined these attitudes in my research, my recent studies of extra dimensions of space, beyond the familiar "up-down", "left-right" and "forward-backward", have made me more than usually convinced that they must really exist.

Perhaps the best way to understand what these extra dimensions would be is the way Edwin Abbott described them in his book *Flatland*, written in the late 19th century. Suppose there was a society that, unlike ours, could detect and experience a world with only two dimensions: the Flatland of the title. Its inhabitants wouldn't perceive a third dimension, even though the dimension really did exist. If an object like a sphere were to pass through their universe, Flatlanders would never perceive it in its entirety; instead, they would see a succession of disks that grew in size and then became smaller. Because they register only two dimensions, Flatlanders could only mathematically piece together the fact that the object they had seen was the analogue of their disk, but in one higher dimension.

Similarly, the fact that we see only three dimensions doesn't mean there might not be more. Einstein's theory of general relativity doesn't stipulate any particular number of dimensions. And from the perspective of his theory of gravity, there's nothing special about three dimensions of space. People have often made the mistake of believing only in what they could see. Extra dimensions might turn out to be one among many aspects of the cosmos about which we were initially mistaken.

String theory is another reason to believe extra dimensions might exist. It consistently incorporates our theories of the very small and the very big in the universe – quantum mechanics and general relativity – which no earlier theory had accomplished. This doesn't prove string theory is right, and it's critical that we do further research. Because it promises to be a more comprehensive theory than any other we know of, a so-called theory of quantum gravity, string theory is well worth studying.

However, it doesn't naturally describe a world with three dimensions of space. It more naturally suggests a world with many more, perhaps nine or 10. A string theorist doesn't ask whether extra dimensions exist; instead, two critical questions that a string theorist asks are: where are they and why haven't we seen them? Even if you're sceptical about string theory, recent research has provided perhaps the most compelling argument for extra dimensions: a universe with these dimensions might contain answers to physics puzzles that have no convincing solutions without them. That alone makes extra dimensions worthy of investigation.

The history of physics is the story of discovering different, more basic elements of matter as we've developed the tools to explore different length and energy scales. Once scientists could observe matter on smaller scales, they discovered atoms and quarks, and after they could study further distances in the universe, physicists and astronomers discovered galaxies and dark matter. Extra dimensions might be hidden (for now) but none the less be part of reality. More detailed observations at higher energies and shorter distances might eventually reveal their existence.

These as-yet-unseen dimensions could be flat, like the dimensions we are accustomed to. Or they could be warped, like reflections in a fun-house mirror. They might be tiny, far smaller than an atom, or they might be big, or even infinite in size, yet still be hard to see. Our senses register only three large dimensions, so an infinite extra dimension might sound incredible. But an infinite unseen dimension and parallel universes within it are some of the bizarre possibilities for what might exist in our cosmos.

To see why extra dimensions are not ruled out by our apparently three-dimensional observations, we need to understand how dimensions can exist, but be invisible. In 1920, almost immediately after Einstein completed his theory of general relativity, Theodor Kaluza suggested an extra dimension of space, and in 1926, Oskar Klein proposed a reason why we wouldn't see it. An extra dimension could be rolled up into such a tiny size that it would have no visible effects. If you think of extra dimensions rolled up like a garden hose, the width of the "hose" could be so tiny that we'd never notice it. Any variations over this tiny distance would be washed out, much as the atomic structure of this piece of paper is imperceptible.

But although physicists have known for years that extra dimensions could be rolled up, it wasn't until 1999 that Raman Sundrum (who was then a post-doctoral fellow at Boston University) and I (then a professor at MIT) discovered another reason that extra dimensions might be hidden. Einstein's theory of relativity tells us that energy and matter curve space and time. We found that spacetime with extra dimensions could be so extremely warped that even an infinite extra dimension could exist but escape detection. The success with which our theory mimics three dimensions suggests that all evidence that apparently points to three dimensions of space supports the idea of such "warped" extra-dimensional universes equally strongly. None the less, our idea was so different from older notions that it took a while for some physicists to accept. Fortunately for us, however, Stephen Hawking and a few others immediately appreciated its radical implications.

