THEORY OF EVERYTHING

Michael Duff

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INSTANT EXPERT

12

FOUR FUNDAMENTAL FORCES

What holds the quarks and leptons, or building-block particles, together? As far as we can tell, there are four fundamental forces: gravity, which keeps Earth going round the sun; electromagnetism, responsible for phenomena such as light and electricity; the weak nuclear force, responsible for radioactivity; and the strong nuclear force, which binds neutrons and protons in the atomic nucleus.

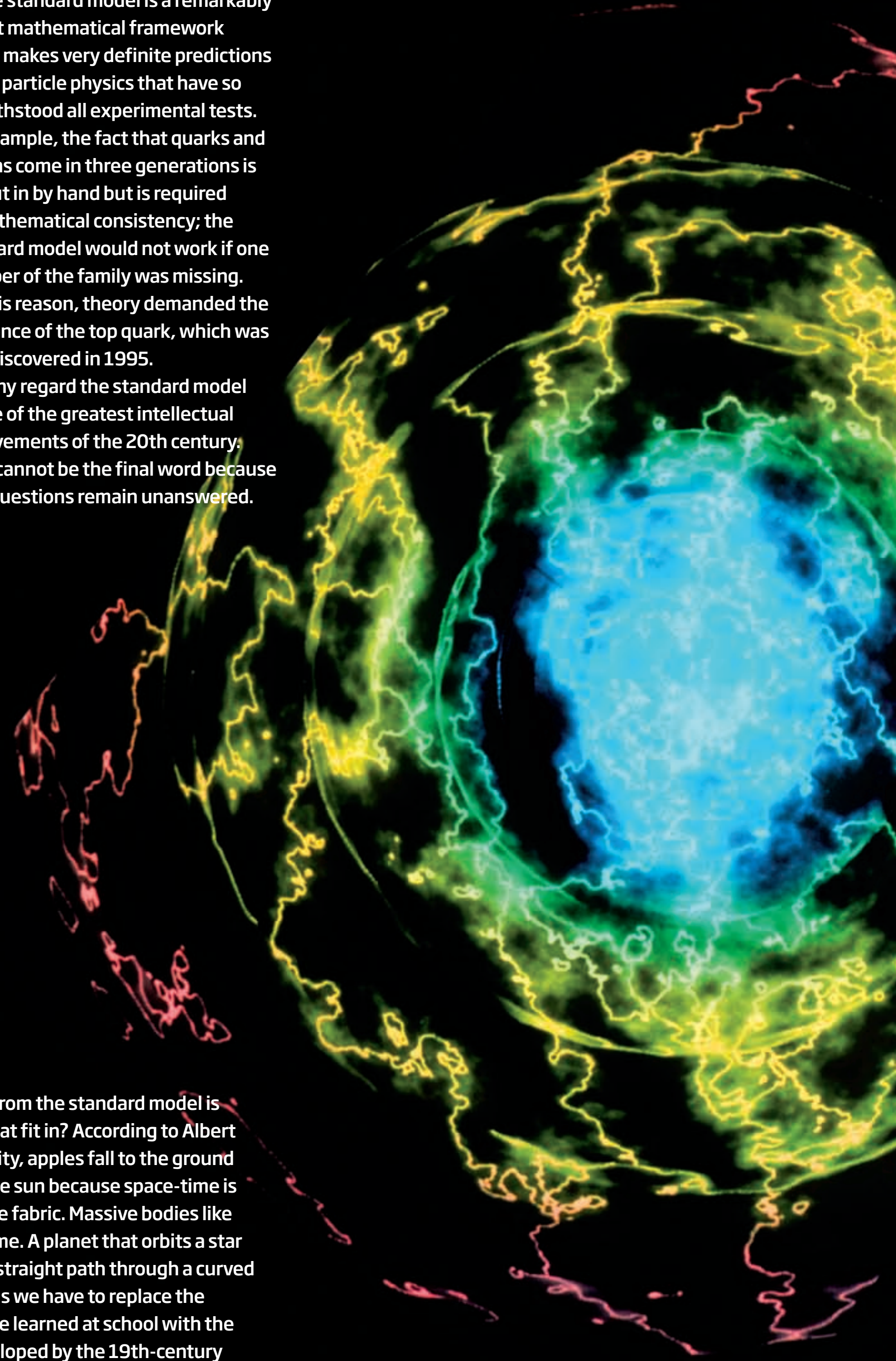
But what exactly is a force? The modern view is based on a theoretical framework called quantum field theory. This says that the forces between building-block particles are carried or "mediated" by another set of particles. The most familiar of these is the photon, the mediator of the electromagnetic force. When two electrons repel one another, they do so by swapping a photon. This idea was backed up so well by experiments that theorists invented other force-carrying particles: the gluon for mediating the strong force, and the W and Z particles for the weak force.

