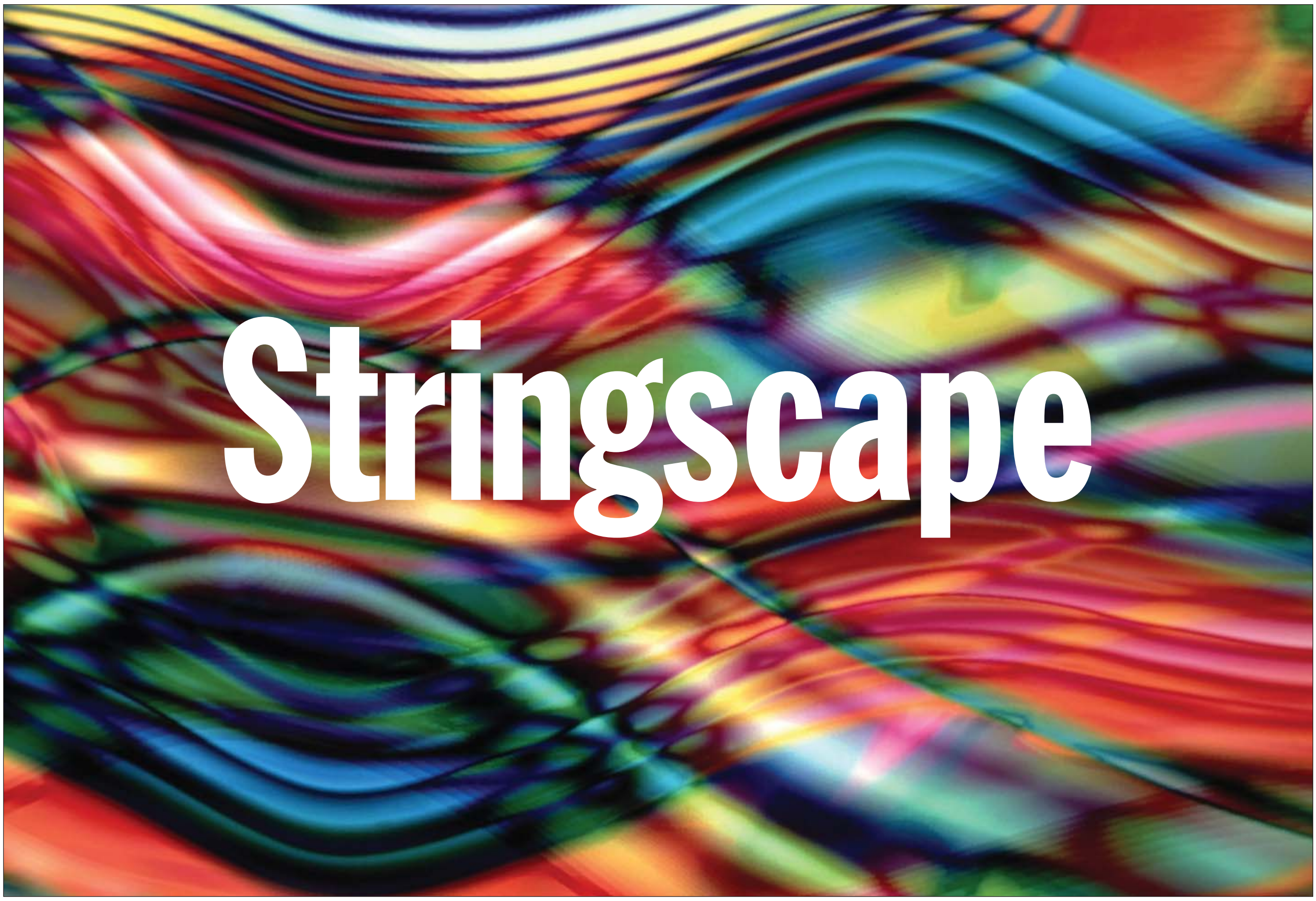

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Stringscape

In its near 40-year history, string theory has gone from a theory of hadrons to a theory of everything to, possibly, a theory of nothing. Indeed, modern string theory is not even a theory of strings but one of higher-dimensional objects called branes. **Matthew Chalmers** attempts to disentangle the immense theoretical framework that is string theory, and reveals a world of mind-bending ideas, tangible successes and daunting challenges – most of which, perhaps surprisingly, are rooted in experimental data

Matthew Chalmers is Features Editor of *Physics World*

Problems such as how to cool a 27 km-circumference, 37 000 tonne ring of superconducting magnets to a temperature of 1.9 K using truck-loads of liquid helium are not the kind of things that theoretical physicists normally get excited about. It might therefore come as a surprise to learn that string theorists – famous lately for their belief in a theory that allegedly has no connection with reality – kicked off their main conference this year – Strings07 – with an update on the latest progress being made at the Large Hadron Collider (LHC) at CERN, which is due to switch on next May.

The possibility, however tiny, that evidence for string theory might turn up in the LHC's 14 TeV proton–proton collisions was prominent among discussions at the five-day conference, which was held in Madrid in late June. In fact, the talks were peppered with the language of real-world data, particles and fields – particularly in relation to cosmology. Admittedly, string theorists bury these more tangible concepts within the esoteric grammar of higher-dimensional mathematics, where things like "GUT-branes", "tadpoles" and "warped throats" lurk. However, Strings07 was clearly a physics event, and not one devoted to mathematics, philosophy or perhaps even theology.

But not everybody believes that string theory is physics pure and simple. Having enjoyed two decades of being glowingly portrayed as an elegant "theory of everything" that provides a quantum theory of gravity and unifies the four forces of nature, string theory has taken a bit of a bashing in the last year or so. Most of this criticism can be traced to the publication of two books: *The Trouble With Physics* by Lee Smolin of the Perimeter Institute in Canada and *Not Even Wrong* by Peter Woit of Columbia University in the US, which took string theory to task for, among other things, not having made any testable predictions. This provided newspaper and magazine editors with a great hook for some high-brow controversy, and some reviewers even went as far as to suggest that string theory is no more scientific than creationism (see *Physics World* February pp38–39).

Some of the criticism is understandable. To most people, including many physicists, string theory does not appear to have told us anything new about how the world really works despite almost 40 years of trying. "Sadly, I cannot imagine a single experimental result that would falsify string theory," says Sheldon Glashow

At a Glance: String theory

- String theory implies that “elementary particles” are just manifestations of a more fundamental layer of nature described by 1D strings 10^{-35} m in length
- The theory emerged in 1968 from attempts to describe the strong force, but it soon graduated to being a potential “theory of everything” that could unify gravity with the other three forces in nature
- String theory is a framework that describes all the fundamental interactions in terms of the string tension, but this elegant picture only holds true in a 10D world that is supersymmetric
- In order to describe our asymmetric 4D world, researchers have to find ways to “compactify” the extra dimensions and break supersymmetry – leading to a vast “landscape” of at least 10^{500} solutions
- Controversially, some researchers have invoked the anthropic principle to interpret the string-theory landscape, but others are holding out for some kind of dynamical selection principle
- Since 1995 researchers have known that string theory is actually a theory of higher-dimensional objects called branes, which facilitate deep mathematical connections called dualities
- In certain cases, these dualities make string theory equivalent to quantum field theory, and suggest that string theory has a unique 11D formulation called M-theory
- Despite not having made a clear prediction that might rule it out, string theory has given physicists a better understanding of black holes and provided an analytical tool for studying an extreme state of matter called the quark–gluon plasma
- Evidence for string theory may also turn up at the Large Hadron Collider at CERN in the form of new particles, and cosmological data are providing further avenues to test string theory
- As our best working theory of quantum gravity, string theory could help answer questions that no other theory can tackle, such as the nature of the Big Bang singularity

of Harvard University, who shared the 1979 Nobel Prize for Physics for his role in developing the unified electroweak theory that forms the core of the Standard Model of particle physics. “I have been brought up to believe that systems of belief that cannot be falsified are not in the realm of science.”

String theory is certainly unprecedented in the amount of time a theoretical-physics research programme has been pursued without facing a clear experimental test. But while one can debate whether it has taken too long to get this far, string theory is currently best thought of as a theoretical framework rather than a well-formulated physical theory with the ability to make specific predictions. When viewed in this light, string theory is more like quantum field theory – the structure that combines quantum mechanics and special relativity – than the Standard Model, which is a particular field theory that has been phenomenally successful in describing the real world for the last 35 years or so.

Ed Witten of the Institute for Advanced Study (IAS) at Princeton University, who is widely regarded as the leading figure in string theory, admits that it is difficult for someone who has not worked on the topic to understand this distinction properly. “String theory is unlike any theory that we have dealt with before,” he says. “It’s incredibly rich and mostly buried underground. People just know bits and pieces at the surface or that they’ve found by a little bit of digging, even though this so far amounts to an enormous body of knowledge.”