The following year another physicist, Andreas Karch, and I found that space can be even more spectacular: the universe can appear to have three spatial dimensions in some regions but appear to have, or in fact have, more (or fewer) in others. Our notion of three-dimensional "sinkholes" extended the Copernican revolution beyond anything we had imagined. Not only is the Earth not the centre of the universe, but our domain might be a tiny isolated pocket with three spatial dimensions inside a universe that harbours many more. This was a huge revelation, one that convinced me we have a lot more to understand about extra dimensions of space, and one that also made the idea of extra dimensions more credible; isn't it presumptuous to rule out something whose implications we don't even fully comprehend?

> 'An extra dimension could be rolled up like a garden hose'

But perhaps the most convincing reason to believe in extra dimensions is that they permit new connections among properties of the observed universe and have a real possibility for explaining some of its more mysterious features. Extra dimensions can have implications for the world we see and explain phenomena that seem incomprehensible when viewed from the perspective of a three-spatial-dimensional observer (or theorist). We wouldn't understand the shapes of the continents unless we add the dimension of time and recognise how they were once connected together in a supercontinent. Similarly, some problems in physics are more readily understood with extra dimensions of space.

Chief among these questions is why the gravitational force is so weak. Gravity might not appear to be all that weak when you're hiking up a mountain, but bear in mind that the gravitational force of the entire Earth is acting on you. Think how feeble gravity must be for you to counter the force of the much larger Earth when you pick up a ball. In fact, if the Earth were your size, gravity wouldn't be noticeable at all. For more than 30 years, physicists (including myself) have explored this conundrum, and they've found no completely compelling solution.

But with an additional warped dimension, it's natural for gravity to be weak in our vacinity. In our warped spacetime geometry, gravity is very strong in one region of a fourth dimension of space (a fifth dimension of spacetime) but very weak everywhere else. For me, the explanation for the weakness of gravity is sufficient reason in itself to take the possibility of extra dimensions seriously. The mystery is the biggest gaping hole in our understanding of the physics of elementary particles, and an extra dimension provides an answer.

As a scientist, even if I believe that extra dimensions exist in nature, I don't have blind faith and I'm willing to be proved wrong. We don't yet know how to experimentally test all extra-dimensional theories. But the fabulous thing is that if the theory I just told you about – the one that explains the weakness of gravity – is correct, we will see experimental evidence within the next five years.

