DUSAN PETRICIC

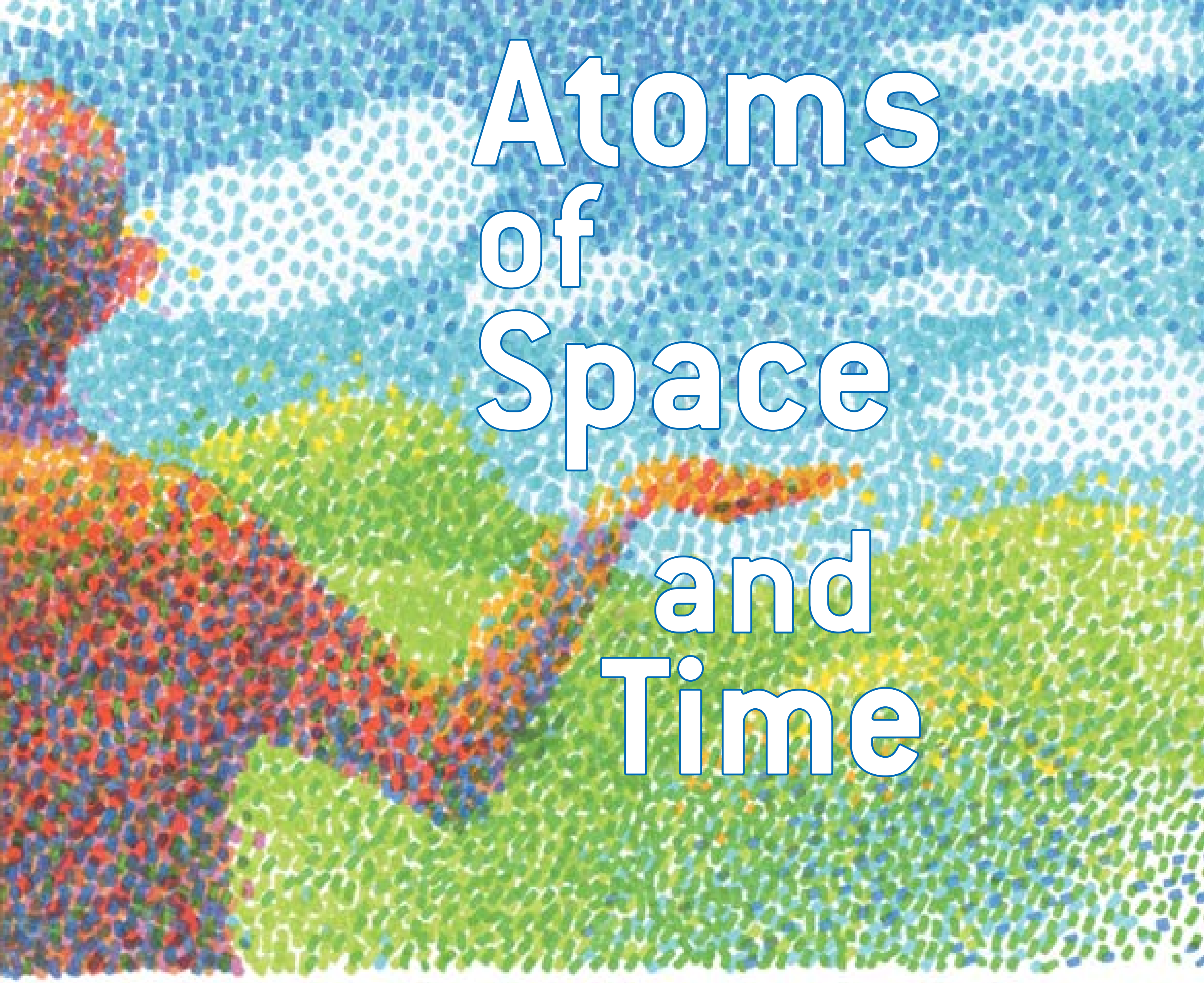
We perceive space and time to be continuous, but if the amazing theory of loop quantum gravity is correct, they actually come in discrete pieces

By Lee Smolin

A little more than 100 years ago most people—and most scientists—thought of matter as continuous. Although since ancient times some philosophers and scientists had speculated that if matter were broken up into small enough bits, it might turn out to be made up of very tiny atoms, few thought the existence of atoms could ever be proved. Today we have imaged individual atoms and have studied the particles that compose them. The granularity of matter is old news.