Sure enough, the existence of the gluon and W and Z was confirmed in the 1970s and 80s. When you put all this together with the as yet undiscovered Higgs boson, whose job it is to give particles their mass, you get the standard model of particle physics.

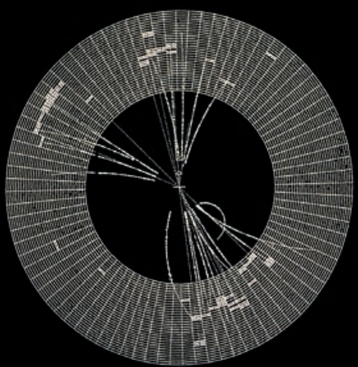
The standard model is a remarkably robust mathematical framework which makes very definite predictions about particle physics that have so far withstood all experimental tests. For example, the fact that quarks and leptons come in three generations is not put in by hand but is required by mathematical consistency; the standard model would not work if one member of the family was missing. For this reason, theory demanded the existence of the top quark, which was duly discovered in 1995.

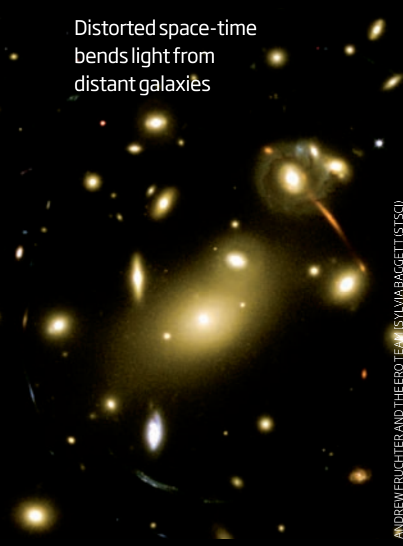
Many regard the standard model as one of the greatest intellectual achievements of the 20th century. Yet it cannot be the final word because vital questions remain unanswered.

ARSCIMED/SPL BELOW: DESY/NASA



The gluon's discovery was a boost for the standard model





Distorted space-time bends light from distant galaxies

ANDREW FRUCHTER AND THE ERO TEAM (SYLVIA BAGGETT (STSCI) RICHARD HOOK (ST-ECF); ZOLTAN LEVAY (STSCI))/NASA

GRAVITY

One glaring omission from the standard model is gravity; where does that fit in? According to Albert Einstein's view of gravity, apples fall to the ground and the Earth orbits the sun because space-time is an active and malleable fabric. Massive bodies like the sun bend space-time. A planet that orbits a star is actually following a straight path through a curved space-time. This means we have to replace the Euclidean geometry we learned at school with the curved geometry developed by the 19th-century mathematician Bernhard Riemann.

Einstein's description of gravity has been confirmed by watching light from a distant star being bent around the sun during a total solar eclipse. This is a very different picture of a force from that given by the standard model of particle physics, which says that forces are carried by particles. Extending this idea would suggest that gravity is mediated by a force-carrying particle known as the graviton.