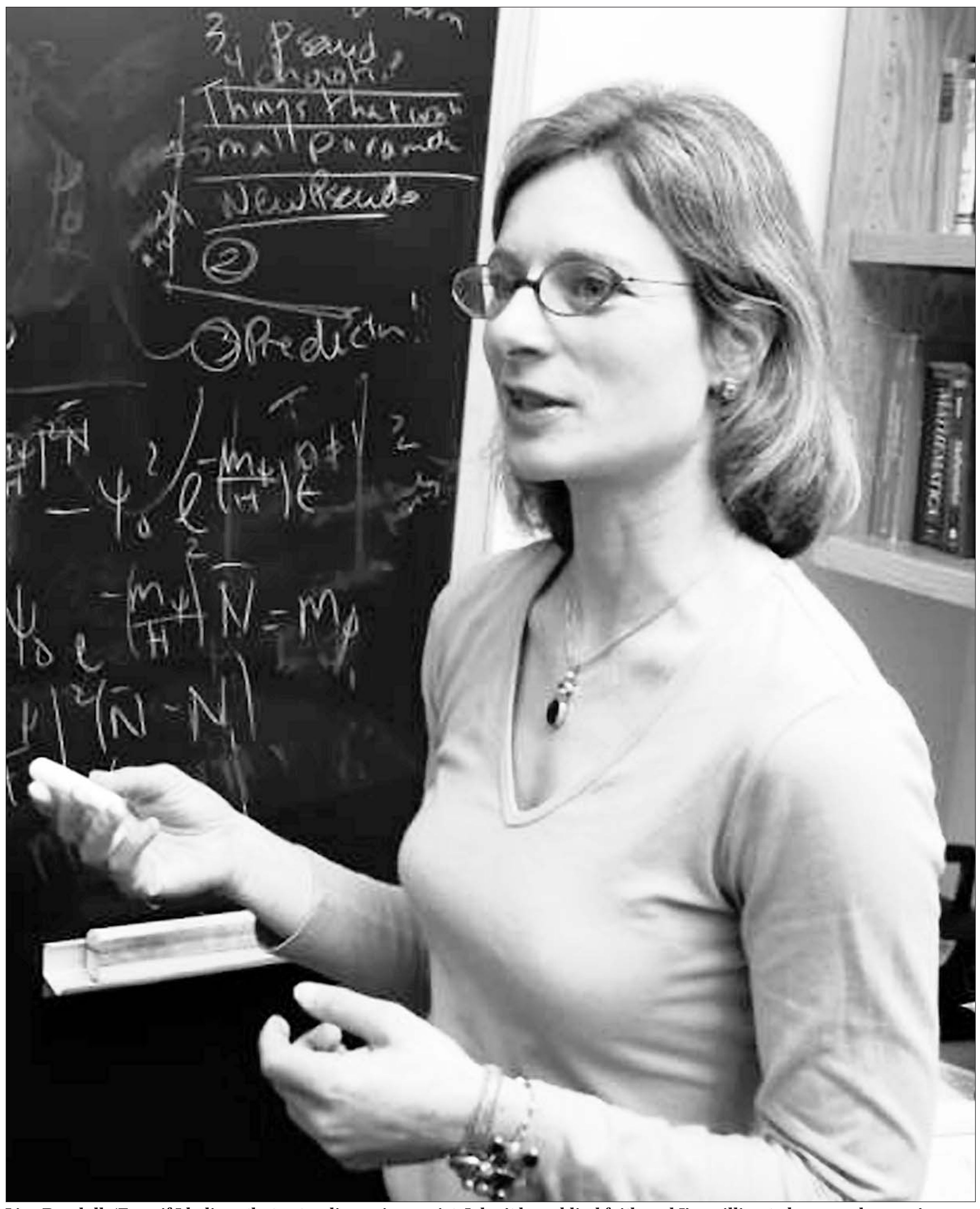
These tests that high-energy experimenters will perform are critical to confirming (or ruling out) our ideas.

The evidence will take the form of Kaluza-Klein particles, which are 1,000 times smaller than the proton and travel in extra dimensions, but would register in experiments as extra-heavy particles in what appears to be a three-spatial-dimensional world. If warped extra dimensions explain the weakness of gravity, the Large Hadron Collider that will begin operation at CERN in Geneva in two years will have enough energy to make such particles (you need lots of energy to make heavy particles, as we know from Einstein's most famous equation, $E=mc^2$). If experimenters discover them, my belief in extra dimensions will be proved justified.

Those of us who no longer straitjacket ourselves to theories with only three dimensions of space have found amazing consequences of Einstein's equations that had escaped physicists for years. The range of possibilities for what might lie in the cosmos are remarkable, and we're still only beginning to understand them all. I'm fairly confident new dimensions are out there and it's more a question of if and when we'll find them. Given how much extra dimensions – or whatever we discover – will tell us about the fundamental nature of our universe, do we have any choice but to explore?

Lisa Randall is professor of theoretical physics at Harvard University. Her new book, Warped Passages *(Penguin), is available for £18 + £2.25 p&p. To order, call Telegraph Books Direct on 0870 155 7222.*

Prof Randall will be speaking on "Hidden Dimensions" at the Cheltenham Science Festival, Saturday, June 11. Tel: 01242 227979, email boxoffice @cheltenham.gov.uk or visit cheltenhamfestivals.org.uk.