Some critics also slam string theory for its failure to answer fundamental questions about the universe that only it, as our best working model of quantum gravity, can seriously address. Some of these questions, says David Gross of the University of California at Santa Barbara (UCSB) – who shared the 2004 Nobel prize for his work on quantum chromodynamics (QCD) – have been around since the days of quantum mechanics. “String theory forces us to face up to the Big Bang singularity and the cosmological constant – problems that have either been ignored until now or have driven people to despair,” he says.

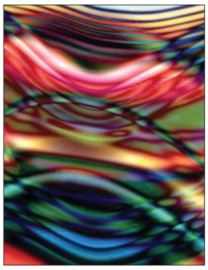
Gross also thinks that many people expect string theory to meet unfairly high standards. “String theory is full of qualitative predictions, such as the production of black holes at the LHC or cosmic strings in the sky, and this level of prediction is perfectly acceptable in almost every other field of science,” he says. “It’s only in particle physics that a theory can be thrown out if the 10th decimal place of a prediction doesn’t agree with experiment.”

So what is stopping string theory from making the sort of definitive, testable predictions that would settle once and for all its status as a viable theory of nature? And why does the prospect of working on something that could turn out to be more fantasy than physics continue to attract hundreds of the world’s brightest students? After all, a sizable proportion of the almost 500 participants at Strings07 were at the very beginning of their careers. “I feel that nature must intend for us to study string theory because I just can’t believe that humans stumbled across something so rich by accident,” says Witten. “One of the greatest worries we face is that the theory may turn out to be too difficult to understand.”

Irresistible appeal

In some ways, string theory looks like a victim of its own success. It did not seek to bridge the two two pillars of modern physics – quantum mechanics and Einstein’s general theory of relativity – while simultaneously unifying gravity with the three other basic forces in nature: electromagnetism, the strong and the weak forces. Rather, string theory began life in 1970 when particle physicists realized that a model of the strong force that had been proposed two years earlier to explain a plethora of experimentally observed hadrons was actually a theory of quantum-mechanical strings (see box on page 39).

In this early picture, the quarks inside hadrons appear as if they are connected by a tiny string with a certain tension, which meant that the various different types of hadrons could be neatly organized in terms of the different vibrational modes of such 1D quantum strings. Although this model was soon superseded by QCD – a quantum field theory that treats particles as being point-like rather than string-like – it soon became clear that the stringy picture of the world was hiding something



> String theory is a theory of the “DNA” of a universe, but we only get to study a single “life form” – our own local patch of space. It’s as though Gregor Mendel had only a single pea and a simple magnifying glass to work with, from which he was expected to discover the double helix and the four bases A, C, G and T
>
> **Leonard Susskind**, Stanford University

altogether more remarkable than mere hadrons.

One of several problems with the initial hadronic string model was that it predicted the existence of massless "spin-2" particles, which should have been turning up all over the place in experiments. These correspond to vibrations of strings that are connected at both ends, as opposed to the "open" strings the harmonics of which described various hadrons. But in 1974 John Schwarz of the California Institute of Technology and others (see box on page 39) showed that these closed loops have precisely the properties of gravitons: hypothetical spin-2 particles that crop up when you try to turn general relativity, a classical theory in which gravity emerges from the curvature of space–time, into a quantum field theory like the Standard Model. Although the fundamental string scale had to be some 10^{20} orders of magnitude smaller than originally proposed to explain the weakness of the gravitational force, string theory immediately presented a potential quantum theory of gravity.

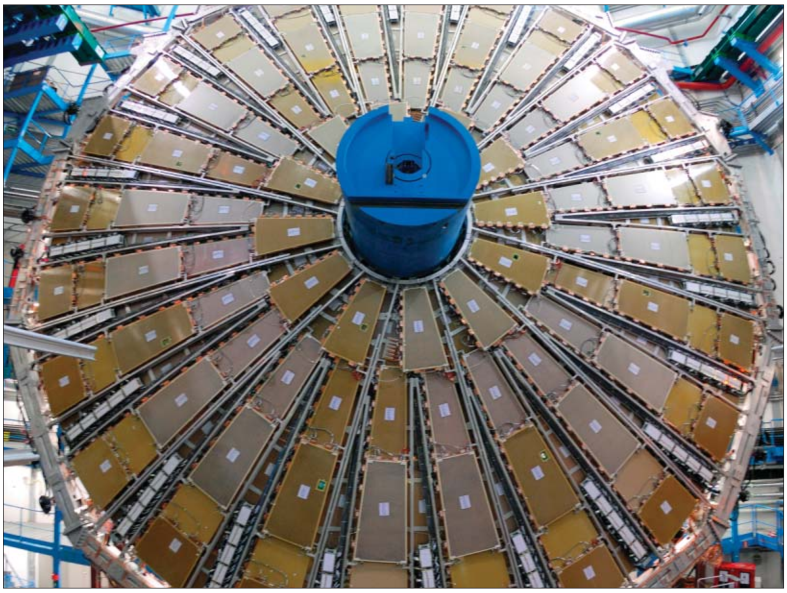
"Quantum field theories don't allow the existence of gravitational forces," says Leonard Susskind of Stanford University, who in 1970 was one of the first to link hadrons with strings. "String theory not only allows gravity, but gravity is an essential mathematical consequence of the theory. The sceptics say big deal; the string theorists say BIG DEAL!"

String theory succeeds where quantum field theory fails in this regard because it circumvents the short-distance interactions that can cause calculations of observable quantities to diverge and give meaningless results. In the Standard Model – which is based on the gauge symmetry or gauge group SU(3) × SU(2) × U(1), where SU(3) is QCD and SU(2) × U(1) the unified electroweak theory – elementary particles interact by exchanging particles called gauge bosons. For instance, photons mediate the electromagnetic interaction, which is described by the original and most successful field theory of all time: quantum electrodynamics (QED), which was developed by Feynman and others in the 1940s.

String theory is different to religion because of its utility in mathematics and quantum field theory, and because it may someday evolve into a testable theory (aka science)
Sheldon Glashow, Boston University

Pictorially, these interactions take place where and when the space–time histories or "world lines" of point-like particles intersect, and the simplest of such Feynman diagrams corresponds to the classical limit of the quantum theory. Provided the strength of the underlying interaction – which is described by the coupling constant of the theory, or the fine-structure constant in the case of QED – is weak, theorists can calculate the probabilities that certain physical processes occur by adding up all the quantum "loop" corrections to the basic underlying diagram (see box on page 42).

When trying to incorporate gravity into the Standard Model, however, such "perturbative expansions" of the theory (which amount to power series in the coupling constant) go haywire. This stems from the fact that Newton's gravitational constant is not dimensionless like, say, the fine-structure constant. As a result, gravitons – which arise from quantizing the space–time metric in general relativity – lead to point-like interactions with infinite probabilities. String theory gets round this by replacing the 1D paths traced out by point-like particles in space–time with 2D surfaces swept out by strings. As a result, all the fundamental interactions can be described topologically in terms of 2D "world sheets" splitting and reconnecting in space–time. The probability that such interactions occur is given by a single parameter – the string tension – and the short-distance divergences never arise. "String theory grew up as the sum of the analogue of Feynman diagrams in 2D," says Michael Green of Cambridge University in the UK. "But working out the rules of 2D perturbation theory is only the start of the problem."

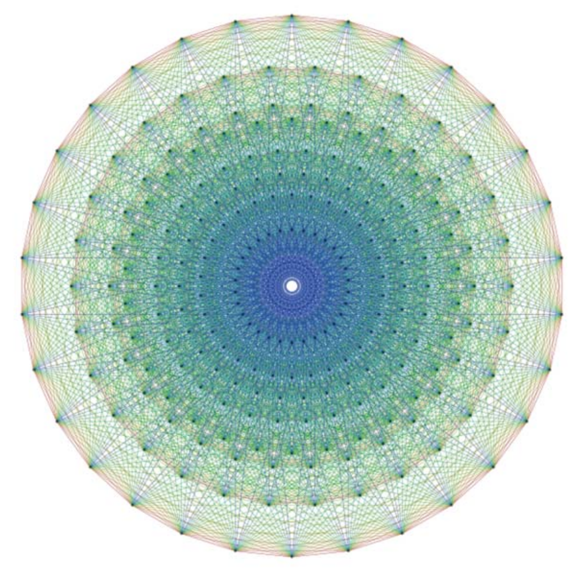


CERN

Hidden dimensions High-energy collisions at CERN's Large Hadron Collider might be sufficient to excite harmonics of the fundamental string, which would appear as new particles in, for example, the ATLAS detector.