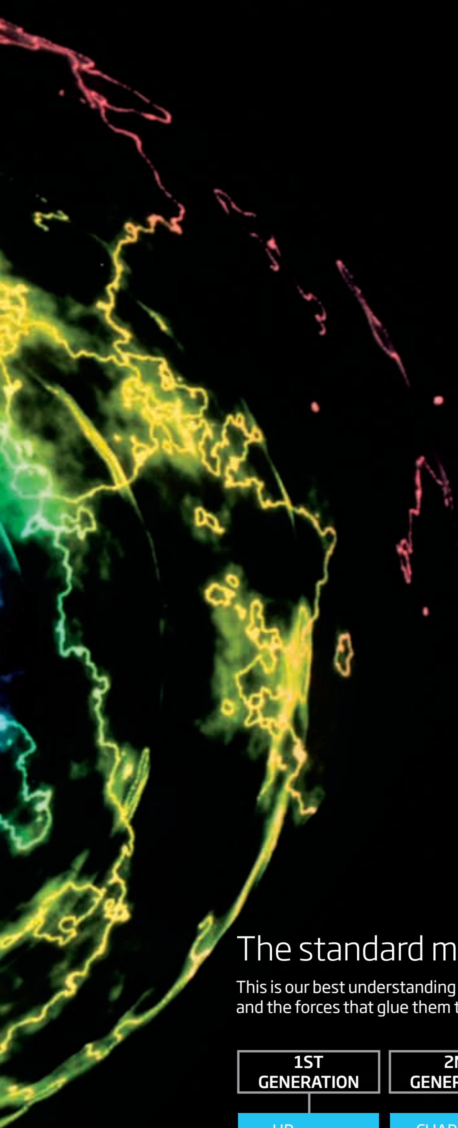
THE BIG QUESTIONS

Theoretical physicists like to ask big questions. How did the universe begin? What are its fundamental constituents? And what are the laws of nature that govern those constituents? If we look back over the 20th century, we can identify two pillars on which our current theories rest.

The first is quantum mechanics, which applies to the very small: atoms, subatomic particles and the forces between them. The second is Einstein's general theory of relativity, which applies to the very large: stars, galaxies and gravity, the driving force of the cosmos.

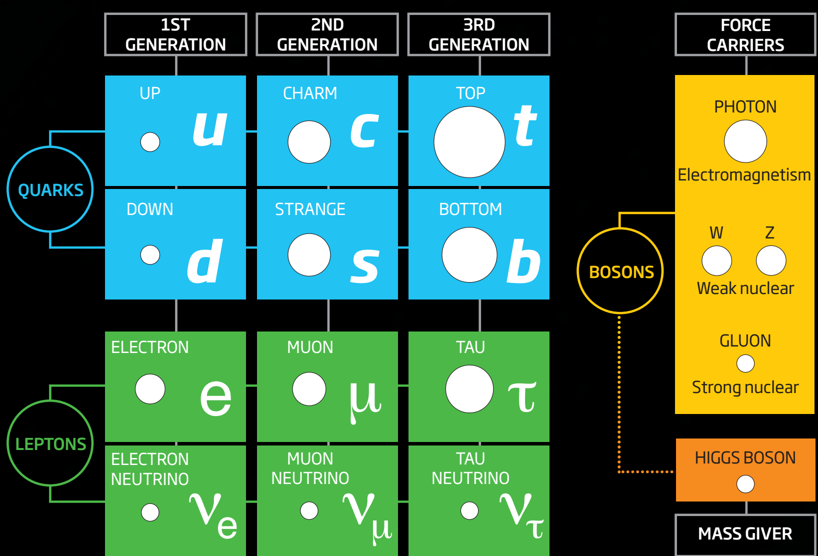
The problem we face is that the two are mutually incompatible. On the subatomic scale, Einstein's theory fails to comply with the quantum rules that govern the elementary particles. And on the cosmic scale, black holes are threatening the very foundations of quantum mechanics. Something has to give.

