A Universe of Bubbling Loops

A theory of everything is the Holy Grail of physicists. Yet, in the search for this theory that unites all forces, they are brought up short by the limits of what the human mind can actually grasp. Today, loop quantum gravity is considered a promising candidate for the solution to this problem. **THOMAS THIEMANN** *from the* **MAX PLANCK INSTITUTE FOR GRAVITATIONAL PHYSICS** *in Potsdam is one of its leading proponents worldwide. In the following article he reports on his work.*

PHOTO: MPI FOR GRAVITATIONAL PHYSICS

Since the beginning of the 20th century, physics has celebrated some brilliant successes. Not only has it developed quantum theory and the theory of relativity, it has also demonstrated their validity in numerous experiments. Gradually, theories were developed that describe the electromagnetic force, the nuclear force and weak interaction, as well as their connection with fields and particles. Today, we have physical theories that correctly describe natural processes over a huge range of distances – from the diameter of a proton to the expanse of the visible universe. And all of that with mathematical formulas that fit on a sheet of paper!

However, despite these great feats, physics remains essentially a patchwork. There is still no theory of everything, one that takes into account and explains every force and every particle. The biggest names in physics have tried, but none of them has yet had any success. Particularly the attempt to reconcile the phenomena of the fourth interaction, namely gravity, with quantum theory always comes up against an unyielding mathematical limit. Today there are various approaches to overcome this, the most significant ones being string theory and loop quantum gravity.

String theory assumes that all types of elementary particles, from leptons to electrons to quarks, which make up protons and neutrons, manifest themselves as different states of excitement of a single type of object: strings. These strings vibrate like the strings on a guitar (hence the name) in a space that has 10 or 11 dimensions.

Loop quantum gravity does not need this multidimensionality. It remains within the 4 familiar dimensions of space and time and postulates that they are not continuous, but consist of quanta (the smallest indivisible units) – the loops. Using this imagery, it is possible to picture the world as having a web-like structure: space is not smooth like a plastic film, but textured like terry cloth. The same also applies to time: it consists of tiny steps whose further breakdown is neither possible nor practical.

Why didn't we ever notice this structure before? Because it is extremely fine. The smallest unit, a loop, is approximately 10^{-33} centimeters long. This is called the Planck length, calculated from three natural constants: the speed of light, Planck's constant and the gravitational constant. Similarly, a time quantum is the time a particle traveling at the speed of light would take to move through a space quantum. In other words, the surface of an A4 sheet of paper would be made up of 10^{68} – or 1 followed by 68 zeros – of these loops.

For more than 10 years, from 1984 to 1996, string theory and loop quantum gravity were developed totally isolated from each other. Then the two theories slowly converged, but even today, they are still fundamentally incompatible. Nevertheless, scientists take both very seriously, and an increasing number – currently around 300 worldwide – are working on loop theory and similar approaches to quantum gravity.

This image, as well as that on the left above, shows an artist's impression of quantized space. They are snapshots of a dynamic geometry consisting of loops. Matter can be present only where the geometry is activated.