This is because perturbation theory only works if space–time has some rather otherworldly properties, one of which is supersymmetry. While the strings in the initial hadronic theory were bosonic (i.e. their vibrations corresponded to particles such as photons that have integer values of spin in units of Planck's constant), the world is mostly made up of fermions – particles such as electrons and protons, which have half-integer spins. In the mid-1970s Schwarz and others realized that the only way string theory could accommodate fermions was if every bosonic string vibration has a supersymmetric fermionic counterpart, which corresponds to a particle with exactly the same mass (and vice versa). String theory is thus shorthand for superstring theory, and one of the main goals of the LHC is to find out whether such supersymmetric particles actually exist.

The other demand that string theory places on space–time is a seemingly ridiculous number of dimensions. The original bosonic theory, for example, only respects Lorentz invariance – an observed symmetry of space–time that states there is no preferred direction in space – if it is formulated in 26 dimensions.



Pretty weird The complex root systems of the symmetry group E_8, which is important in heterotic string theory, resides in 8D (shown here in 2D).

Superstrings require a more modest 10 dimensions: nine of space and one of time. But in order to explain the fact that there are only three spatial dimensions, string theorists have to find ways to deal with the additional six, which is usually done by "compactifying" the extra dimensions at very small scales.

"To call them extra dimensions is a misnomer in some sense because everything is granular at the Planck [string] scale," says Green. "Because they are defined quantum mechanically, they should be thought of as some kind of internal space–time structure." Indeed, while the job of string theorists would be much easier if the universe was 10D and not 4D, the fact that strings have six extra dimensions into which they can vibrate can account for the otherwise mysterious intrinsic properties of elementary particles, such as their spins and charges.

Superstring revolutions

In 1984 Green and Schwarz sparked what is now referred to as "the first superstring revolution", when they showed that the quantum-mechanical anomalies in superstring theory (for example those that violated gauge invariance) cancelled when the theory was formulated in 10D and had a particular symmetry group, SO(32). This not only meant that string theory was highly constrained and thus a viable physical theory, but also that it incorporated the Standard Model symmetry group. And while out by a factor of about three, string theory actually became the first theory in physics to predict the number of space–time dimensions.

Early claims that string theory would provide a "theory of everything" now seem hollow indeed. But we'll soon be awash in LHC data, and we haven't yet channelled the flood of recent advances in cosmology into fundamental physics. With luck, string theory might become a theory of something

Frank Wilczek, Massachusetts Institute of Technology

String theory immediately went from being a fringe activity to mainstream theoretical physics. But by the time the revolution was over in 1985, researchers were faced with five different string theories: Type I, which contains open and closed strings; Type II, which contains just closed strings but has two versions (A and B) reflecting the fact that the vibrations can travel in opposite directions; and two "heterotic" theories, SO(32) and $E_8 \times E_8$, which allow different kinds of vibrations to move in the two possible directions. "It's as if we had discovered five different classical approximations to the same underlying string theory, similar to finding the Feynman diagrams of five quantum field theories," says Green (see box on page 42).

Although uncomfortable with this lack of uniqueness, string theorists pressed on with the problem of how do 2D perturbation theory in the five different theories, as well as how to compactify the extra six dimensions. This continued well into the 1990s, with many researchers driven by the conviction that the end of theoretical particle physics was in sight. But although some of this work had a major impact on pure mathematics – with the study of 6D "Calabi–Yau" spaces making Witten in 1990 the first physicist to be awarded the prestigious Fields Medal – string theory refused to be tamed. In fact, rather than just five different classical "backgrounds" of the theory, researchers currently face an unruly "landscape" of 10^{500} possibilities when string theory is forced to conform to our 4D world.

"Remarkably, after nearly 40 years, we still don't know what string theory truly is," exclaims Gross. "From the start, string theory was a set of rules for constructing approximate solutions in some consistent classical background – and that's all it still is." What has changed, says Gross, is that the various solutions are now known to be related via a web of mathematical connections called dualities. "In certain cases, these dualities make string theory equivalent to quantum field theory," he says.

The dualities between the five different string theories emerged in 1995 during "the second superstring revolution", and revealed that strings perceive space–time rather differently to point particles. For example, a circle of radius R in the extra dimensions of the Type IIA theory is equivalent to one with a radius $1/R$ in Type IIB theory under "T duality", while "S duality" links a strong coupling constant in Type I theory to a weak one in SO(32) heterotic theory – where it may be possible to use perturbation theory. In addition to making certain calculations in string theory tractable, dualities such as these enabled Witten to conjecture that string theory has a unique but unknown underlying 11D formulation, which he called "M-theory".

Witten's result, which he presented at the Strings95 conference at the University of Southern California, led to enormous progress in understanding the "non-perturbative" sector of string theory – i.e. situations where attempts to approximate the theory as a series of increasingly complex Feynman diagrams fails. Non-perturbative effects are crucial in getting quantum field theory to describe the real world, particularly in the case of QCD. This is because perturbation theory only applies to the basic, individual quark interactions, where the strong force is relatively weak, and not to

Strings in context

- **1968** Gabriele Veneziano discovers that the Euler "beta function" brings order to the measured scattering amplitudes of different types of hadrons.
- **1970** Leonard Susskind, Yoichiro Nambu and Holger Neilsen independently identify Veneziano's amplitudes with solutions to a quantum-mechanical theory of 1D bosonic strings.
- **1971** Claud Lovelace realizes string theory requires 26 dimensions; Yuri Gol'fand and Eugeny Likhtman discover supersymmetry in 4D; John Schwarz, André Neveu and Pierre Ramond realize that string theory requires supersymmetry to accommodate fermions as well as bosons; Gerard 't Hooft shows that electroweak unification proposed by Steven Weinberg in 1967 is "renormalizable", thus making gauge theories physically viable.
- **1973** Julius Wess and Bruno Zumino develop supersymmetric quantum field theories; David Gross, Frank Wilczek and David Politzer discover asymptotic freedom and so establish QCD; combined with electroweak theory, the Standard Model is established.
- **1974** Schwarz and Joel Scherk (and, independently, Tamiaki Yoneya) realize that string theory contains gravitons, and propose a unified framework of quantum mechanics and general relativity; Sheldon Glashow and Howard Georgi propose grand unification of the Standard Model forces via the symmetry group SU(5).
- **1976** Stephen Hawking claims that quantum mechanics is violated during the formation and decay of a black hole; mathematicians reveal Calabi–Yau spaces.
- **1978** Eugène Cremmer, Bernard Julia and Scherk construct 11D supergravity, which incorporates supersymmetry in general relativity.
- **1981** Schwarz and Michael Green formulate Type I superstring theory; Georgi and Savas Dimopoulos propose the supersymmetric extensions of the Standard Model.
- **1982** Green and Schwarz develop Type II superstring theory; Andrei Linde and others invent modern inflationary theory from which the multiverse follows.
- **1983** The discovery of W and Z bosons at CERN seals a decade of success for the Standard Model; Ed Witten and Luis Alvarez-Gaumé show that the gauge anomalies cancel in Type IIB superstring theory.
- **1984** Green and Schwarz show that the anomalies in Type I theory cancel if the theory is 10D and has either SO(32) or $E_8 \times E_8$ gauge symmetry; T duality is discovered.
- **1985** Gross, Jeff Harvey, Ryan Rohm and Emil Martinec construct heterotic string theory; Philip Candelas, Andrew Strominger, Gary Horowitz and Witten find a way of compactifying the extra six dimensions using Calabi–Yau spaces.
- **1987** Weinberg uses anthropic reasoning to place a bound on the cosmological constant.
- **1994** Susskind proposes the holographic principle by extending work done by 't Hooft.
- **1995** Paul Townsend and Chris Hull, and Witten, propose that Type IIA theory is the weak-coupling limit of 11D "M-theory"; Polchinski discovers D-branes; Witten and others conjecture that all five string theories are linked by dualities, some of which are facilitated by D-branes.
- **1996** Witten and Polchinski discover that Type I theory and SO(32) heterotic theory are linked by S-duality; Witten and Petr Hořava show $E_8 \times E_8$ is the low-energy limit of M-theory; Strominger and Cumrun Vafa derive the Bekenstein–Hawking black-hole entropy formula using string theory; Susskind and others propose a candidate for M-theory called Matrix theory.
- **1997** Juan Maldacena discovers the equivalence between string theory and quantum field theory (AdS/CFT duality), thus providing an exact manifestation of the holographic principle.
- **1998** The experimental discovery of the accelerating expansion of the universe suggests a small, positive vacuum expectation value in the form of a cosmological constant; Lisa Randall and Raman Sundrum propose braneworld scenarios as an alternative to compactification.
- **1999** Gia Dvali and Henry Tye propose brane-inflation models.
- **2003** The KKLT paper shows that supersymmetry can be broken to produce a small, positive vacuum expectation value using flux compactification to deal with extra dimensions; Susskind coins the term "landscape" to describe the vast solution space implied by flux compactification, and invokes the anthropic principle and the multiverse to explain the cosmological constant; the KKLMMT paper extends KKLT to cosmology.
- **2004** Hawking admits he was wrong about black holes and concedes bet to John Preskill.
- **2005** String theory is mentioned in the context of RHIC quark–gluon plasma thanks to application of AdS/CFT, thereby returning the theory to its roots as a description of hadrons.

larger systems such as protons and other hadrons.

