Physics World

FEATURE

The new universe around the next corner

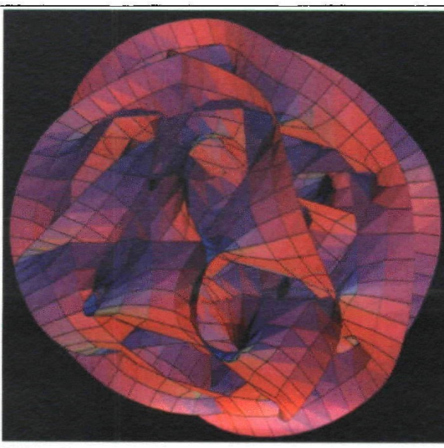
To cite this article: Lee Smolin 1999 *Phys. World* **12** (12) 79

Relativity, quantum mechanics, particle physics and cosmology are all pieces of a grand theory of everything that will finally replace the Newtonian view of the world. This new theory may be closer than many people think – and could even be tested by experiment

The new universe around the next corner

Lee Smolin

THE 20th century has been a period of scientific revolution, unmatched in scope by anything that has come before, save perhaps the Copernican revolution in the 16th century. Ever since Newtonian physics was overthrown at the beginning of this century, we have been living through a period of transition, during which the new theory that will replace Newtonian physics as a unified framework for the description of everything in nature has been steadily coming into focus. Big pieces of this theory have been discovered, such as relativity, quantum theory, the Standard Model of particle physics, and the standard big-bang cosmology. But it is very clear that we do not yet have the full theory, because that must be based on a single theoretical framework, and such a framework is still lacking. Thus, as humanity emerges into a new century, the completion of the new theory that will finally replace Newtonian physics remains the primary goal of theoretical physics.



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String theory is one way of unifying gravity and quantum mechanics in the quest for a theory of everything. According to some versions of string theory, six of the universe's ten dimensions are curled up into Calabi–Yau spaces like the one shown here

The theory we are searching for must unify relativity and quantum theory, which is why it is often called a "quantum theory of gravity". If we do not succeed in unifying these theories, then we will not have a real physical theory at all, in the sense that both relativity and quantum theory, in their present forms, each cannot make any predictions about a wide range of physical phenomena. There are also many domains where we expect that the two theories overlap, and where no predictions are possible without some kind of unification. These phenomena occur at extremely small distances or, equivalently, at extremely high energies – some 20 orders of magnitude away from the scales at which we do particle physics with accelerators. This high-energy domain is called the Planck scale.

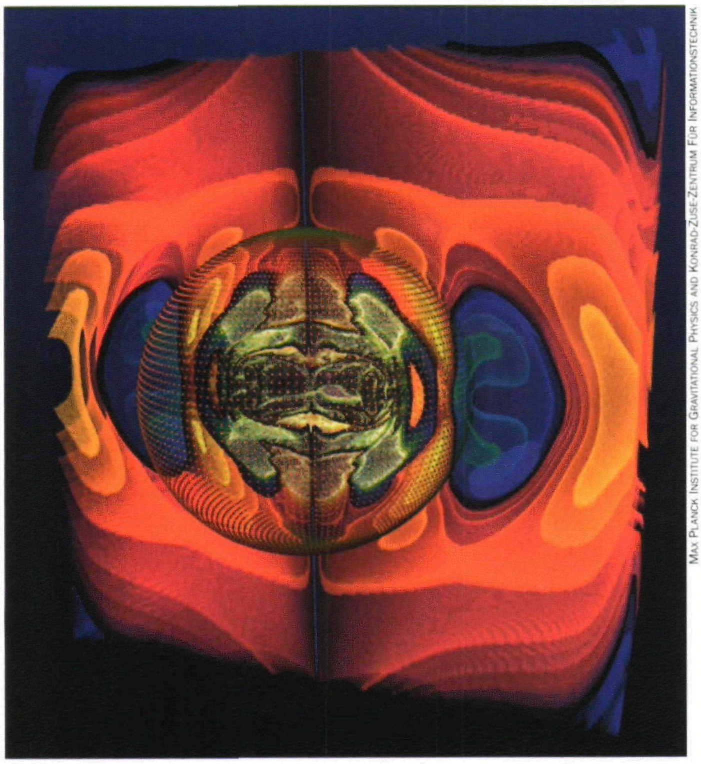
At the same time, the unification of our existing theories is only a part of what we are looking for. No less significant is the fact that, as we have learned from Einstein's general theory of relativity, the universe as a whole is a dynamic entity. Einstein's theory presents space and time not as a fixed, unchanging background to nature, but as an evolving network of relationships that make time and matter one inseparable system. And other aspects of the universe – such as its overall organization and, perhaps, even the laws that govern the interactions of the elementary particles – seem to have as much to do with its early history as they do with any *a priori* principles. The consequence of this is that the search for an understanding of the fundamental particles and forces is connected to the history of the universe. At their roots, cosmology and particle physics have become inseparable.