An all-embracing theory of physics that unifies quantum mechanics and general relativity would solve this problem, describing everything in the universe from the big bang to subatomic particles. We now have a leading candidate. Is it the much anticipated "theory of everything"?



The standard model

This is our best understanding of the building blocks of matter and the forces that glue them together



BUILDING BLOCKS

At the end of the 19th century, atoms were believed to be the smallest building blocks of matter. Then it was discovered that they have a structure: a nucleus made of protons and neutrons, with electrons whizzing around it. In the 1960s, the atom was divided even further when it was theorised, then confirmed by experiments, that protons and neutrons are composed of yet smaller objects, known as quarks.

Do these layers of structure imply an infinite regression? All the theoretical and experimental evidence gathered so far suggests not: quarks really are the bottom line. We now believe that quarks are fundamental building blocks of matter along with a family of particles called the leptons, which includes the electron (see table, left).

More or less everything we see in the world around us is made from the lightest quarks and leptons. The proton consists of two up quarks and one down quark, while a neutron is made of two downs and one up. Then there is the electron along with the electron neutrino, an extremely light particle involved in radioactivity.

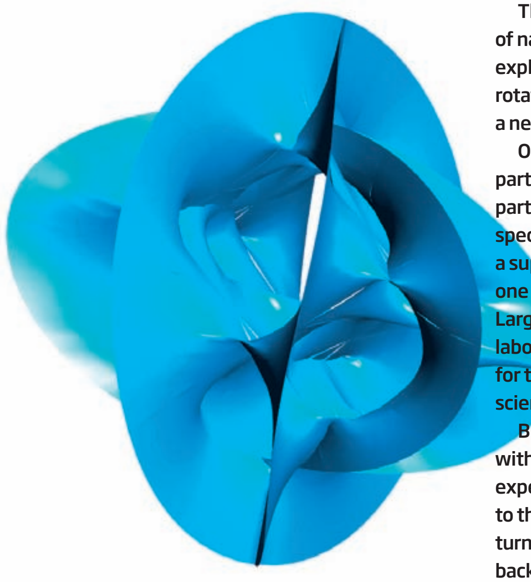
Nature is not content to stop there. There are two more "generations" of quarks and leptons which are like the first, but heavier. In addition, all these particles have antimatter partners which have the same mass but opposite charge.

"Supersymmetry offers a connection between the properties of quantum particles and space-time"

2. SUPERSYMMETRY

The quarks and leptons that make up matter seem very different to the particles that carry nature's forces. So it came as a great surprise in the 1970s when theorists showed that it is possible to construct equations which stay the same when you swap the two around.

This suggests the existence of a new symmetry of nature. Just as a snowflake's underlying symmetry explains why it can look the same even after you rotate it, so the equivalence of particles is down to a new symmetry, called supersymmetry.



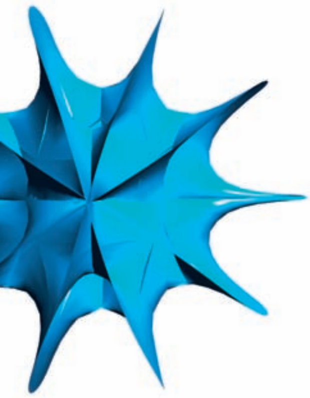
One prediction of supersymmetry is that every particle in the standard model has a supersymmetric partner, thereby doubling the number of particle species. Enormous energies are required to make a supersymmetric particle, which may be why no one has found one yet. Experiments at the powerful Large Hadron Collider at the CERN particle physics laboratory near Geneva, Switzerland, are looking for them. Finding one would rank among the biggest scientific discoveries of all time.