In recent decades, physicists and mathematicians have asked if space is also made of discrete pieces. Is it continuous, as we learn in school, or is it more like a piece of cloth, woven out of individual fibers? If we could probe to size scales that were small enough, would we see "atoms" of space, irreducible pieces of volume that cannot be broken into anything smaller? And what about time: Does nature change continuously, or does the world

Atoms of Space and Time



evolve in series of very tiny steps, acting more like a digital computer?

The past 16 years have seen great progress on these questions. A theory with the strange name of "loop quantum gravity" predicts that space and time are indeed made of discrete pieces. The picture revealed by calculations carried out within the framework of this theory is both simple and beautiful. The theory has deepened our understanding of puzzling phenomena having to do with black holes and the big bang. Best of all, it is testable; it makes predictions for experiments that can be done in the near future that will enable us to detect the atoms of space, if they are really there.

Quanta

MY COLLEAGUES AND I developed the theory of loop quantum gravity while struggling with a long-standing problem in physics: Is it possible to develop a quantum theory of gravity? To explain why this is an important question—and what it has to do with the granularity of space and time—I must first say a bit about quantum theory and the theory of gravity.

The theory of quantum mechanics was formulated in the first quarter of the 20th century, a development that was closely connected with the confirmation that matter is made of atoms. The equations of quantum mechanics require that certain quantities, such as the energy of an atom, can come only in specific, discrete units. Quantum theory successfully predicts the properties and behavior of atoms and the elementary particles and forces that compose them. No theory in the history of science has been more successful than quantum theory. It underlies our understanding of chemistry, atomic and subatomic physics, electronics and even biology.

In the same decades that quantum mechanics was being formulated, Albert Einstein constructed his general theory of relativity, which is a theory of gravity. In his theory, the gravitational force arises as a consequence of space and time (which together form "spacetime") being curved by the presence of matter. A loose analogy is that of a bowling ball placed on a rubber sheet along with a marble that is rolling around nearby. The balls could represent the sun and the earth, and the sheet is space. The bowling ball creates a deep indentation in the rubber sheet, and the slope of this indentation causes the marble to be deflected toward the larger ball, as if some force—gravity—were pulling it in that direction. Similarly, any piece of matter or concentration of energy distorts the geometry of spacetime, causing other particles and light rays to be deflected toward it, a phenomenon we call gravity.

Quantum theory and Einstein's theory of general relativity separately have each been fantastically well confirmed by experiment—but no experiment has explored the regime where both theories predict significant effects. The problem is that quantum effects are most prominent at small size scales, whereas general relativistic effects require large masses, so it takes extraordinary circumstances to combine both conditions.

Allied with this hole in the experimental data is a huge conceptual problem: Einstein's theory of general relativity is thoroughly classical, or nonquantum. For physics as a whole to be logically consistent, there has to be a theory that somehow unites quantum mechanics and general relativity. This long-sought-after theory is called quantum gravity. Because general relativity deals in the geometry of spacetime, a quantum theory of gravity will in addition be a quantum theory of spacetime.

SPACE IS WOVEN out of distinct threads.

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Physicists have developed a considerable collection of mathematical procedures for turning a classical theory into a quantum one. Many theoretical physicists and mathematicians have worked on applying those standard techniques to general relativity. Early results were discouraging. Calculations carried out in the 1960s and 1970s seemed to show that quantum theory and general relativity could not be successfully combined. Consequently, something fundamentally new seemed to be required, such as additional postulates or principles not included in quantum theory and general relativity, or new particles or fields, or new entities of some kind. Perhaps with the right additions or a new mathematical structure, a quantumlike theory could be developed that would successfully approximate general relativity in the nonquantum regime. To avoid spoiling the successful predictions of quantum theory and general relativity, the exotica contained in the full theory would remain hidden from experiment except in the extraordinary circumstances where both quantum theory and general relativity are expected to have large effects. Many different approaches along these lines have been tried, with names such as twistor theory, noncommutative geometry and supergravity.