Reasons to be cheerful

Let us call the great synthesis that so many of us are searching for Theory X, so as not to prejudice us as to its nature. In this article, I will argue that we are closer to its formulation than many people think, and that while we will have to spend a long time working out its consequences, its formulation may be one of the first triumphs of science in the 21st century.

To explain why I am so optimistic, let me begin by saying something about the field of quantum gravity. Because the problem is so big and fundamental, there is more than one place to start to attack it. One can begin by trying to modify quantum theory in such a way as to include the gravitational force. Or one can start from the other side and try to make quantum theory correspond to the basic principles of relativity theory. Or one can take different features of general relativity and try to express them in quantum-mechanical language. The result is that there are different groups of people searching for quantum gravity from different starting points. Some of them have succeeded in answering the questions they began with, and some have even moved on to try to tackle the questions that they ignored at first.

We now have a collection of different approaches to quan-



MAX PLANCK INSTITUTE FOR GRAVITATIONAL PHYSICS AND KONRAD-ZUSE-ZENTRUM FÜR INFORMATIONSTECHNIK

Gravitational waves are emitted by any accelerating mass, according to the general theory of relativity. This simulation depicts a gravitational wave collapsing to form a black hole, showing that one does not need matter to form a black hole. But can the results of general relativity be unified with quantum mechanics to form a quantum theory of gravity?

tum gravity, going under various names such as string theory, loop quantum gravity, twistor theory, non-commutative geometry, random geometry, causal sets, toposes, and so on. It is natural to wonder what all of these have to do with each other, as well as with the ultimate theory we are all looking for.

One point of view is that these approaches are all rivals and that, like a sailboat race, only one can win. I think this is mistaken. Like the parable of the blind men and the elephant, it is not surprising that different groups of people who took different starting points have understood different aspects of quantum gravity. What we need to do now is to place all our results on the table, take off our blindfolds and see how to fit the different results together.

This is not very different from the state of quantum theory in about 1920, a few years before quantum mechanics proper was invented. At that time there were several different approaches to quantum physics that yielded predictions concerning different experimental domains, such as atomic spectra, the specific heats of materials and the physics of radiation. What remained was to make a synthesis of the different approaches. Of course, this required new ideas, but given the stock of clues that had been assembled, a new generation of bright young people required only a few years to find them. This is what I think will happen with quantum gravity. As long as we are sure to make room for the kinds of young people who dream of doing great things, I will not be surprised if – given how many clues we now have – it only takes a few more years.

It must, of course, be said that the inventors of quantum mechanics had a huge advantage, namely that they were able to test their theories experimentally. But it is important to stress that several approaches to quantum gravity make predictions of phenomena that are so unexpected from any other point of view, that if we could confirm these phenomena experimentally, it would provide convincing evidence for those versions of quantum gravity. These predictions are also completely precise, so that if they do not turn out exactly as forecast, it would falsify the theory that produced them. And, as I will describe at the end of this article, new ideas for how to do such experiments are already being devised.