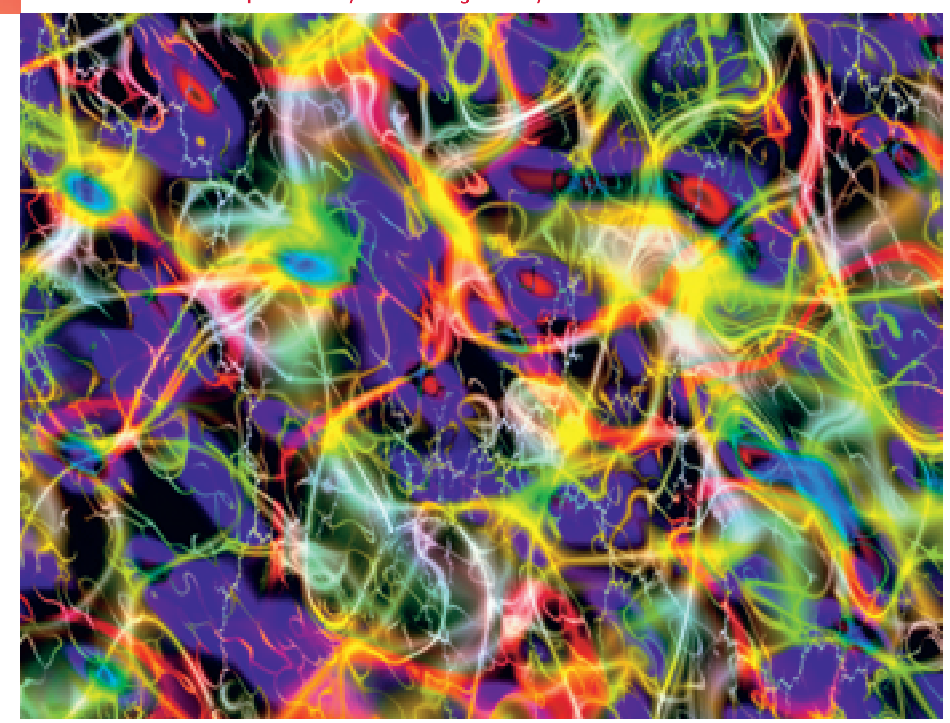


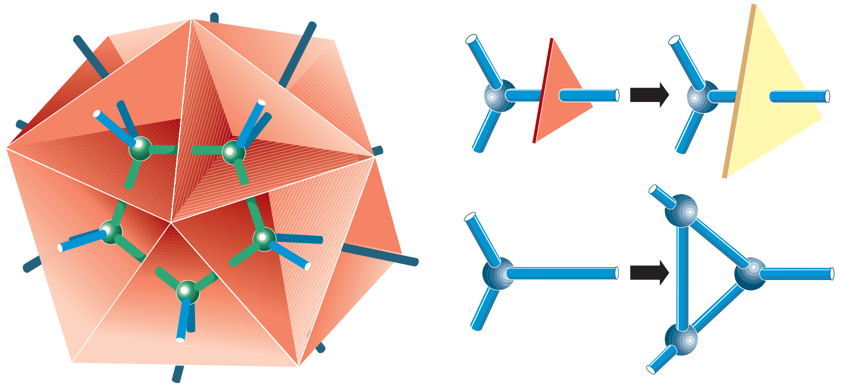
PHOTO: SCIENCE PHOTO LIBRARY

GRAVITY NEEDS NO FIXED TIME

Along with the Perimeter Institute in Waterloo, Canada and the Institute for Gravitational Physics and Geometry in the US, the Max Planck Institute for Gravitational Physics in Potsdam is one of the centers for this research. Around 150 loop theoreticians, including all the leaders in the field, met last October at the *Loops 05* conference in Potsdam to share their latest ideas and progress reports. They also discussed how the theory might be put to the test in experiments.

Of the four known forces – electromagnetic, weak and strong forces and gravity – gravity is the least understood. Unlike the other forces, it resists quantization. Quantization of the other forces has been described by theories such as quantum electrodynamics, quantum flavor dynamics and quantum chromodynamics. Each of these theories, summarized in the Standard Model of matter, is subject to physical predictions that have been measured very precisely and confirmed by experiments in accelerators, such as CERN, DESY and SLAC. There is, therefore, no doubt that quantum theory is the correct description for these forces. So-called interaction mediators – the particles that carry the forces – play a part in it.

What is so different about gravity that it resists quantization? Does it



Such images illustrate the construction of quantized space. On the left, a spin network of polyhedrons, on the right, the development of spins over time. The knots in the left-hand image can split open and create a kind of foam structure.