But there is a reason why theorists are so enamoured with supersymmetry despite 40 years without experimental evidence: it predicts gravity. According to the mathematics of supersymmetry, the act of turning an electron into its supersymmetric partner and back again is identical to moving it through space-time.

This means supersymmetry offers a connection between the properties of quantum particles and space-time, making it possible to incorporate gravity, too. The resulting theory that incorporates the gravitational force and supersymmetry is known as supergravity.

The mathematics of supergravity has an unexpected consequence: space-time can have no more than 11 dimensions. In the early 1980s this prompted a revival of the Kaluza-Klein idea, with up to seven curled-up dimensions. Could these extra dimensions describe the strong, weak and electromagnetic forces?

At first supergravity looked extremely promising, but problems crept in. For a start, 11-dimensional supergravity has trouble describing how quarks and electrons interact with the weak nuclear force. Even more serious is a problem that has dogged all other attempts to reconcile gravity and quantum field theory: when you use supergravity's equations to calculate certain quantum-mechanical processes, the answer is infinity. This makes no sense and is a sure sign that supergravity is at best only an approximation to a viable theory of everything. For these reasons, attention turned to a rival approach called superstring theory.

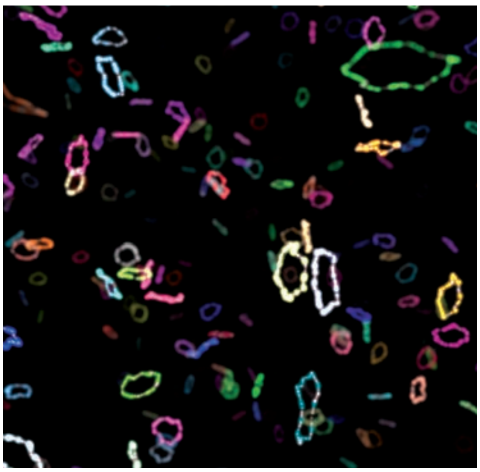


3. THE SUPERSTRING REVOLUTION

In superstring theory, the fundamental building blocks of matter are not point-like particles. Instead they are one-dimensional strings that live in a universe with 10 space-time dimensions. Just like violin strings, they can vibrate in various modes, each one representing a different elementary particle. Certain string vibrations can even describe gravitons, the hypothetical carriers of the gravitational force.

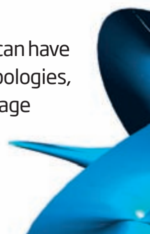
To begin with, superstring theory looked like a theorist's dream. The six extra dimensions could be curled up in such a way as to avoid the problems with the weak force encountered by 11-dimensional supergravity. Also, superstring theory looked just like general relativity when the graviton energy was set sufficiently small. But the most important feature was that the infinities and anomalies that had plagued previous attempts to apply quantum field theory to general relativity no longer existed.

Here, for the first time, was a consistent way to unify gravity with quantum mechanics. Theorists went wild. But after the initial euphoria, doubts began to creep in.

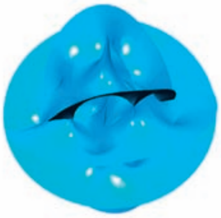


LAGUNA DESIGN/SPL RIGHT: EQUINOX GRAPHICS/SPL

Point-like particles have given way to strings



Extra dimensions can have many different topologies, as shown on this page



THE ROAD TO UNIFICATION

Many attempts have been made to reconcile Einstein's theory of gravity with the quantum description of the other three forces of nature. The latest and most ambitious is called M-theory and it contains three radical ingredients: extra dimensions of space-time, supersymmetry, and extended objects called superstrings and membranes.

ALEX WILD

1. EXTRA DIMENSIONS

One of the earliest attempts at unifying the forces of nature was made in the 1920s, when German physicist Theodor Kaluza melded Einstein's gravitational theory with the electromagnetic theory of James Clerk Maxwell.