Four paths ahead to quantum gravity

It is time to be more specific. I do not have space here to describe all the exciting things that are going on in quantum gravity, but I will describe four approaches that I feel have developed far enough to give us a clue about what the world is like at the Planck scale, where classical ideas about gravitation no longer apply. I will cover only the most essential ideas of each approach – the list of further reading gives more information about these approaches and the scientists who are pursuing them.

First is "semi-classical gravity", an approximate approach in which matter is treated quantum mechanically, while the geometry of space–time is treated strictly according to Einstein's general theory of relativity. While limited, this approach has made several striking predictions. For example, a particle detector accelerated with constant acceleration g through a vacuum will respond as if it were in a thermal bath at temperature $T = hg/2\pi c$, where h is the Planck constant and c is the speed of light. This leads to the prediction that black holes are hot thermodynamic systems with a temperature that is inversely proportional to their mass, and with an entropy that is proportional to their surface area. These discoveries have had a huge heuristic value in focusing our efforts, and they remain – 25 years after they were discovered – the most important clues we have about quantum gravity.

The second main approach is string theory. The unique approach that yields a successful description of quantum gravity at a certain level of approximation, which is called a background-dependent theory. In this approximation, gravitons – which are to gravity what photons are to light – are treated as particles moving in a fixed, non-dynamical space–time. One assumes that the gravitons scatter and interact with each other, but only weakly. What string theory has shown is that to do this consistently, the gravitons have to be seen as excitations of one-dimensional entities, known as "strings", rather than point-like objects. Moreover, for consistency, it turns out that all the other particles and forces in nature must also arise from excitations of these strings. To have understood this aspect of quantum gravity even in this approximation is a great achievement; before string theory was invented people had tried and failed for 30 years to make a quantum theory of gravity that succeeded at this level. But string theory is still only an approximation that cannot address many interesting questions.

Nevertheless, one thing that string theory does very impressively is to unify gravity with the other forces in an elegant and surprising manner. Having said that, string theory has one very serious limitation: no-one knows how to formulate it in a way that transcends the kind of approximation that was originally used to define it. If string theory cannot overcome this approximation, it fails to provide a language for formulating a fundamental theory in which no approximations are made. In particular, the geometry of space and time must, in this fundamental theory, be described fully within the language of quantum theory, and in a way that preserves the key notion that the geometry of space and time is dynamical and not fixed.

A related set of problems arises from that fact that string theory – as it is currently understood – comes in a large, and probably infinite, number of versions, each of which describes a world of different dimensions, with a different spectrum of fundamental particles and interactions between these particles. There are some very exciting hints that these different theories describe different physical phases of some more fundamental theory that transcends the approximation of background dependence. Whether or not this is true, all of the different string theories predict some common behaviour in the scattering of particles at Planck-scale energies. So if this behaviour were observed, it would confirm the conjecture that, within the background-dependent approximation at least, the fundamental excitations of quantum geometry are string-like and not point-like.

The third approach – "loop quantum gravity" – is in many ways complementary to string theory. Loop quantum gravity succeeds where string theory fails in that it can describe the geometry of space and time in a purely quantum-mechanical language. Unlike string theory and semi-classical gravity, however, loop quantum gravity does not need to describe quantum gravitational effects as small excitations of a classical geometry. It therefore leads to the striking prediction that all measures of spatial geometry, such as areas and volumes, must be discrete (rather than continuous) quantities. Like atomic energy levels, these discrete quantities are represented by operators that have purely discrete spectra. These spectra have been computed and give rise to predictions that could be verified – or falsified – by experiments that probe the geometry of space–time at the Planck scale. The result is a picture of the atomic structure of space in which space is built up from a network of very tiny, discrete elements.

At the same time, loop quantum gravity so far fails exactly where string theory succeeds, which is in describing gravitons and their interactions in the approximation where they are seen as small excitations of a classical space–time geometry. Loop quantum gravity has trouble doing this because it cannot explain why the discrete structures it predicts should organize themselves in such a way that they can be approximately described by a smooth classical space–time. This is analogous to many problems in solid-state physics. It is not, for example, easy to predict the macroscopic properties of the different phases that a material may have from an exact description of the atoms of which it is composed.