An approach that is very popular with physicists is string theory, which postulates that space has six or seven dimensions—all so far completely unobserved—in addition to the three that we are familiar with. String theory also predicts the existence of a great many new elementary particles and forces, for which there is so far no observable evidence. Some researchers believe that string theory is subsumed in a theory called M-theory [see "The Theory Formerly Known as Strings," by Michael J. Duff; SCIENTIFIC AMERICAN, February 1998], but unfortunately no precise definition of this conjectured theory has ever been given. Thus, many physicists and mathematicians are convinced that alternatives must be studied. Our loop quantum gravity theory is the best-developed alternative.

Overview/*Quantum Spacetime*

- To understand the structure of space on the very smallest size scale, we must turn to a quantum theory of gravity. Gravity is involved because Einstein's general theory of relativity reveals that gravity is caused by the warping of space and time.
- By carefully combining the fundamental principles of quantum mechanics and general relativity, physicists are led to the theory of "loop quantum gravity." In this theory, the allowed quantum states of space turn out to be related to diagrams of lines and nodes called spin networks. Quantum spacetime corresponds to similar diagrams called spin foams.
- Loop quantum gravity predicts that space comes in discrete lumps, the smallest of which is about a cubic Planck length, or 10^{-99} cubic centimeter. Time proceeds in discrete ticks of about a Planck time, or 10^{-43} second. The effects of this discrete structure might be seen in experiments in the near future.

A Big Loophole

IN THE MID-1980S a few of us—including Abhay Ashtekar, now at Pennsylvania State University, Ted Jacobson of the University of Maryland and Carlo Rovelli, now at the University of the Mediterranean in Marseille—decided to reexamine the question of whether quantum mechanics could be combined consistently with general relativity using the standard techniques. We knew that the negative results from the 1970s had an important loophole. Those calculations assumed that the geometry of space is continuous and smooth, no matter how minutely we examine it, just as people had expected matter to be before the discovery of atoms. Some of our teachers and mentors had pointed out that if this assumption was wrong, the old calculations would not be reliable.

So we began searching for a way to do calculations without assuming that space is smooth and continuous. We insisted on not making any assumptions beyond the experimentally well tested principles of general relativity and quantum theory. In particular, we kept two key principles of general relativity at the heart of our calculations.

The first is known as background independence. This principle says that the geometry of spacetime is not fixed. Instead the geometry is an evolving, dynamical quantity. To find the geometry, one has to solve certain equations that include all the effects of matter and energy. Incidentally, string theory, as currently formulated, is not background independent; the equations describing the strings are set up in a predetermined classical (that is, nonquantum) spacetime.

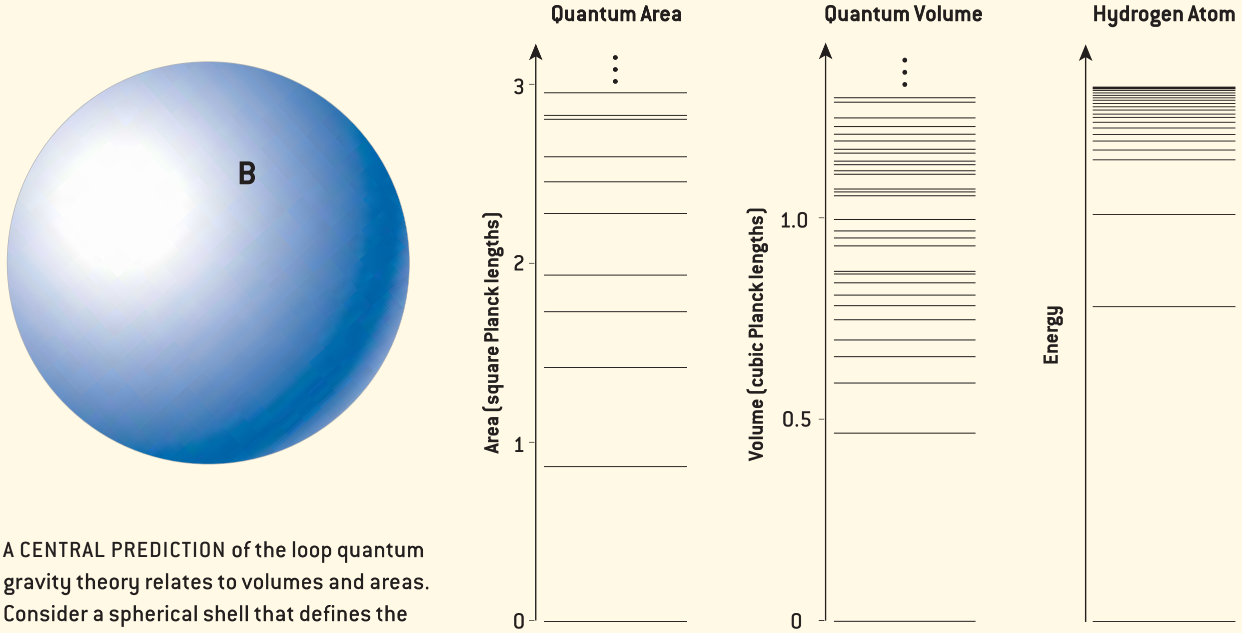
The second principle, known by the imposing name diffeomorphism invariance, is closely related to background independence. This principle implies that, unlike theories prior to general relativity, one is free to choose any set of coordinates to map spacetime and express the equations. A point in spacetime is defined only by what physically happens at it, not by its location according to some special set of coordinates (no coordinates are special). Diffeomorphism invariance is very powerful and is of fundamental importance in general relativity.