In the case of string theory, non-perturbative effects hold the key to why supersymmetry is "broken" at the low energies present in the universe today, which it must be in order to explain the fact that no-one has ever seen a supersymmetric particle. This is similar to the way the electroweak symmetry of the Standard Model must be broken (via the Higgs mechanism) below the TeV scale to explain why we perceive the electromagnetic and weak forces as separate entities. This rich but much more mysterious enclave of string theory also governs how the extra dimensions are compactified, and thus how string theory might make predictions that can be tested against experiment in the 4D world.

Getting real

String theorists are the first to admit that they have no idea what the underlying equations of string- or M-theory actually look like. But as a framework, string theory makes several generic predictions that are unlikely to depend on the details of these equations. The most important is that string theory provides a finite (i.e. non-divergent), consistent, quantum theory of gravity that reduces to general relativity at large distances and low energies. However, this is also the reason why it is practically impossible to test string theory directly, because it means the natural scale of superstrings is the Planck length.

The Planck length comes from a straightforward dimensional analysis of the three fundamental constants that any theory of quantum gravity must include: Newton's gravitational constant, Planck's constant and the speed of light. Its value is 10^{-35} m, which means that to observe strings directly we would need a particle accelerator with an energy of 10^{19} GeV – 15 orders of magnitude greater than that of the LHC. "We have known since Planck that physics has this tiny scale that we are never going to be able to access directly," remarks Joe Polchinski of UCSB. "But, thankfully, theorists have not let such obstacles get in their way."

One of the big successes of string theory as a quantum theory of gravity has been its ability to model black holes, which are classical solutions of general relativity where gravitational and quantum effects are both large. "I've just co-authored a textbook that has a 60-page chapter on black holes in string theory, and it only scratches the surface of this vast topic," says Schwarz. In particular, string theory has led to a deeper understanding of the thermodynamic properties of black holes at the microscopic level, and therefore helped to resolve a potentially disastrous paradox raised by Stephen Hawking of Cambridge University over three decades ago.

While at various occasions more modesty would have been called for, string theorists have the right to be enthusiastic about their findings and to report about them. The best thing physicists in other branches of research can do is to try to obtain interesting, promising new results themselves

Gerard 't Hooft, University of Utrecht

In 1976, having in conjunction with Jacob Bekenstein of the Hebrew University of Jerusalem used semiclassical arguments to show that black holes have a well-defined entropy and can therefore radiate, Hawking claimed that information is lost during the production and decay of a black hole. Since information is encoded in the quantum states of particles and fields, this implied that quantum mechanics breaks down at the Planck scale. If true, this would spell death for string theory or any other quantum theory of gravity.

String theory was not qualified to address this problem until 1995, when Polchinski discovered the significance of objects called D-branes that were known to be lurking in the mathematics of the theory. D-branes, Polchinski realized, are hypersurfaces to which all open strings are fixed, and they come in any number of dimensions allowed by string theory (for example, a 2D brane or "2-brane" is a membrane in ordinary terminology). D-branes have zero thickness but a huge mass. This means that by wrapping lots of them around, say, a circle in the extra dimensions string theorists can build a very special, if somewhat fictional, kind of supersymmetric black hole.

In 1996 this approach enabled Andrew Strominger and Cumrun Vafa of Harvard University to derive precisely the same Bekenstein–Hawking entropy formula that had been worked out semiclassically 20 years earlier by simply treating D-branes as conventional quantum states and adding them up. Although string theory, like general relativity, cannot deal directly with the singularity at the centre of black holes, theorists have since derived exactly the same formula for more realistic black-hole models – results that ultimately contributed to Hawking's admission in 2004 that he was wrong. "To my mind, only the most cynical sceptic would think that the application of string theory to black holes has not made a major contribution to physics," says Susskind.

D-branes have also transformed string theory from a theory of strings to a richer theory that also includes other extended objects. To non-string theorists, D-branes may seem like fairly arbitrary additions, but they turn out to be a special type of a more general higher-dimensional object called p-branes that were in the mathematics right from the start and are essential for making string theory consistent. It was only after Polchinski's reinterpretation of D-branes and Witten's M-theory conjecture in 1995, among other contributions, that researchers were able to go beyond the approximate perturbative techniques and understand these objects, which are much more massive than strings. As well as facilitating the deep dualities between the five different string theories, branes are the basic ingredients of M-theory. "String theory" is thus a misnomer on two fronts: it is neither a "theory", at least in the sense usually meant in physics, nor is it based on strings.

The world on a brane

One of the most mind-bending implications of D-branes, which may even reveal itself at the LHC, is that you could be stuck to a giant one right now. "If you have the faith," says Green, "you can believe that we live in a 3-brane universe and that the extra six dimensions might be large enough to detect."

Such "braneworld" scenarios arise because the gauge fields of the Standard Model are described by open strings, which are forever confined to flop about in the "world volume" of a D-brane (a 3-brane in our case). Because gravitons are described by closed loops of string, however, they are banished to the higher-dimensional "bulk", where they drift around and only occasionally come into contact with our brane. As well as providing a neat explanation for why we perceive gravity to be so much weaker than the other three forces – a conundrum in particle physics known as the hierarchy problem – such "warped" geometries imply that the extra dimensions in string theory might be large enough to detect. Indeed, the extra dimensions could be right in front of our noses and we would never know it, since photons are forever shackled to our brane.

The most direct test of such extra dimensions would be to measure a departure from the inverse square law of gravity, since this is a direct consequence of the fact that space is 3D (in a 2D world, for instance, gravity is simply inversely proportional to distance). In fact, our inability to experimentally confirm the inverse-square law below a scale of about 0.1 mm is the only reason why braneworld scenarios are admissible in the first place (see *Physics World* April 2005 pp41–45).

But even if the extra dimensions were 100 million times smaller than 0.1 mm, which according to Green is still "ridiculously large", then it would imply that the

It is an enormous success in itself that string theory can produce a small cosmological constant. Approaches based on quantum field theory require absurd fine-tuning to link the very small with the very large

Michael Green, Cambridge University

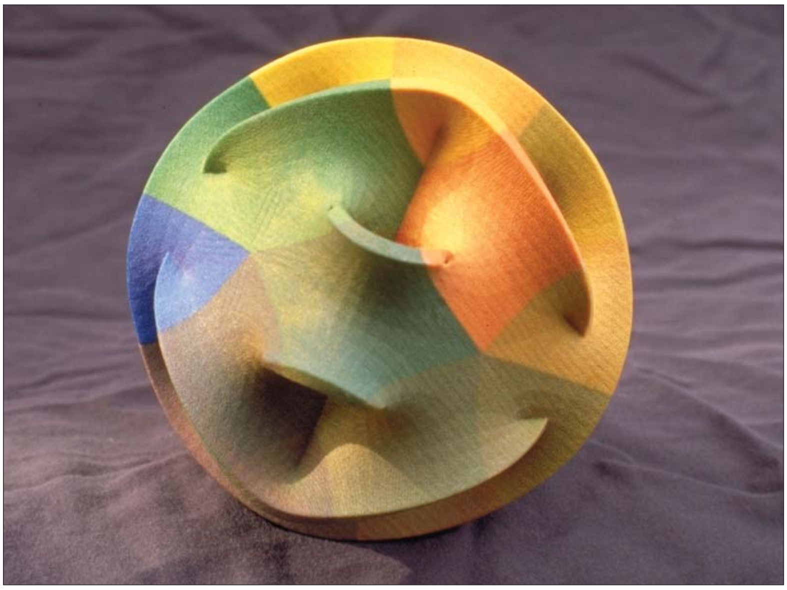
energy of the Planck scale is as low as 1 TeV. That would increase the string scale from 10^{-35} m to a mere 10^{-18} m, which means that the high-energy proton–proton collisions at the LHC might be sufficient to excite higher harmonics of the string. The "true" strength of gravity in the extra dimensions may even be sufficient to generate mini black holes by the thousand, which would evaporate almost immediately by decaying via Hawking radiation.

Lisa Randall of Harvard University, who along with Raman Sundrum of Johns Hopkins University has considered how D-branes alter the geometry of space–time, says that the precise signature of the extra dimensions that you would see at the LHC depends on the particular brane model you assume. "You could see 'Kaluza–Klein' particles, which are similar to particles that we know already but are much heavier because they travel in the extra dimensions," she says. "In our models these particles generally decay in the detector because the warped geometry gives them a large interaction probability, but they could interact extremely weakly and simply escape the detector – leaving no trace other than missing energy." A similar signature would be left by ordinary particles that literally disappear into the extra dimensions, although Green believes that the extra dimensions are much too small to see braneworld physics at the LHC. "If I was an experimentalist, then this is probably the last explanation for missing energy that I would turn to," he says.