To see how quantum geometry organizes itself into a state in which space can be described to a very good approximation as an almost flat 3-D continuum, physicists have been learning to apply various methods from statistical physics.

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Loop quantum gravity is another way of unifying quantum mechanics and relativity. But unlike string theory, it manages to describe the geometry of space and time in purely quantum-mechanical terms, and predicts that areas and volumes should be discrete, rather than continuous, quantities. This picture shows a numerical experiment in which a discrete quantum geometry is modelled and the process by which a smooth classical space emerges from it is studied. The image is taken from a simulation of a statistical-mechanical model that realizes some of the objectives of loop quantum gravity. In the model studied here, space and time each have one dimension. (See http://www.nbi.dk/~ambjorn/lqg2/)

These results indicate that quantum geometry has different phases and that in only some of them does anything like our classical notion of space exist. It turns out that the process by which smooth classical geometry can emerge out of the quantum world may be a kind of "freezing", like the process that creates ice from water. This suggests that the big bang may be more properly thought of as "the big freeze", in which our universe emerged as quantum geometry cooled to a temperature much below that of the Planck scale.

The fourth and last developments are a set of new approaches to the interpretation of quantum theory. These have been invented to resolve a set of puzzles and paradoxes that arise when one thinks of extending quantum mechanics from the level of atoms to become a theory of the whole universe – so-called quantum cosmology. These puzzles and paradoxes arise because the observer in quantum theory is normally outside the system being studied. So what are we to do if the observer is instead part of the system, which must be the case if the system is the whole universe? To say that one is observing the universe "from outside it" would therefore be meaningless. Any such approach must therefore make sense of quantum theory where the quantum state includes the description of the observer.

While this problem is very old, a new set of ideas has recently been proposed to solve it. These ideas are called "relational" approaches to quantum cosmology. They extend the mathematical structure of quantum theory in such a way that the division between "system" and "observer" can be made differently depending on the situation of the observer. These relational approaches take into account the fact that any observer inside the universe can only observe a limited set of things that may be true of it. They reveal a kind of relativity principle, which makes it possible to extend quantum theory so that the limited views that different observers can have of the universe are all taken into account. There are several different versions of such approaches, known by a variety of names such as "consistent histories", "quantum causal histories" and "topos theory approaches". Although these various approaches are likely to be just different ways of saying the same thing, we cannot yet be certain about this because they are so new.

The world according to quantum gravity

In the rest of this article, I would like to describe a picture of the physical world that comes from combining the robust and characteristic results of these four approaches to quantum gravity. This picture may not be right – but what is important is that, for the first time, we have enough results on the table to be able to put together a more-or-less complete picture of what experimentalists may find when they probe the Planck

Quantum gravity and the new mathematics

Developing a theory of quantum gravity will require more than good ideas. It will also force us to invent a new type of mathematics, for the existing mathematical language of theoretical physics will not be good enough. The new mathematical language that has begun to appear in papers on quantum gravity is generally called "category theory". This is an alternative framework for the foundations of mathematics, in which one begins not with sets, but with relationships. Category theory provides the natural mathematical language for quantum gravity, because it allows us to describe quantum systems composed only of systems of relationships that do not live in any classical world. In such a world there is no background classical geometry. We must then seek a different kind of description, which does not rely on a picture of objects or fields moving with respect to a fixed "space".

One very powerful tool that helps us to do this is based on taking very seriously the way in which we use group theory in quantum mechanics. Recall that a group is a set of operations that describe a symmetry. A symmetry is an operation by which a system may be transformed, for example by rotating or translating it, but without changing the relationships among its parts. When we apply group theory to a quantum system, the "representation" of the group is a very useful idea. A representation is a space, or a set of objects, on which the transformations that make up the group can act. For example, in quantum theory, particles of different spin provide different representations of the group of rotations. Each transforms in a characteristic, and different, way when they are rotated.