By carefully combining these two principles with the standard techniques of quantum mechanics, we developed a mathematical language that allowed us to do a computation to determine whether space is continuous or discrete. That calculation revealed, to our delight, that space is quantized. We had laid the foundations of our theory of loop quantum gravity. The term "loop," by the way, arises from how some computations in the theory involve small loops marked out in spacetime.

The calculations have been redone by a number of physicists and mathematicians using a range of methods. Over the years since, the study of loop quantum gravity has grown into a healthy field of research, with many contributors around the world; our combined efforts give us confidence in the picture of spacetime I will describe.

Ours is a quantum theory of the structure of spacetime at the smallest size scales, so to explain how the theory works we need to consider what it predicts for a small region or volume. In dealing with quantum physics, it is essential to specify precisely what physical quantities are to be measured. To do so, we consider a region somewhere that is marked out by a boundary, B [*see illustration below*].

QUANTUM STATES OF VOLUME AND AREA



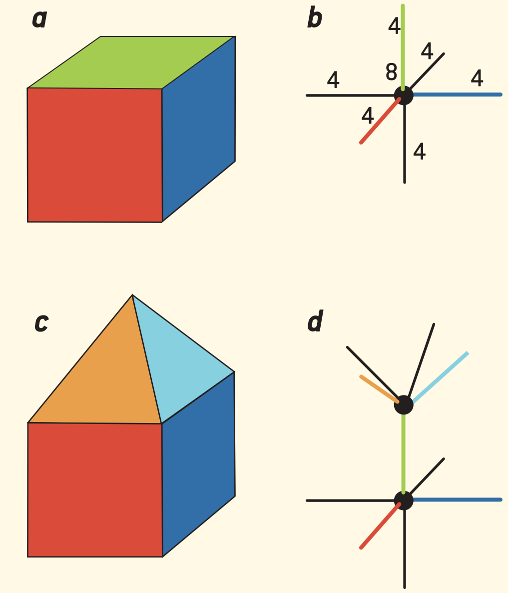
A CENTRAL PREDICTION of the loop quantum gravity theory relates to volumes and areas. Consider a spherical shell that defines the boundary, B, of a region of space having some volume (*above*). According to classical (nonquantum) physics, the volume could be any positive real number. The loop quantum gravity theory says, however, that there is a nonzero absolute minimum volume (about one cubic Planck length, or 10^{-99} cubic centimeter), and it restricts the set of larger volumes to a discrete series of numbers. Similarly, there is a nonzero minimum area (about one square Planck length, or 10^{-66} square centimeter) and a discrete series of larger allowed areas. The discrete spectrum of allowed quantum areas (*left*) and volumes (*center*) is broadly similar to the discrete quantum energy levels of a hydrogen atom (*right*).