Illustrations: Frankfurter Allgemeine Sonntagszeitung, Oct. 20, 2005/F.A.Z.-Grafik Döring

even need to be quantized? The answer can be found by carefully considering Einstein's theory of relativity. According to this theory, gravity is not a force in the traditional sense, but is equivalent to geometry. A planet does not orbit a star because interaction-carrying particles (gravitons) facilitate an exchange of forces between them; rather, the planet orbits the star because the star bends the geometry of spacetime. In the same way a ball in a mini-golf game is diverted by a dip and rolls toward the lowest point, the dent in space caused by the star influences the planet's path and makes it circular. In other words, matter curves space.

A Model from Classical Physics

In this sense, the general theory of relativity is much more than a theory of gravity – it also realizes Einstein's basic idea of the geometrization of physics. For him, gravity is synonymous with geometry and is therefore independent of fixed spacetime. It is this principle of the underlying independence of the general theory of relativity that cannot be reconciled with quantum theory. Proponents of loop quantum gravity have implemented this idea logically and have quantized, not gravity, but the geometry of space itself.

But how can a world be constructed only from quanta? An analogy from classical physics can help us here: in the Maxwell theory of electromagnetic fields, the interesting quantities are electrical and magnetic fluxes. For example, magnetic flux can be shown as an integral over a surface or as a linear integral over the edge of this surface. This is how the image of loops is created – they are the edges of the flux surfaces. These quantities are interesting as they are invariant (that is, unchanging) in the face of movement of any kind.

In the Maxwell theory, for example, it is possible to rescale the potential – in other words, to move the zero point – without any physical changes being visible. The loops are invariant in the face of such rescaling. As quantum gravity theoreticians also deal with loop integrals, these objects of the theory have commonly been dubbed loops since the mid-1980s. With many complicated mathematical operations, it is now possible to construct a dynamic spacetime from these loops. To do this, they are combined, in the form of spatial structures, into graphs or – in mathematical terms – into functions. Each loop is always linked to all of its neighbors. In this way, an infinite number of these graphs form, to put it simply, a kind of crystal. However, this crystal is not rigid, but honeycombed because, like most objects in the quantum world, all of its tiny elements are constantly changing. Space thus no longer has the smooth, Euclidian geometry that, in our experience, describes the visible world, but rather consists of a seething mass of tiny loops. Similar to the way electrons incessantly orbit the nucleus of an atom, here, the geometry of space dances and surges.

The edges between the crystal surfaces are particularly important; like the surfaces themselves, they are labeled with quantum numbers. As the loops are all linked together, everything is vastly interconnected – so nonlinear. Nevertheless, the theorists use only those mathematical tools with which they are already familiar. They exploit mathematics to the logical extreme. They also use everything that the quantum field theorists have come up with in the last century. Even when they put something new together, they use new varieties of familiar constructions.

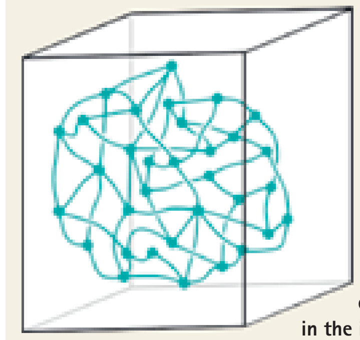
Accordingly, gravity creates the space in which everything happens. The theorists also want to bring matter into the game. However, as loop theory creates its own spacetime, the particle terminology from quantum mechanics, which is based on a fixed spacetime, cannot be used here. The particle term from other theories can nevertheless build on loop theory, as it is possible to develop a similar language for matter and, as it were, pack it on top of what has previously been said. At the same time, the forces develop from this. Photons are described by loops; quarks and electrons, on the other hand, sit at specific points on this structure.

Loops Require Only Four Dimensions

The loop quantum gravity approach is consciously conservative: it is based solely on facts that are supported by experiment; it does not require additional assumptions; and it analyzes the consequences of the interplay of the principles of the general theory of relativity and quantum theory. Aiming for rigorous mathematical consistency, the theory is taken to its logical limits. This guarantees that either the right theory is constructed or, in the course of analysis, it is systematically determined which new structures are required, rather than having to guess at them.