A very basic question in quantum theory is: what happens when these different representations are combined? In basic quantum theory, this is the problem of "addition of angular momentum". It is quite surprising when one encounters this subject in a first-year quantum-mechanics course, for – all of a sudden – one is studying structures that seem much simpler than where they came from. Indeed, to analyse a system in terms of representations of its symmetry group is a trick that helps immensely in every area of quantum physics.

However, when we do this we imagine we are usually just employing a lucky trick, and that the more complicated picture in terms of differential equations in space is the fundamental one. What category theory tells us is that we can invert this picture and take the very simple view given by thinking about representations of symmetries (and how they combine) to be fundamental, while the more complicated picture in terms of wavefunctions that satisfy differential equations in space is secondary and derived.

In different approaches to quantum gravity, such as string theory and loop quantum gravity, we have found that we can exploit this to give a fundamental quantum-mechanical description of the geometry of space and time, in which there is no continuum and no differential equations. Basically everything is counting, albeit counting according to the rules of quantum theory! Another way to say this is that geometry has become part of quantum theory: it has become non-commutative, in the sense that the non-commutivity of operators in quantum theory has been taken down to the level at which space is defined.

One illustration of the power of this new mathematics is that it has been used to construct completely a large class of quantum gravitational theories, which are called "topological" quantum field theories. These are theories in which there is no classical geometry at all, and all the degrees of freedom live on the boundaries of space–time. But this is exactly what the holographic principle calls for and, not surprisingly, it has been found that at both the classical and quantum level, all known gravitational theories arise from deforming the mathematical structures of topological quantum field theories.

Very recently, a second role for category theory has appeared, which is to provide a mathematical language for a quantum theory of cosmology. It turns out to give a natural mathematical language for addressing the problem of how to describe quantum physics in the case of cosmology in which the observer is necessarily part of the system. This makes it possible, for the first time, to formulate quantum theory in a precise way so we can make sense of the requirement that everything described by the theory must concern things seen by observers inside the universe.

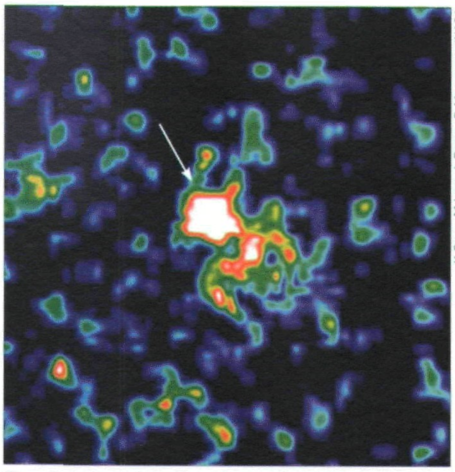
I believe that these developments are beginning to reveal the natural mathematical language for the quantum theory of gravity. It is a language that is fundamentally quantum and discrete, according to which purely quantum processes are described easily without ever having to use differential equations or see the world in terms of objects propagating in "space". It is a world built from relationships alone.

scale. There are seven main features to this picture.

- Space, time and all physical quantities are about relationships between things in the world. There is no fixed background, the structure of space and time are dynamical, as is everything in them. In other words, there is nothing to time but the relationships between things that happen, such as "before" and "after". There is nothing "fundamental" behind these relationships. This means that the fundamental theory knows nothing of points in space or moments in time, it knows only about relationships between things that happen.
- The fundamental "stuff" of the world will not turn out to be fields, and it will not be geometry either. It will instead be information – or rather, because process must be more important than stuff, it will be the flow and transformation of information. This is why thermodynamics appears whenever quantum physics is confronted with a non-trivial causal structure, as in black holes.
- Geometrical quantities, such as area and volume, are discrete. At the fundamental level, they are like electric charge or the energy levels of an atom, coming in fixed, discrete amounts. This leads to a very elegant description of geometry at the purely quantum-mechanical level, which may be expressed in terms of discrete mathematics. Just as we talk about the quantum state of an atom, one can talk about the quantum state of the geometry of a region of space. A quantum state of the space–time geometry is described as a certain kind of graph, called a "spin network", the edges and nodes of which are labelled by discrete numbers, analogous to the quantum numbers of atomic orbitals.
- The fundamental excitations of the quantum geometry are not point-like, but are one-dimensional or more-than-one-dimensional. Just as hitting a drum creates sound waves, so disturbing the geometry of space creates (in quantum-mechanical terms) extended objects with one or more dimensions.
- The notion of what is an observable physical quantity changed drastically when quantum theory was invented, and it seems that it will have to change again for quantum gravity. This time we will have to give up the notion of a field, which is essentially an idea from the 19th century. According to our notion of a field, observable quantities are associated with