The universe we live in appears to have four dimensions. Space has three – right-left, forwards-backwards and up-down – and the fourth is time. Kaluza rewrote Einstein's theory as if there were five space-time dimensions. This gives the gravitational field some extra components which he thought could be interpreted as Maxwell's electromagnetic field. Amazingly, he showed that these extra components precisely matched Maxwell's equations. So electromagnetism comes for free if you are willing to buy a fifth dimension for gravity.

Why can't we see a fifth dimension? In 1926, Swedish physicist Oskar Klein came up with an answer. He supposed that the fifth dimension is not like the other four, but is instead curled up into a circle that is too small to see.

To see how this works, consider a simpler analogy: an ant on a tightrope. As well as walking along the tightrope, the ant can choose to walk around its circumference at any point. Only the ant is aware of the additional circular dimension. Viewed from a distance much, much larger than the ant's size, the rope looks very different: it is essentially a one-dimensional line and the extra dimension is hidden.

This is how Klein envisaged Kaluza's five-dimensional universe and his calculations even showed how small the extra dimension should be curled up. At 10^{-35} metres across, the fifth dimension is too small to probe even with the most powerful particle accelerators, which act as windows into the subatomic realm. Hence we have the impression that we live in a four-dimensional world.

Kaluza and Klein's idea lay dormant for many years. In some ways it was ahead of its time, partly because we knew so little about the weak and strong forces. It was revived by the arrival of supersymmetry.

THE M-THEORY REVOLUTION

All the work on strings, membranes and 11 dimensions was brought together in 1995 by Edward Witten, the string-theory guru at the Institute for Advance Study in Princeton, under one umbrella called M-theory. M, he says, stands for magic, mystery or membrane according to taste.

Witten showed that the five different string theories and 11-D supergravity were not rival theories at all. They were merely different facets of M-theory. Having one unique theory was a huge step forward. It also turned out that M-theory and its membranes were able to do things strings alone could not.

Take black holes, for example, which are excellent laboratories for testing our theories. In 1974, Stephen Hawking showed that black holes are not entirely black – instead they can radiate energy due to quantum effects. This means that black holes have temperature and another thermodynamic property called entropy, which is a measure of how disorganised a system is.

Hawking showed that a black hole's entropy depends on its area. Yet it should also be possible to work out its entropy by accounting for all the quantum states of the particles making up a black hole. However, all attempts to describe a black hole in this way had failed – until M-theory came along. Amazingly, M-theory exactly reproduces Hawking's entropy formula. This success gave us confidence that we were on the right track .

In 1998, Juan Maldacena, also of the Institute for Advanced Study, used membranes to explore what would happen inside a hypothetical universe with many dimensions of space and gravity. He showed that everything happening on the boundary of such a universe is equivalent to everything happening inside it: ordinary particles interacting on the boundary's surface correspond precisely to how membranes interact on the interior. When two mathematical approaches describe the same physics in this way, we call it a duality.

This duality is remarkable because the world on the surface of the universe looks so different to the world inside. If Maldacena's idea is applied to our universe, it could mean that we are just shadows on the boundary of a higher-dimensional universe.

Maldacena's paper has been cited over 7000 times. This is partly because his idea has found applications in unexpected areas of physics, including superconductivity and fluid mechanics, regardless of whether M-theory is the theory of everything or not.

More recently, my colleagues and I have found yet another area of physics to which M-theory can be applied: the black-hole/qubit correspondence. A classical bit is the basic unit of computer information and takes the value 0 or 1. A quantum bit, or qubit, can be both 0 and 1 at the same time. Only when we measure it do we fix which one it is, and the outcome cannot be predicted with certainty. This gives rise to the phenomenon of entanglement between two or more qubits, where measuring one qubit affects the other no matter how far apart they are. Einstein called this effect "spooky action at a distance".