A more likely, although by no means certain, scenario at the LHC is the discovery of supersymmetry. This is one of the main goals of the ATLAS and CMS collaborations, since despite originating in string theory supersymmetry is arguably more important for particle physics. For example, in the context of the "minimal supersymmetric extension" of the Standard Model (MSSM), unbroken supersymmetry at the electroweak scale solves the hierarchy problem because the supersymmetric particles cancel out quantum corrections that would cause the Higgs mass to diverge. Supersymmetry also leads to "grand unification", whereby the coupling constants of the three Standard Model forces meet at much higher energies, and the lightest supersymmetric particle provides a natural candidate for the non-luminous dark matter known to make up the vast bulk of the mass in the universe.

"Supersymmetry is very important to string theory, but there are no compelling a priori theoretical arguments about how or at what scale it is broken," says Susskind. "The unpleasant fact – and believe me, I don't like it – is that if supersymmetry is discovered, it will be considered good for string theory; but if it isn't discovered, it won't rule the theory out. So we cannot really say that finding supersymmetry at the LHC is a prediction of string theory." In fact, string theory may not even require supersymmetry at all, says Shamit Kachru, also at Stanford University. "Supersymmetric solutions are the easiest to study, but the theory has a vast array of non-supersymmetric solutions where supersymmetry breaking takes place at energies much higher than the electroweak scale."

The inability of supersymmetry to provide a definitive test of string theory highlights string theory's status as a framework to describe fundamental physics rather than a theory with specific predictions. Quantum field theory faces analogous difficulties. "Suppose someone came up to you and said look, we've got this fantastic theoretical structure called quantum field theory, which incorporated quantum mechanics, Lorentz invariance, generalizations of classical fields, but suppose that the specific application to electrodynamics [i.e. QED] had not been made," says Green, "then you wouldn't know what its physical predictions were, so it would not be possible to falsify." To its practitioners, says Green, string theory is pretty much in that position – a framework that encompasses all of the key ingredients to unite quantum gravity with the other forces, even though it is yet to make very specific predictions.



Kayla Jacobs

Warping the fabric of space–time The extra six dimensions in string theory are usually "compactified" on 6D spaces called Calabi–Yau manifolds, but each different way in which this can be done describes a universe with a different set of particles and fields.

Future historians of science will have to decide just how much of the excitement of string theory was inherent to string theory, and how much was imposed by Ed Witten's very unusual intelligence. I'd guess about 40/60

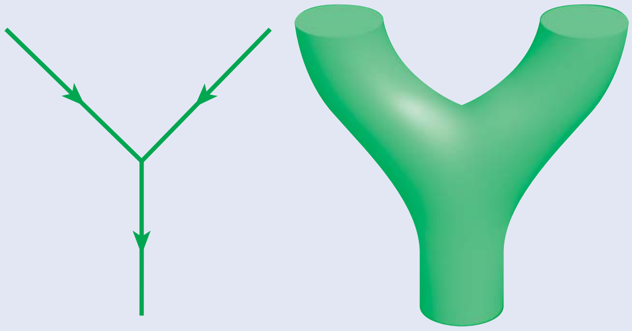
Howard Georgi, Harvard University

Given that string theory is often criticized for not being as well formulated as the Standard Model, it is therefore ironic that one of the most concrete models of string theory that researchers have to date – a formulation of quantum gravity in certain negatively curved geometries – is mathematically equivalent to a quantum field theory similar to QCD. As well as taking string theory back to its origins as a description of hadrons, Gross says that the dualities between string theory and field theory could mean that string theory is just that: a type of quantum field theory.

An analytical tool

The connection between string theory and field theory was the subject of more than half of the presentations at Strings07. Research in this corner of string theory took off in 1997 when Juan Maldacena, now at the IAS in

Why can't string theory predict anything?



String theory replaces a microscopic world-view based on point-like elementary particles with one based on 1D strings. Compared with the particle view, however, strings have got physicists virtually no further forward in explaining what they see when they actually probe nature at small scales using machines like the LHC. This may not be surprising given that strings are 10^{20} times smaller than particles such as protons and neutrons. But why is it so hard to turn stringy ideas into hard predictions?

The theoretical framework of the particle world-view is quantum field theory (QFT), which describes particle interactions as being due to the exchange of a field quantum (photons, for example, mediate the electromagnetic force). For some deep reason, a type of QFT called a gauge theory describes the electromagnetic, strong and weak interactions extraordinarily well, and has done for nearly 35 years via the Standard Model of particle physics. Because QFT allows particles to appear from "nothing" via quantum fluctuations of the underlying fields, the vacuum is not really empty space at all. The starting point for calculating physical quantities in both field theory and string theory, since string theory is rooted in the same quantum-mechanical principles as QFT, is therefore to write down the appropriate "Lagrangian" and understand the vacuum.

In the Standard Model, this is reasonably straightforward, since the Lagrangian is fixed once you know the particles and ensure that the interactions between these particles respect gauge symmetry (which in the case of electrodynamics, for example, makes the values of measured quantities independent of the intrinsic phase of the electron wavefunction). As for the vacuum, in order to give particles their masses theorists invoke a scalar field called the Higgs field that has a non-zero value in the vacuum.

Once you have got the Lagrangian, you can then derive a set of Feynman rules or diagrams that allow you to calculate things. The simplest diagram you can draw corresponds to the classical limit of the theory (i.e. where there are no quantum fluctuations) and yields a probability amplitude for a particular physical process, for example an electron scattering off another electron. By then adding the contributions from increasingly complex diagrams (using perturbation theory), QFT allows you to refine the calculations of this probability – to a precision of 10 decimal places in the case of quantum electrodynamics.

The stringy world-view turns these 1D diagrams into 2D diagrams, since the space–time history of a string traces out a 2D surface rather than a line. This is great for incorporating gravity, which the Standard Model ignores, because gravitational interactions of point-like particles lead to infinities in the calculations. The problem is that theorists do not know what the Lagrangian is in string theory. Instead, researchers have five sets of possible Feynman rules, each of which approximates the physics described by a different Lagrangian (i.e. a different formulation of string theory). The upside is that the five different string theories are linked by dualities that suggests string theory has a unique underlying structure (called M-theory); so it does not matter too much which one you work with. The downside is that the five "backgrounds", as string theorists call them, live in 10D space–time.

If we lived in a 10D world, then it would just be a case of finding an experiment to verify which of the five backgrounds fits best. But when you curl up six of the dimensions on a Calabi–Yau manifold in an attempt to describe the four dimensions of the real world, you produce a slightly different background with its own set of Feynman diagrams. Indeed, the number of 4D Lagrangians you can get is about 10^{500}, each of which corresponds to a different way of compactifying the 6D manifold, choosing fluxes and choosing branes (i.e. "non-perturbative" effects that are extremely difficult to calculate). Since each result corresponds to a different universe, you really need to study all 10^{500} in order to find out whether or not string theory describes the real world (unlike in QFT, where if you see something in nature you do not like, then you can add a new particle or field into the Lagrangian). The punch-line of this string theory "landscape", however, is that it is the only explanation physicists can offer for the cosmological constant – a property of the vacuum that was discovered in 1998 and which QFT gets wrong by a factor of at least 10^{60}.

Princeton, found that a quantum-gravity theory formulated in a curved 5D "anti de Sitter" (AdS) space–time describes exactly the same physics as a simple 4D quantum field theory with conformal symmetry (CFT) that lives on the boundary of that space–time. These conformal field theories include supersymmetric versions of QCD, and appear as if they are "holographic projections" of the higher-dimensional theory.

"We already had direct experimental evidence for the strings that confine quarks inside hadrons," says Maldacena. "But AdS/CFT duality gives a concrete realization of this idea for certain QCD-like gauge theories." Crucially, the gravity theory in AdS/CFT duality – which operates in five large and five compact dimensions – can be solved in situations where the equations of the 4D theory are intractable, i.e. when the coupling strength of the gauge theory is large. For instance, AdS/CFT-type dualities have helped put string models of black holes on much firmer ground, since they allow gravity to be made so weak that a black hole is no longer "black" and is therefore much easier to handle.

AdS/CFT duality really hit the big time in 2005 when it was responsible for getting string theory a mention in the context of a major experimental result. The reason was that it had enabled researchers at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory in the US to model certain aspects of the quark–gluon plasma – an extreme state of matter in which quarks behave as if they are free particles. At such large separations, the strong force becomes unmanageable analytically, which means that string theory can help out where perturbative QCD fails. Susskind says that by studying heavy-ion collisions you are also studying quantum gravity that is "blown up and slowed down by a factor of 10^{20}".