magnitudes that vary separately at each point of space, like the value of the magnetic field. While this has become a very intuitive idea, it seems that we will not be able to speak of the world in this way when we have a quantum theory of gravity. Instead, a new principle called the "holographic principle" states that observable quantities are only connected with information that flows across boundaries. These are boundaries that separate the system being studied from the observer. In other words, the theory will not permit us to speak about what happened at particular points in space–time. It will only allow us to say what information arrived at a particular observer.

The principle also imposes a fundamental restriction on the information that a particular observer can know. This plays a role that is rather like the uncertainty principle. The restriction is on the amount of information that can flow across any surface in space: there cannot be more bits of information than the area of the surface, measured in units of the Planck area, which is $G\hbar/c^3$, or about 10^{70} m^2, where G is the gravitational constant and $\hbar$ is the Planck constant divided by 2π. In other words, only one bit can flow across for every 10^{70} m^2.


K SAHU, M LIVIO, L PETRO, D MACCHETTO/NASA

Quantum theories of gravity predict that space has a discrete – rather than continuous – structure at the tiniest scales. If this is the case, it must have a measurable effect on light that travels across space. Although studies of the light emitted by gamma-ray bursts – such as this one recorded by the Hubble Space Telescope – have failed to detect any evidence for a discrete structure, tests at higher resolution could soon tell a different story

Of course, in ordinary experimental physics we do not come close to this boundary. But our theories seem to require that it is there. Although there is not space here to give the argument why we believe this, it boils down to showing that if the limit were exceeded, it would be possible to use black holes to violate the second law of thermodynamics.

The holographic principle may seem mad, but there is increasing evidence that it is in fact realized in quantum theories of gravity. This is an indication of how far we have come, as the holographic principle fits into our developing picture of quantum gravity, but does not even make sense in a conventional theory.

- The parameters in the laws of physics are all dynamical. In all known dynamical theories – whether fields or particles, whether classical or quantum mechanical – there are parameters, such as the value of the electric charge, that are assumed to be fixed for all time. These parameters yield the values of fundamental quantities, such as the masses of particles and the strengths of the different interactions. A very surprising and characteristic feature of string theory is that this is no longer the case. Every time a parameter has shown up in the theory, it has turned out, on closer examination, to actually be a dynamical quantity that changes with time according to some law of motion, and can thus vary from solution to solution. There are good reasons to suspect that this must be true of any consistent quantum theory of gravity.

One consequence of this is that many of the properties of our world, such as the dimension of space and the masses of the different elementary particles, are able to vary from solution to solution. This means that the values of these quantities that we see in our part of the universe cannot be explained from first principles. Instead, they will have something to do with why one solution to the theory describes our world rather than another, which in turn is likely to have something to do with the history of our own universe.

- All distinctions between different particles and forces are due to "symmetry breaking", according to which a theory may have a symmetry that is not realized in its particular solutions. In this context, symmetry breaking means that, at the fundamental level, there is no difference between matter and geometry; they are both combined in a single unified description. This means that the description of physics at the Planck scale must be very different from physics in ordinary quantum theory. In both string theory and loop quantum gravity, this requirement is accomplished by replacing geometric descriptions by algebraic ones, so that the degrees of freedom are not described in terms of positions in some space, but in terms of representations of some algebra.