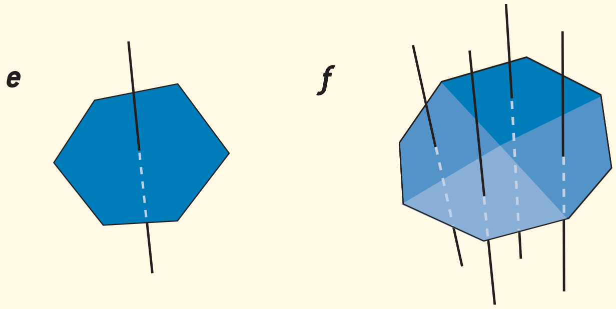
SOURCE: AREA AND VOLUME DATA FROM ROBERTO DE PIETRI AND CARLO ROVELLI (http://arxiv.org/abs/gr-qc/9602023); NADIA STRASSER

VISUALIZING QUANTUM STATES OF VOLUME

DIAGRAMS CALLED SPIN NETWORKS are used by physicists who study loop quantum gravity to represent quantum states of space at a minuscule scale. Some such diagrams correspond to polyhedra-shaped volumes. For example, a cube (*a*) consists of a volume enclosed within six square faces. The corresponding spin network (*b*) has a dot, or node, representing the volume and six lines that represent the six faces. The complete spin network has a number at the node to indicate the cube's volume and a number on each line to indicate the area of the corresponding face. Here the volume is eight cubic Planck lengths, and the faces are each four square Planck lengths. (The rules of loop quantum gravity restrict the allowed volumes and areas to specific quantities: only certain combinations of numbers are allowed on the lines and nodes.)

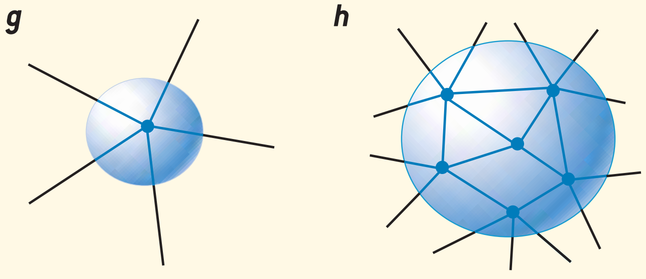
If a pyramid sat on the cube's top face (*c*), the line representing that face in the spin network would connect the cube's node to the pyramid's node (*d*). The lines corresponding to the four exposed faces of the pyramid and the five exposed faces of the cube would stick out from their respective nodes. (The numbers have been omitted for simplicity.)





One quantum of area

Larger area



One quantum of volume

Larger volume

In general, in a spin network, one quantum of area is represented by a single line (*e*), whereas an area composed of many quanta is represented by many lines (*f*). Similarly, a quantum of volume is represented by one node (*g*), whereas a larger volume takes many nodes (*h*). If we have a region of space defined by a spherical shell, the volume inside the shell is given by the sum of all the enclosed nodes and its surface area is given by the sum of all the lines that pierce it.

The spin networks are more fundamental than the polyhedra: any arrangement of polyhedra can be represented by a spin network in this fashion, but some valid spin networks represent combinations of volumes and areas that cannot be drawn as polyhedra. Such spin networks would occur when space is curved by a strong gravitational field or in the course of quantum fluctuations of the geometry of space at the Planck scale.

The boundary may be defined by some matter, such as a cast-iron shell, or it may be defined by the geometry of spacetime itself, as in the event horizon of a black hole (a surface from within which even light cannot escape the black hole's gravitational clutches).

What happens if we measure the volume of the region? What are the possible outcomes allowed by both quantum theory and diffeomorphism invariance? If the geometry of space is continuous, the region could be of any size and the measurement result could be any positive real number; in particular, it could be as close as one wants to zero volume. But if the geometry is granular, then the measurement result can come from just a discrete set of numbers and it cannot be smaller than a certain minimum possible volume. The question is similar to asking how much energy electrons orbiting an atomic nucleus have. Classical mechanics predicts that that an electron can possess any amount of energy, but quantum mechanics allows only specific energies (amounts in between those values do not occur). The difference is like that between the measure of something that flows continuously, like the 19th-century conception of water, and something that can be counted, like the atoms in that water.

The theory of loop quantum gravity

NADIA STRASSER

predicts that space is like atoms: there is a discrete set of numbers that the volume-measuring experiment can return. Volume comes in distinct pieces. Another quantity we can measure is the area of the boundary B. Again, calculations using the theory return an unambiguous result: the area of the surface is discrete as well. In other words, space is not continuous. It comes only in specific quantum units of area and volume.