We assess a philosophy of this nature, which might look like a highly intelligent game, based on whether it progresses the description of nature beyond the existing theories – and loop theory does just that. It requires, as I already mentioned, only our four dimensions, and it also manages to avoid a shortcoming of the general theory of relativity: applying its equations logically gives rise to bizarre physical situations, known as spacetime singularities. These are the points in space where the curvature, and thus the concentration, of matter is infinitely large. Black holes are such singularities, as is the Big Bang.

Graphic: MPI for Gravitational Physics



The Lego Bricks of Loop Theory

In loop quantum gravity, the basic structure of spacetime turns out to be discrete: the values of areas and volumes can be changed in (naturally tiny) steps and there are minimum areas and space volumes below which the space cannot be further divided – in the same way that it is not possible to build an object with a Lego set that is smaller than the smallest Lego brick available. The basic structure of space is a "spin network" of linked knots as shown in the illustration. The smallest conceivable volume, a space quantum, contains one knot. Any volume, therefore, consists of a certain number of knots. If another knot is added, the space content increases by one characteristic space quantum.

Quantization of space helps to avoid such singularities. This example from atomic physics is an analogy: according to the classical Maxwell theory of electromagnetism, atoms should not exist at all. This is because electrons, which move in an orbit, normally emit bremsstrahlung, thus losing energy. Each electron that circles the atomic nucleus would therefore fall into the nucleus after a short time. The atoms would be unstable and we would positively burn up. Quantum theory explains why this does not happen: the permitted energy levels in the atom are discrete, that is, quantized. Experiments also allow this to be read from the atomic spectra: there are no bremsstrahlung lines because the atom emits none – the classic singularity disappears.

Quantizing spacetime achieves a similar situation. Martin Bojowald from Pennsylvania State University in the US has applied my work on the dynamics of loop quantum gravity to a quantum cosmology model and discovered that the singularity predicted by the general theory of relativity as the Big Bang no longer figures in loop theory – quite like the example of the atom with discrete energy levels. Although this is not proof that there are no singularities at all in loop quantum gravity, it can be considered an initial first indication. Instead of singularities, there are values that might become big, but remain finite. Calculating the largest possible curvature yields a value of one divided by the square of the Planck length, or 10^{66} cm^{-2}.

What does this mean for the Big Bang? It is not yet fully understood, but it might mean that the universe had no initial singularity at all. In

According to Einstein's general theory of relativity, gravity is synonymous with geometry. A "dent" caused by a star in space, for instance, affects the path of a planet and shapes it into an orbit. Matter thus curves space.