Lisa Randall: 'Even if I believe that extra dimensions exist, I don't have blind faith and I'm willing to be proved wrong'

Vote for the future face of science

FameLab, the nationwide talent hunt for the new faces of science, reaches its climax next week at the Cheltenham Science Festival. Readers can vote for the 12 finalists, based on video performances, at Channel 4's FameLab website, channel4.com/famelab.

Bleep is the *mot juste* for quantum misery

Prof Steve Jones
View from the lab

Documentaries are the latest wave in films. *Fahrenheit 9/11* and *Spellbound* – one based on spilling blood, the other on spelling bees – gained a global audience. According to the *New York Times*, 80 of last year's 500 American releases fall into that category. They include *What the Bleep do We Know?*, a big hit in the US, screened here a couple of weeks ago. It claims to be about quantum physics but is instead, I have to report, the higher – the highest – tosh.

We can, apparently, change the molecular structure of water by writing "Love" or "Hate" on the bottle; and because we ourselves are 60 per cent water, physics explains unhappiness.

Why do people waste time on absurd ideas based on the language of science but the logic of blind belief? Flat earths, intelligent designers and quantum misery: all are feeble, for they turn on the evidence from opinion. Science has opinions based on evidence and everyone can gain something from it. Quantum theory is mostly above my head but full of surprises.

The idea turns on the notion that on a minute scale light and matter act as both as particles and as waves. The crucial experiment shot electrons (which, at rest, behave much like particles, with a mass of their own) through two tiny slits in a screen – and, like waves on a pond, they showed a pattern of interference with each other as they emerged on the other side. The cosmic snag is that the act of measurement alters the system: we cannot as a result know both an electron's speed and its position. Heisenberg, the architect of that uncertainty idea was stopped for speeding. He was asked: "Professor, have you any idea how fast you were going?" "No," he replied , "but I know exactly where I am!"

***Bleep* does the job with basketballs – but that makes no sense, for they are far too big. Those who believe that life is quantum need to know where the process stops, and Newtonian physics takes over. Newton certainly works for apples and – everyone once assumed – for biology too.**

However, largish objects can also behave in an uncertain way. Buckminsterfullerene – the 60-carbon molecule that looks like a football – shows quantum interference when fired through paired slits, although it is many times bigger than a hydrogen atom. The goalkeeper in a quantum football game would be in trouble, for the molecule could, in effect, swerve around both sides of him before reconnecting at the back of the net.

The carbon football is far smaller than anything that can be seen in the cell – but now a biological molecule has been shown to have a quantum nature, given the chance. Porphyrin is responsible for the colour of green plants, and of red blood. To everyone's surprise, the molecule, when shot through paired slits, shows interference, just like a wave. The Austrians who did the research suggest that even small viruses might go in for a touch of the quantum in the right conditions. But what are those consitions? As Heisenberg realised, that mysterious world turns on a certain lack of information. As we learn more about an object, it is forced to edge into the Newtonian universe of speed cameras, where velocity and position can be measured at the same time. For porphyrin, any collision with other molecules says something about where it must be, as its neighbours rebound from the blow. Large molecules have internal vibrations that hint at their location; and as things get warmer their energy acts as a beacon, revealing what must be kept secret to pass the Heisenberg test. A quantum cell could exist only in an ice cold vacuum, unsuited to life.

I was chatting to the Duke of Edinburgh the other day, and he too was interested in porphyrin. His blue blood descends from George III – who had an inherited problem with the chemical because of an error in the way he broke down his blood cells. George's illness was distressing, and some of his descendants might also have had the disease. Fortunately, science has come up with treatments (today, Porphyria Awareness Day, celebrates that fact). The Duke had not seen *Bleep*; but given his scepticism about New Age nonsense it would no doubt receive a right royal kick up the backside, with position and speed carefully calculated.

Steve Jones is professor of genetics at UCL