Dam Son of the University of Washington, who is not a string theorist, has witnessed the benefits of AdS/CFT duality at RHIC. "String theory has given us new tools to deal with strongly coupled gauge theories that will hopefully apply to real QCD at RHIC," he says. "The gauge/gravity duality has already allowed us to estimate the quantum limit on how perfect the RHIC quark–gluon plasma can be, and so far this limit is consistent with data [see *Physics World* June 2005 pp23–24]. Furthermore, several research groups have recently applied string theory to the energy loss of heavy quarks moving in the plasma, with encouraging results."

Most string theorists think that the dualities between string theory and gauge theories are so powerful that it is only a matter of time before the gravity "dual" of real-world QCD is worked out. "String theory would not be in its current state without dualities such as the Maldacena conjecture, which showed that strings are emergent entities and not the starting points of the theory as was traditionally thought," says Polchinski. "The successful application of AdS/CFT to RHIC physics was surprising because we first thought it was nothing more than an abstract analogy." One of the more fun trends in this area, adds Polchinski, is to apply AdS/CFT dualities to problems in condensed-matter physics, some of which are rooted in 2D quantum field theories that have no classical limit. "I keep hoping that maybe before getting at the underlying equation of string theory we have to solve the problem of high-temperature superconductivity!" he jokes.

Polchinski's humour is not shared by condensed-matter physicist Philip Anderson of Princeton University, who shared the 1977 Nobel Prize for Physics for his work on electronic structure in magnetic and disordered systems. "The last thing we need is string theorists," he says. "Anything out there is hype. Superconductivity is an experimental science, and most string theorists have no idea how to understand an experiment because they have never looked at one!"

Driven by dimensions

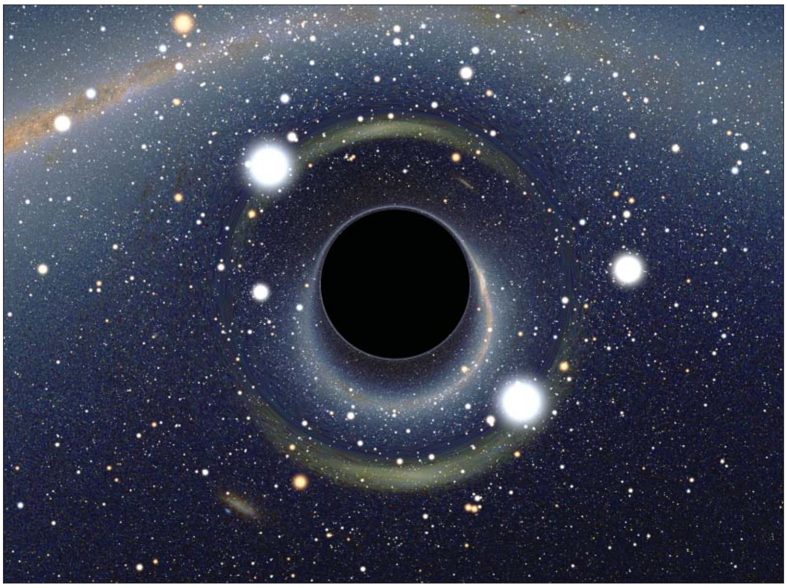
However useful string theory may turn out to be as a tool for working on quantum field theories, this is hardly why some 1500 physicists worldwide have invested their careers in the subject. The real reason is that, in addition to providing a quantum theory of gravity, string theory promises to unify all of nature's fundamental forces. It therefore has at the very least to rival the phenomenal success of the Standard Model in its ability to describe the rich spectrum of particles and interactions that experimentalists observe. "After gravity, the second most striking general feature of string theory is that it is so natural to obtain something qualitatively similar to the Standard Model from it," says Witten. "That is not to say that the details of the Standard Model are well described, because they're definitely not."

The general problem is how to get from the natural symmetry of string theory in 10D to the messy asymmetric world of particle physics in 4D without losing too much explanatory power – a problem that Witten and others (see box on page 39) partially solved in 1985 by using 6D spaces called Calabi–Yau manifolds.

This triggered a huge amount of model building efforts, since the 4D "effective theories" that result when such 6D spaces are compactified capture many of the key features of the Standard Model. "In the past, many formal string theorists believed, somewhat naively in my view, that the theory would somehow select the Standard Model as its preferred solution," says Fernando Quevedo of Cambridge University. "But string phenomenologists took the different attitude of building models that are as realistic as possible." A fraction of string theorists currently work in this area, and for the last six years they have held their own "string phenomenology" conference.

String theory is a fantastic box of tools waiting for its killer application, and I am convinced it will eventually revolutionize our understanding of the universe

John Ellis, CERN



Information on the brane As a quantum theory of gravity, string theory has given physicists a better understanding of the thermodynamic properties of black holes at the microscopic scale.

For example, in addition to the gauge fields of the strong and electroweak interactions, the models contain quarks and leptons with the right spins, charges and other quantum properties. Moreover, these particles are "chiral" – a vital property of electroweak interactions that distinguishes left from right – and are also arranged in three generations just like in the Standard Model (this is achieved in Calabi–Yau manifolds that contain the right number of "handles" or "holes", for example). Some models contain Higgs particles too, and even the "Yukawa" couplings to the Higgs that give particles their masses, although it should also be said that there are thousands of Calabi–Yau manifolds that do not reproduce anything like the Standard Model structure.

One rather important property of particles that string phenomenologists have experienced difficulty in explaining, however, is their masses – although the situation is not much better in the Standard Model, where these masses are put in "by hand". In its 10D, supersymmetric form, string theory contains an infinite "tower" of massive states in multiples of Planck's constant, which correspond to the harmonics of the vibrating quantum string. At the relatively low energies probed so far, string theory therefore predicts that the masses of even the heaviest Standard Model particles – the top quark, and the W and Z bosons of the weak interaction, which are measured to be less than 0.1 TeV – are zero.

To generate particle masses, string theorists have to find some mechanism that breaks supersymmetry at low energies. But in doing so they also have to tame a host of parameters called "moduli", which govern the size and shape of the compact dimensions. A typical compactification contains up to 100 moduli, each of which corresponds to a scalar field in the 4D theory, and since supersymmetry ensures that these fields are massless, string theory therefore predicts a host of long-range, gravitational-like forces that we simply do not observe.

"For the last 20 years the main obstacles for string theory in making contact with low-energy physics have been the related problems of supersymmetry breaking and moduli stabilization," says Quevedo. "I was worried that my career was going to end before someone worked out how to do this."

Across the landscape

The breakthrough came in 2001, and the fact that Calabi–Yau compactifications can support fluxes similar to electric or magnetic fluxes. Polchinski, Kachru and others realized that by switching such fluxes on (they already existed in certain "supersymmetric tensors" of the theory but had been set to zero) and by "threading" them around and through the warped topologies of Calabi–Yau spaces, many moduli could be constrained such that they acquired a mass and therefore did not contradict experiment. But researchers still could not give masses to the remaining moduli, nor break supersymmetry in such "flux compactifications" in a controllable way at sufficiently low energies.

> It is too early to tell how the string landscape is populated. Anthropic arguments ought to work unless it is very selectively populated, but we just don't know whether that is the case. It seems to me that at this point, all avenues should be tried
>
> **Steven Weinberg**, University of Texas at Austin

That feat was achieved in 2003 by Kachru along with Renata Kallosh and cosmologist Andrei Linde, a wife and husband team at Stanford University, and Sandip Trivedi of the Tata Institute for Fundamental Research in India, by throwing other ingredients such as "anti-D-branes" into the mix. The "KKLT" paper is one of the most important in string phenomenology and cosmology, although the mechanism that breaks supersymmetry is not understood in sufficient detail to satisfy more formal string theorists (see *Physics World* November 2003 pp21–22).

Quevedo and many others have since built on the KKLT scenario to generate better models with testable predictions. "For the first time we can compute the masses of the supersymmetric particles in large classes of models, and are collaborating with hard-core phenomenologists to embed our models in the same analysis chains that will allow conventional field theory such as the MSSM to be tested against LHC data," says Quevedo. He adds that the models of him and his co-workers also contain a tentative dark-matter candidate in the form of a MeV-mass particle that decays into an electron–positron pair. "This may explain the 511 keV signal at the centre of our galaxy and would have a distinctive signature that, while not able to falsify string theory itself, would constrain classes of string models."

The LHC is the main driving force behind such model-building efforts, which include the warped-geometry models of Randall and Sundrum as well as numerous others. Although many of their proponents are phenomenologists before they are string theorists, these models may – to borrow Witten's metaphor – guide string theorists in where best to dig to reveal what lies beneath. If nothing else, string phenomenology shows that string theory is very much in touch with the world of experiment, as illustrated by recent progress made in accommodating the 1998 discovery that neutrinos have a very small mass.