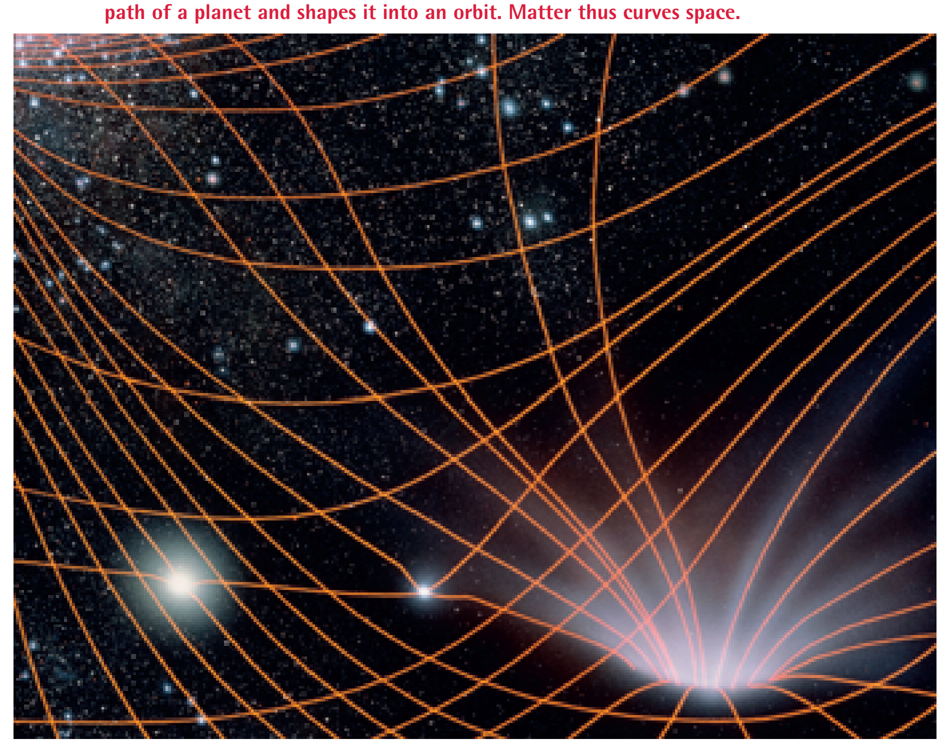


Photo: Science Photo Library

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Loop quantum gravity has provided the first mathematical basis for calculating back further than the Big Bang.

other words, the universe has always existed; it had no beginning. It may, at some point, have been quite small, but before that, it may have also been just as large as it is today.

The Infinitely Long Fall into the Black Hole

By no means does the loop theory dispute that there was a Big Bang. At that time, the entire universe was packed into a very tiny volume – but not to zero. From a philosophical standpoint, it makes a big difference whether it must be assumed that everything had a beginning or whether it was always there. Loop quantum gravity has now also provided a mathematical basis that allows calculations to back before the Big Bang. This did not previously exist with such clarity.

It works in a very similar way with black holes. The whole theory had to be reconstructed from scratch because many propositions relating to black holes were based on the assumption that they collapse into a point, which is not possible in loop theory. In physical terms, this is something completely different. It means that things can indeed reemerge from a black hole.

A black hole is a strange phenomenon. From the outside, it is possible to see someone fall into it, but it is never possible to observe whether the person really falls into the center because that would take infinitely long – like a star, for example, that collapses into itself. Thus, viewed from the outside, a black hole should not be called a black hole but rather a frozen star. From the outside, it does not look like a dot, but like a sphere that can't get any smaller than the Schwarzschild radius, which marks the sphere from which the object could still escape if it were faster than light – but the special theory of relativity forbids this.

For an observer on the inside of the black hole, however, things look bizarrely different. Someone falling into a black hole falls in finite proper time precisely into the singularity. According to the theory of relativity, they wouldn't have a chance: they would be crushed to an infinitely small dot. The discrepancy between the perceptions that the observer and the intrepid traveler have of a black hole is the result of the peculiarity of the concept of simultaneity. This has already given rise to a few brainteasers in the special theory of relativity.

In loop theory, the total matter doesn't collapse into a point, but is instead stretched infinitely – also for the person who falls into it. Seen from the outside, the black hole looks exactly the same as it did before. The person falling is still stuck in it, but is not crushed into a point.

Whether loop theory is correct with regard to these statements must first be proven through experiments. "If you have a theoretical structure that explains nothing and predicts nothing, you are no longer doing science," says Lee Smolin from the Perimeter Institute.

With a theory like loop gravity, which deals with Planck scales of 10^{-33} centimeters, experimental testing is difficult because the objects are so tiny. It is not, however, as absurd as it sounds: if loop theory is right, then our conception of space is wrong – it is not a smooth, flawless structure, but a crystal on the Planck scale that changes constantly. And this is where an experiment could start out: in our normal world, light does not pass undisturbed through a crystal, but is scattered widely. As a result, the speed of light changes in the crystal and the change depends on the frequency of the light. This is reflected in experiments by the different transit times for photons passing through the crystal.

A similar thing could happen in the quantized spacetime geometry of loop quantum gravity: the speed of light in the vacuum would no longer be an absolute value, but would vary over time. The more energy the photon has, the more strongly it feels the presence of discrete structures, the more its propagation is disrupted – and the more it slows down.