Experimental tests for Theory X

Of course, we have no experimental support for any of these ideas. They may even turn out to be wrong. But if even half of them are right, the quantum theory of gravity will be much more than just a small elaboration of existing quantum field theories. It must involve the invention of an entirely new kind of physical theory. Are we really closing in on the development of such a theory? Certainly the invention of such a theory will require more than just a few good ideas. It will require the growth of new mathematics, because if we only had to apply the usual mathematical formalisms of theoretical physics to find this new theory, then someone among the hundreds of people working on quantum gravity and string theory would surely have discovered it by now. And it will require the development of new experimental techniques, for it is clear that we will never be able to build a particle accelerator that can collide particles at high enough energies to see quantum-gravity effects.

What makes me optimistic is that in the last few years we have seen the emergence of a new mathematical framework for quantum gravity (see box). But perhaps the most exciting recent development in quantum gravity has been the discovery that it may be possible to probe the Planck scale with existing technology. Not surprisingly this is not done by building huge accelerators, but by using the largest system we have access to – the universe. The idea is that if there is really a discrete, atomic structure to the geometry of space, then this must have a small effect on how light travels. This would be similar to the way that light is dispersed by the atoms in the air. This effect is incredibly tiny, but it does add up the further light travels, so that the total effect on a signal is proportional to the distance it has travelled.

Astronomers routinely observe light that has travelled significant fractions of the size of the universe. Over such cosmological scales, they resolve objects with sharp structures in space and time. This makes it possible to put incredible limits on the breakdown of the smooth structure of space. By analysing existing data from X-ray and gamma-ray bursts, it has been possible to show that space is smooth down to scales much smaller than have been probed in particle accelerators. Studies currently underway may show that, with entirely attainable improvements in the resolution of these experiments, it will be possible to see if – as predicted by quantum theories of gravity – the space–time continuum dissolves into a network of relationships among discrete quantum processes.

All of a sudden, those of us working on quantum gravity are faced with the possibility that we may be able to test our theories in the very near future. When this happens, quantum gravity will cease to be a kind of fringe activity, which currently is as much mathematics and philosophy as it is physics. It will then become like most other sciences, and progress will be driven by the interplay of experiment and theory. Once we reach that stage, I do not think it will be too long before ingenuity on both sides leads to the discovery of how to fit the different pieces I have described here into one theory. Moreover, this theory will be compelling as much for its beauty and logical coherence as for its ability to explain what experimentalists see.

Even at that point there will still be much to do; after all, we have known about quantum chromodynamics (the theory of the strong force) for more than 25 years and there are still many experimental and theoretical challenges in that field. Beyond that, new experiments and observations will reveal new puzzles. People a century from now will surely feel as perplexed and excited by the questions on the frontiers of science as we feel now. We cannot know what those questions will be, but unless everything I have described here is shown by experiment to be wrong, I think we can safely predict that they will not be the same questions that have puzzled us so deeply since Einstein first asked, in 1915 or so, what the new quantum theory and the new theory of gravity had to do with each other.

Further reading

String theory

B Greene 1999 *The Elegant Universe* (Jonathan Cape, London)

www.superstringtheory.com

www.strings.ph.qmw.ac.uk/WhatIs/top.html

Loop quantum gravity

R Loll 1998 Discrete approaches to quantum gravity in four dimensions *Living Reviews in Relativity* **1** (http://www.livingreviews.org) – discusses different approaches to quantum gravity

C Rovelli 1998 Loop quantum gravity *Living Reviews in Relativity* **1** (http://www.livingreviews.org) – a recent review of the subject

L Smolin 1997 *Life of the Cosmos* (Weidenfeld and Nicolson, London)

http://vishnu.nirvana.phys.psu.edu – a good Web site for quantum gravity

http://math.ucr.edu/home/baez/README.html – introduces various physical and mathematical topics on quantum gravity

Astrophysical observations to probe the Planck scale

G Amelino-Camelia *et al.* 1998 Potential sensitivity of gamma-ray burster observations to wave dispersion *in vacuo Nature* **393** 763

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