But there is one hard experimental fact that no string theorist has been able to ignore, and one which is currently the source of vivid controversy within the string community itself. It is the discovery, made 10 years ago from observations of distant supernovae, that the expansion of the universe is accelerating. The current best explanation for this "dark energy" is that the vacuum has a small positive energy density called the cosmological constant, with a value of about 10^{-120} in Planck units. If this explanation turns out to be correct, then on top of all its other problems string theory finds itself at the centre of one of the most pressing mysteries in physics: why does the cosmological constant take such an impossibly small value?

String theory is armed to tackle the cosmological constant by way of the KKLT mechanism, since the choice of which fluxes to turn on and how to wrap them around a certain Calabi–Yau manifold leads to a different "vacuum energy". The great success of this approach was that the addition of D-branes broke supersymmetry and "lifted" the vacuum energy to a small, positive value corresponding to the positively curved, "de Sitter" universe that we observe (supersymmetry ensures that the cosmological constant is zero). But with no rules to say precisely which fluxes should be turned on, nor where to put the D-branes, string theorists can generate any one of 10^{500} slightly different yet viable universes. With no way to discriminate between these solutions, this "landscape" – a term coined by Susskind in 2003 to describe the peaks, troughs and valleys sculpted by all the different possible values of the cosmological constant – would seem to turn string theory from a potential theory of everything into a theory of very little – a result that some critics have seized upon.

"This supposed problem with a theory having many solutions has never been a problem before in science," says Green. "There is a "landscape" of solutions to general relativity, yet nobody says the theory is nonsense because only a few of them describe the physics we observe while the rest appear to be irrelevant. The trouble with string theory is that each different solution defines a different set of particles and fields – not just a different space–time geometry."

To pin down one vacuum among these choices, as Michael Douglas of Rutgers University points out, string theorists have would need to measure 50 or more independent parameters (i.e. the moduli) to a precision of 10 decimal places. "Taking the cosmological constant into account, which is measured to about 120 decimal places, we would expect about 10^{250} vacua to match the Standard Model if all the parameters were distributed uniformly," he says.

It turns out, however, that this vast space of similar solutions is just what cosmologists were looking for. "The difficulty of understanding a small, non-zero value for the cosmic acceleration – which implies that our universe is metastable – has led many physicists to think in terms of a multiverse," says Witten.

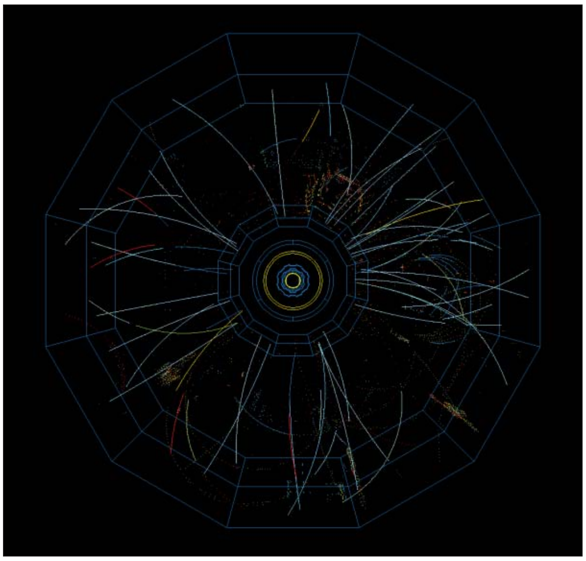
String cosmology

Regardless of any landscapes, string theory was always going to have to face up to cosmology at some point. "Einstein taught us that when you are doing gravity, it's not enough to just describe the universe at a given time," says Gross. "You have to describe everything: the beginning, the middle and the end. The solution of string theory *is* the space–time history – there's nothing special about a state that happens to be metastable for a few billion years." Since such a solution therefore has to deal with cosmological singularities such as the Big Bang – situations, Gross points out, where physicists do not even know how to define observables – none of the current solutions of string theory can describe realistic cosmologies.

Nevertheless, the KKLT scenario has made the building of cosmological models a promising way to connect string theory with experiment in the coming years. "The foundation of string theory cannot be tested in high-energy accelerators, so the early universe is the only laboratory we have to study the relevant energies," says Kallosh. The cosmological epoch in question is inflation – a period of exponential expansion that took place 10^{-35} s after the Big Bang and that explains why the universe is smooth on the largest scales. String theory should, as a fundamental theory, be able to explain the microscopic origins of inflation, namely the scalar field or "inflaton" that is hypothesized to drive the enormous expansion.

In 1999 Gia Dvali of Harvard University and Henry Tye of Cornell University realized that a D-brane in close proximity to an anti-D-brane could do this rather well, with the separation between the branes providing the inflaton field and inflation coming to an end when the branes finally collide. If that sounds outlandish, Paul Steinhardt of Princeton University and Neil Turok of Cambridge University have extended such ideas in an attempt to tackle cosmic evolution by suggesting that the Big Bang was actually caused by a collision between our 3-brane and another, parallel 3-brane. In such "cyclic models" these cataclysmic events take place every few trillion years as our brane floats around in the higher-dimensional bulk, although many string theorists are sceptical of claims that such models can solve the cosmic-singularity problem.

Since 2003, when the KKLT construction gave researchers a better understanding of the vacuum energy, string theorists have developed a handful of more concrete inflationary models that agree well with measurements of the cosmic microwave background from NASA's Wilkinson Microwave Anisotropy Probe mission. The first of these models, dubbed KKLMMT after Maldacena and Liam McAllister of Stanford University joined the KKLT team, prepares the ground for interpreting possible experimental discoveries such as cosmic strings.



Brookhaven National Laboratory

Branching out Powerful "dualities" between string theory and quantum field theory have allowed researchers to model certain aspects of heavy-ion collisions at Brookhaven's Relativistic Heavy Ion Collider.

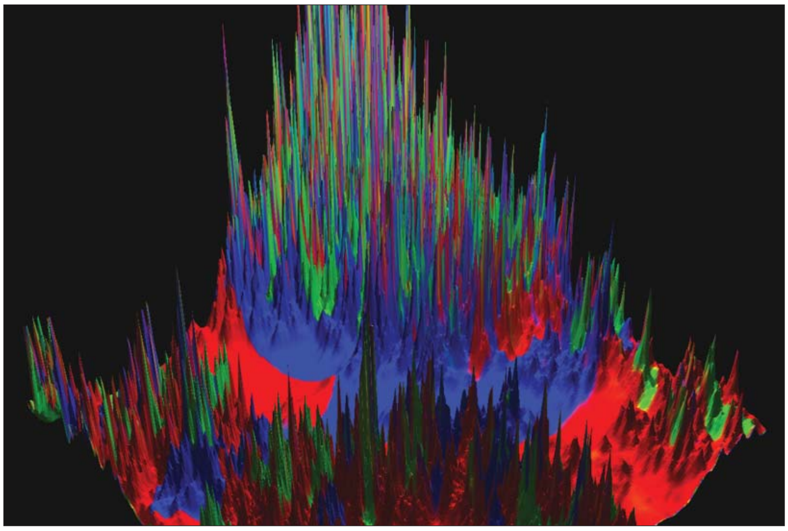
Cosmic strings are fundamental strings that have been blown up to cosmic scales during inflation. Being very massive, they would reveal their presence via gravitational lensing and leave a spectacular signature. "D-strings joining with fundamental strings at junctions could lead to a network of strings in the sky, which would be incontrovertible evidence for string theory", says Green. Such massive strings would also be a source of gravitational waves, so it is possible that gravitational-wave detectors such as LIGO in the US could pick them up. "It's a long shot, but we should know the answer within 5–10 years," says Polchinski.

Gravitational waves could also be produced in phase transitions in the early universe, during which our 3-brane stabilized from a higher-dimensional brane scenario (see *Physics World* June pp20–26). But if gravitational waves were to be detected in the cosmic microwave background, perhaps by the Planck surveyor mission due to be launched next year, then most string-inflation models would be ruled out. This is because the inflationary energy – which governs the amplitude of such primordial gravitational waves – must have been low enough to prevent the six compact dimensions in string theory from being stretched to macroscopic scales along with the three that we observe.

This is a clear example of how string-cosmology models could be falsified by experiment, although Kallosh thinks that string theory's explanation of the cosmological constant is also amenable to experimental test. "The KKLT construction in the context of the landscape offers an explanation for dark energy that at present fits

The main problem in string theory is our lack of understanding of cosmological singularities such as the Big Bang. We do not know if time originated with the Big Bang. If it did, we cannot describe the emergence of time in a precise way. But black holes could help us understand this problem

Juan Maldacena, Institute for Advanced Study, Princeton



Populating the string-theory landscape The cosmological model of inflation predicts that fluctuations in the inflaton field (height of spikes) led to a "multiverse" of different universes.

all the data," she says. "But although observational cosmology is unlikely to rule out the cosmological constant in the next 10 years, this construction may not remain a good explanation in the long-term future."