For reasons we do not fully understand, the mathematics that describes qubit entanglement is exactly the same as that which governs certain black holes in M-theory. It turns out that these black holes fall into 31 classes, depending on their mass, charge and entropy. We recently used this to predict that four qubits can be entangled in 31 different ways. This can, in principle, be tested in the lab and we are urging experimentalists to find ways of doing just that.

Events at the boundary of a universe reveal what is happening inside

PLAINPICTURE/AMANAIMAGES RIGHT: WILFRID HOFFACKER/PLAINPICTURE

In 1990, Edward Witten won the Fields medal, the mathematics equivalent of the Nobel prize. This shows just how closely mathematics and string theory tie together

Juan Maldacena's work showed that the physics inside a region of space can be described by what happens on its boundary. While his idea originated in M-theory, it has gone on to revolutionise many areas of theoretical physics, making Maldacena one of today's most influential physicists

Particles may be more like bubbles in a world with extra dimensions

DANMCCOY/SCIENCE FACTION/CORBIS

Our leading candidate for a theory of everything is known as M-theory. It grew from a merger of the two seemingly different approaches: 11-dimensional supergravity and 10-dimensional superstring theory. Could this be the final theory of everything?

BRANE POWER

Superstring theory had some serious shortcomings. One problem is that there is not one, but five, mathematically consistent superstring theories, each competing for the title of the theory of everything. We faced an embarrassment of riches.

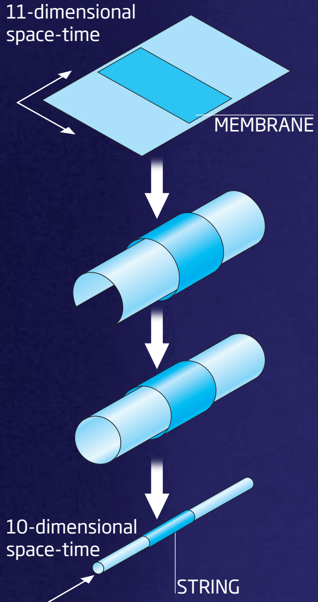
A second puzzle soon became apparent, too. Supersymmetry says that the universe has a maximum of 11 dimensions, yet the mathematics of superstring theory states there should be 10. What gives? And there was a related question: why stop at one-dimensional strings? Why not two-dimensional membranes which might take the form of a sheet or the surface of bubble?

It turns out that supersymmetry and membranes do go together. Just as superstrings live in 10 dimensions, it was calculated in 1987 that "supermembranes" can live in an 11-dimensional space-time dictated by supergravity.

Moreover, if the 11th dimension is curled up, as Kaluza and Klein's early work suggested it could be, then it is possible to wrap the membrane around it. If curled up tightly enough, this wrapped membrane would look like a string in 10 dimensions.

Despite these attempts to revive 11 dimensions with the new ingredient of membranes, most string theorists remained sceptical. For many years there were two camps: string theorists with their 10-dimensional theory, and the membrane theorists working in 11 dimensions. It wasn't clear whether they were on the same page or not.

A membrane in 11 dimensions can be rolled up to appear as a string in 10 dimensions. The two are equivalent



A LANDSCAPE OF UNIVERSES

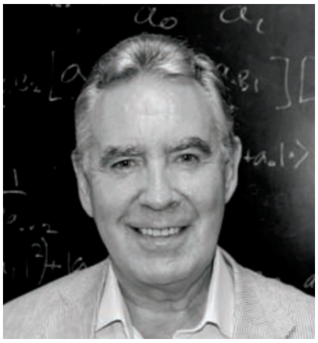
The geometrical and topological properties of the curled-up extra dimensions dictate the appearance of our four-dimensional world, including how many generations of quarks and leptons there are, which forces exist, and the masses of the elementary particles. A puzzling feature of M-theory is that there are many (possibly infinitely many) ways of curling up these dimensions, leading to a "multiverse" – a number of different universes. Some may look like ours, with three generations of quarks and leptons and four forces; many will not. But from a theoretical point of view they all seem plausible.