However, these transit time differences, which are a result of the impact of gravity, would be so small (even if they were linear) that they would be impossible to measure, even with the greatest accuracy – at least that is what physicists thought for a long time. In 2001, however, Giovanni Amelino-Camelia from La Sapienza University in Rome and John Ellis from CERN in Geneva cast doubt on this assumption with some bold speculations. The trick they suggest is "to wait long enough" in the experiment – meaning one to ten billion years! It is not necessary for experimental physicists to sit out this time themselves – the universe will do that for them; there are galaxies from which light takes billions of years to get to Earth.

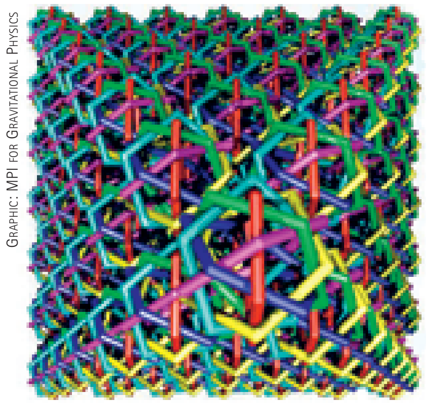
Gamma ray bursts, which reach us now and again from distances of around ten billion light years, are particularly suitable for informing physicists that the different light waves have left the starting line. If these can be broken down with sufficient precision, the light they emit might reveal a frequency-dependent shift in the transit time. Based on predictions from loop quantum gravity, it could indeed be within the measurable range.

Planck to Supply Proof of the Loops

At the Loops 05 conference, Oliver Winkler and Stefan Hofmann from the Perimeter Institute put forward another idea for experimentally testing loop quantum gravity. They have been addressing the effects quantized spacetime had on quantum fluctuation when the very young universe was still expanding exponentially. Using a highly simplified model, Winkler and Hofmann calculated that the frequency spectrum of this quantum fluctuation must have changed constantly. This would still be making itself felt today as temperature fluctuations in the cosmic background radiation.

As the scale of the effect is around 1 percent, it could be measured with the Planck satellite planned for launch in 2007. If the model is correct, this would also present a good opportunity to experimentally test predictions for quantum gravity. The result of these measurements is of enormous significance. If loop theory is correct, it will have far-reaching consequences, and physics textbooks will have to be rewritten. One of the conclusions would be that the world is discrete and not continuous. This is not noticeable in everyday life, but it plays a role in drastic situations, such as black holes and the Big Bang.

The situation today is similar to that at the beginning of the last century, when nothing was known about quantum mechanics. However, the new theory would not completely displace the previous rules, as it finds expression only in extreme circumstances. We still use Newtonian mechanics today, although it has actually been overtaken by the theory of relativity.



Graphic: MPI for Gravitational Physics

According to loop theory, space is full of tiny loops, analogous to the magnetic flow lines of Maxwell theory.

A Table Has States

The hydrogen atom has precisely defined levels of energy. The same can be posited for a table surface, for example. According to loop theory, it also has a spectrum. The table can assume only certain values for its area, not just any random values, because its geometry is quantized. If the length of the table could be measured precisely to the Planck length, then that would be visible, depending on the table's eigenstate. If a loop is removed, the area of the table would change by certain units of the Planck area (10^{-66} cm^2). This is analogous to the excitation states of the hydrogen atom. Each has a different energy. However, the excitation states of the table are not expressed by energy levels, but by the loop variables, or more precisely, their spin quantum numbers. The area of the table also has a discrete spectrum because its geometry is excited.

Dr. Thomas Thiemann, 38, works at the Max Planck Institute for Gravitational Physics in Potsdam and is one of the pioneers of loop quantum gravity. He has been at Pennsylvania State University, Harvard University and the Perimeter Institute in Canada. There, as well as at Beijing Normal University, he held a visiting professorship.

Photos: Private source

Dr. Brigitte Röthlein has turned her curiosity into a career. She is a physicist and freelance science writer, writing on everything to do with the natural sciences and technology. She is particularly passionate about basic research, where (as here) she sees herself as an interpreter for what is often difficult subject matter.