The A-word

Many string theorists would be very happy if the cosmological constant did turn out to be the wrong explanation for dark energy, since it might mean that the vacuum is unique after all – and not some random metastable point in a landscape of 10^{500} others. "That would restore my long-standing hope that we can one day derive the fine-structure constant from first principles," says Witten.

Others like Susskind, however, think that they already have an explanation for the cosmological constant. The reason why is that inflation provides a compelling physical mechanism to populate the string-theory landscape, since quantum fluctuations of the inflaton field would have caused different regions of space–time to inflate and therefore give rise to a "multiverse" of causally disconnected universes with different cosmological constants.

"The only consistent explanation that I know of for the cosmological constant – as inconsistent ones come along about every three months – is that as a consequence of inflation, the universe is extremely big and as diverse as possible," explains Susskind. "The landscape appears to be so big that statistically it will allow the small cosmological constant that is needed for our existence: we are talking about the A-word!" The A-word is "anthropic"– the idea that the properties of nature are dictated by the fact that we are here to observe them – and gets string theorists even more worked up than mentioning "Smolin" or "Woit".

Although he has reservations about the use of the anthropic principle, in 1987 Steven Weinberg of the University of Texas at Austin, who shared the 1979 Nobel prize for electroweak theory, used anthropic reasoning to set an upper bound on the cosmological constant by quantifying just how different its value could be while still allowing galaxies and thus humans to exist. Polchinski, who in 2000 was one of the first to see the potential role of anthropic reasoning in string theory, recalls how he felt in 1998 when supernova data confirmed Weinberg's prediction of this extremely small number. "Although it was already clear that string theory fitted Weinberg's anthropic estimation of the cosmological constant, I was very unhappy when it was confirmed because I didn't want that explanation to be right."

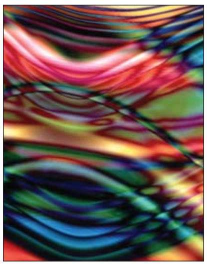
For Susskind and other proponents of the anthropic landscape, however, the prize came with the KKLT paper in 2003, when Linde and the rest of the team used inflationary theory to estimate the decay time of the metastable universe implied by the KKLT mechanism. It turned out that this was exactly the same number that Susskind had arrived at for the lifetime of a de Sitter universe using quite general arguments from string theory. "When we told Susskind and his collaborators the news," recalls Linde, "they were happy because it confirmed Susskind's intuition about the landscape." Linde says that from a cosmologist's point of view, the possibility of justifying the use of the anthropic principle in the context of inflation is one of the best arguments in favour of string theory.

Gross admits, with some dismay, that anthropic reasoning is a logical solution to the cosmological-constant problem. "What gets me upset, however, is when people try to make it into a strong principle that would allow you to calculate the probability that we exist in a 'likely' universe. The trouble is that we don't know what the hell we're talking about when it comes to the very early universe," he says.

Gross points out that physicists have managed to explain smaller numbers in the past. "The proton mass is 10^{19} times smaller than its natural scale, the Planck mass, so we could have thrown our hands up in the air about that. But instead we came up with asymptotic freedom [for which Gross shared the Nobel prize]: QCD says that the relevant ratio of masses is not 10^{19}, it is $\log(10^{19})$ because of the way the coupling constant changes with energy, which QCD can explain. If we had a similar compelling dynamical mechanism for why the cosmological constant has such an unnaturally small value, 95% of the people following anthropic arguments – including Susskind – would give them up."

Not all string theorists take such strong positions in the anthropic debate as Gross and Susskind. "The anthropic interpretation of the landscape is relatively trivial," says Schwarz. "We do not know how much of fundamental physics can be deduced mathematically and how much is determined environmentally. All this anthropic stuff is an attempt to account for properties in the latter category, but I think this focus is premature when we don't know what belongs in each category."

Kachru, who is "in the middle" when it comes to how



I don't know the answer. But I have a sneaking suspicion that it is much too early to suggest that there is no answer and that everything is determined anthropically

David Gross, University of California at Santa Barbara to interpret the landscape, thinks the idea has been oversold. “Before Newton’s theory of gravity came along, people were really puzzled by the ratio of the distances between the planets,” he says. “But when his theory was developed it did not solve that problem – the ratios were determined by the initial conditions instead. People could have said that since we happen to live at the right distance from the Sun for water to be a liquid, there is a deep anthropic lesson to be learned from Newtonian gravity. But instead they moved on to tackle other dynamical questions. The same could apply to our understanding of the cosmological constant today.”

Towards the next revolution

It has been 23 years since “the first superstring revolution”, and half as long since the second. Does this mean that string theorists are due for a third revolution in their understanding of strings? According to Susskind, the landscape *is* the next revolution, and from a cosmological viewpoint one that is even more of a revolution than the others. “In terms of changing the way we think about the world, the anthropic landscape is certainly as big as the other revolutions,” adds Polchinski. “At some point, however, the revolution will be: what is the equation? How far away that is isn’t clear, neither is what form the equation will take.”

Most string theorists agree that finding the underlying equations of string theory or M-theory is the biggest challenge that they face. After all, no matter how good phenomenologists are at building models, every “solution” of string theory studied so far is an approximate one. “This is certainly a question that interests me,” says Witten, “but if I don’t work on it all the time, it’s because it’s difficult to know how to make progress.”

Gross, meanwhile, thinks that the first real revolution in string theory is yet to happen. “Quantum mechanics took about 20 years to develop, which culminated in a period of rapid change with Heisenberg and Schrödinger. But unlike what happened in string theory in the mid-1980s and 1990s, the quantum-mechanical revolution uprooted the whole notion of classical determinism in a way that still hasn’t been totally understood today. What we need is some bright young mind playing around and making clever guesses – like Heisenberg, who was messing around with observables and little pieces of the commutation relations until he stumbled across matrices – to complete the string revolution.” Indeed, one of the aspects of string theory that bothers Susskind is that it offers no insights into the puzzles of quantum mechanics.

So what of all those grand promises of a theory of everything made by string theorists in the heady days of the mid-1980s? “I have been critical in the past of some of the rhetoric used by string-theory enthusiasts,” says Howard Georgi of Harvard University, who co-invented the supersymmetric extension of the Standard Model in 1981. “But I think that this problem has largely corrected itself as string theorists learned how complicated string theory really is. I am concerned about the focus of young theorists on mathematical details, rather than what I would consider the real-world physics of scattering experiments, but with any luck the LHC will take care of that by reminding people how interesting the real world can be.”

As for threats coming from outside the string-theory community, few string theorists think that the sometimes negative portrayal of string theory in the popular arena recently has had much of an effect other than to irritate people. “The reason that the ‘Smoit [Smolin/Woit] onslaught’ has not done serious damage is that string theory has had relevant things to say to a wide community of physicists and mathematicians, from black-hole theorists to nuclear physicists to particle phenomenologists to geometers. People in good physics departments know that,” says Susskind.

Gerard ’t Hooft of the University of Utrecht, who shared the Nobel prize in 1999 for his work on electroweak theory, thinks that discussions about the merits of theories should be limited to professional circles. “By addressing a larger public, one generates the impression that quite general arguments could suffice to disqualify this kind of research, but that is definitely not the case. An impressive body of mathematical knowledge has been unearthed by string theorists, and the question as to what extent this mathematics describes the real world is a very technical one.”

Longer term, however, some of the biggest concerns of string theorists are experimental. “The problem is that particle physics and cosmology are expensive, and sometimes what is discovered is hard to explain to politicians or even to scientists in other fields,” says Witten. “I don’t think that funding for theorists is the problem, as I think that provided there are exciting ideas out there then people will want to work on them.” That said, the LHC is drawing potential new recruits towards phenomenology at the expense of more formal research in string theory.

There is an incredible amount that is understood, an unfathomable number of details. I can’t think of any simple way of summarizing this that will help your readers. But despite that, what’s understood is a tiny, tiny amount of the full picture

Ed Witten, Institute for Advanced Study, Princeton

It is therefore fitting that Strings08 is going to be held at CERN. Originally planned to coincide with the highest energy collisions ever generated – when mini black holes, supersymmetry and extra dimensions might have been lighting-up the LHC’s giant underground detectors – faulty magnets and other delays have meant there might not be quite as much data as string theorists would have liked when they turn up at the lab next August. Faced with the messy world of experiment, it seems as if string theorists once again find themselves a few steps ahead.

But researchers need to bridge a rather more gaping chasm between experiment and theory before they can verify that nature’s fundamental layer really is a cacophony of vibrating strings. Most theorists seem prepared to wait for a definitive answer as to whether string theory is a viable physical theory. “There is a story”, says Weinberg, “that when Chou En-Lai [the Chinese premier] was asked what he thought about the French Revolution, he replied that ‘It’s too soon to tell.’ I feel that way about string theory.” ■