The traditional view is that there is one universe and a unique set of fundamental laws. The alternative view, which is gaining credibility, says that there are multiple universes out there with different laws of physics, and one of these universes just happens to be the one we are living in. Each of these universes must be taken seriously.

So is M-theory the final theory of everything? In common with rival attempts, falsifiable predictions are hard to come by. Some generic features such as supersymmetry or extra dimensions might show up at collider experiments or in astrophysical observations, but the variety of possibilities offered by the multiverse makes precise predictions difficult.

Are all the laws of nature we observe derivable from fundamental theory? Or are some mere accidents? The jury is still out.

In my opinion, many of the key issues will remain unresolved for quite some time. Finding a theory of everything is perhaps the most ambitious scientific undertaking in history. No one said it would be easy.


IMPERIAL COLLEGE LONDON

Michael Duff

Michael Duff holds the Abdus Salam Chair of Theoretical Physics at Imperial College London

NEXT INSTANT EXPERT
Linda Gottfredson
INTELLIGENCE
2 July

ANSWERING THE CRITICS

The job of theoretical physicists is twofold: first, to explain what our experimental colleagues have discovered; and second, to predict phenomena that have not yet been found. The history of scientific discovery shows that progress is achieved using both methods.

Quantum theory, for example, was largely driven by empirical results, whereas Einstein's general theory of relativity was a product of speculation and thought experiments, as well as advanced mathematics.

Speculation, then, is a vital part of the scientific process. When Paul Dirac wrote down his equation describing how quantum particles behave when they travel close to the speed of light, he wasn't just explaining the electron, whose properties had been well established in experiments. His equation also predicted the hitherto undreamed-of positron, and hence the whole concept of antimatter.

Such speculation is not a flight of fancy. It is always constrained by the straightjacket of mathematical consistency and compatibility with established laws. Even before it was tested experimentally, Einstein's theory of general relativity had to pass several theoretical tests. It had to yield special relativity and Newtonian mechanics in those areas where they were valid, as well as predict new phenomena in those where they were not.

It is a common fallacy that physics is only about what has already been confirmed in experiments. Commentators in this magazine have unfairly compared the study of cosmic strings – macroscopic objects that may have been formed in the early universe – to UFOs and homeopathy, on the grounds that cosmic strings have yet to be observed (*New Scientist*, 9 February 2008, p 22). Another stated that until M-theory is backed by empirical evidence, it is no better than "faith" (*New Scientist*, 11 September 2010, p 5).

Yet support for superstrings and M-theory is based on their ability to absorb quantum mechanics and general relativity, to unify them in a mathematically rigorous fashion, and to suggest ways of accommodating and extending the standard models of particle physics and cosmology. No religion does that.

By the same token, some alternative ideas purporting to be theories of everything have had to be rejected even before their predictions could be tested – not on the grounds of faith but because they were mathematically erroneous. What separates theoretical speculation from faith is that we modify or reject theories in the light of new evidence and discovery.

The most effective way for critics of M-theory to win their case would be to come up with a better alternative. So far nobody has.

RECOMMENDED READING AND LINKS

"The membrane at the end of the universe" by Michael Duff and Christine Sutton, *New Scientist*, 30 June 1988, p 67

"The theory formerly known as strings" by Michael Duff, *Scientific American*, February 1998, p 64

"The illusion of gravity" by Juan Maldacena, *Scientific American*, November 2005, p 56

The Elegant Universe: Superstrings, hidden dimensions and the quest for the ultimate theory by Brian Greene (Vintage, 2005)

The Grand Design: New answers to the ultimate questions of life by Stephen Hawking and Leonard Mlodinow (Bantam Press, 2010)

"Four-bit entanglement from string theory" by Leron Borsten and others, arxiv.org/abs/1005.4915

The official string theory website superstringtheory.com

Cover image
Equinox Graphics/SPL