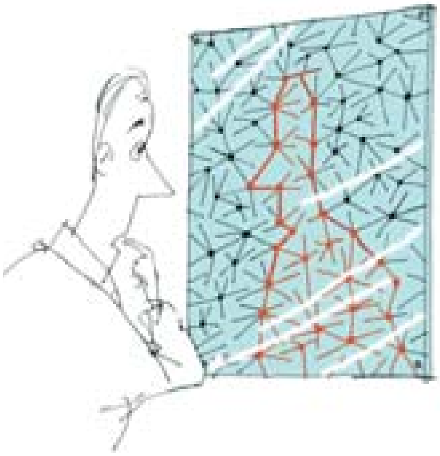
The possible values of volume and area are measured in units of a quantity called the Planck length. This length is related to the strength of gravity, the size of quanta and the speed of light. It measures the scale at which the geometry of space is no longer continuous. The Planck length is very small: 10^{-33} centimeter. The smallest possible nonzero area is about a square Planck length, or 10^{-66} cm^2. The smallest nonzero volume is approximately a cubic Planck length, 10^{-99} cm^3. Thus, the theory predicts that there are about 10^{99} atoms of volume in every cubic centimeter of space. The quantum of volume is so tiny that there are more such quanta in a cubic centimeter than there are cubic centimeters in the visible universe (10^{85}).

Spin Networks

WHAT ELSE DOES our theory tell us about spacetime? To start with, what do these quantum states of volume and area look like? Is space made up of a lot of little cubes or spheres? The answer is no—it's not that simple. Nevertheless, we can draw diagrams that represent the quantum states of volume and area. To those of us working in this field, these diagrams are beautiful because of their connection to an elegant branch of mathematics.

To see how these diagrams work, imagine that we have a lump of space shaped like a cube, as shown in the illustration on the opposite page. In our diagrams, we would depict this cube as a dot, which represents the volume, with six lines sticking out, each of which represents one of the cube's faces. We have to write a number next to the dot to specify the quantity of volume, and on each line we write a number to specify the area of the face that the line represents.

Next, suppose we put a pyramid on top of the cube. These two polyhedra, which share a common face, would be depicted as two dots (two volumes) connected by one of the lines (the face that joins the two volumes). The cube has five other faces (five lines sticking out), and the pyramid has four (four lines sticking out). It is clear how more complicated arrangements involving polyhedra other than cubes and pyramids could be depicted with these dot-and-line diagrams: each polyhedron of volume becomes a dot, or node, and each flat face of a polyhedron becomes a line, and the lines join the nodes in the way that the faces join the polyhedra together. Mathematicians call these line diagrams graphs.



MATTER EXISTS at the nodes of the spin network.

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Now in our theory, we throw away the drawings of polyhedra and just keep the graphs. The mathematics that describes the quantum states of volume and area gives us a set of rules for how the nodes and lines can be connected and what numbers can go where in a diagram. Every quantum state corresponds to one of these graphs, and every graph that obeys the rules corresponds to a quantum state. The graphs are a convenient shorthand for all the possible quantum states of space. (The mathematics and other details of the quantum states are too complicated to discuss here; the best we can do is show some of the related diagrams.)

The graphs are a better representation of the quantum states than the polyhedra are. In particular, some graphs connect in strange ways that cannot be converted into a tidy picture of polyhedra. For example, whenever space is curved, the polyhedra will not fit together properly in any drawing we could do, yet we can still easily draw a graph. Indeed, we can take a graph and from it calculate how much space is distorted. Because the distortion of space is what produces gravity, this is how the diagrams form a quantum theory of gravity.

For simplicity, we often draw the graphs in two dimensions, but it is better to imagine them filling three-dimensional space, because that is what they represent. Yet there is a conceptual trap here: the lines and nodes of a graph do not live at specific locations in space. Each graph is defined only by the way its pieces connect together and how they relate to well-defined boundaries such as boundary B. The continuous, three-dimensional space that you are imagining the graphs occupy *does not exist* as a separate entity. All that exist are the lines and nodes; they *are* space, and the way they connect defines the geometry of space.

These graphs are called spin networks because the numbers on them are related to quantities called spins. Roger Penrose of the University of Oxford first proposed in the early 1970s that spin networks might play a role in theories of quantum gravity. We were very pleased when we found, in 1994, that precise calculations confirmed his intuition. Readers familiar with Feynman diagrams should note that our spin networks are *not* Feynman diagrams, despite the superficial resemblance. Feynman diagrams represent quantum interactions between particles, which proceed from one quantum state to another. Our diagrams represent fixed quan-

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tum states of spatial volumes and areas.

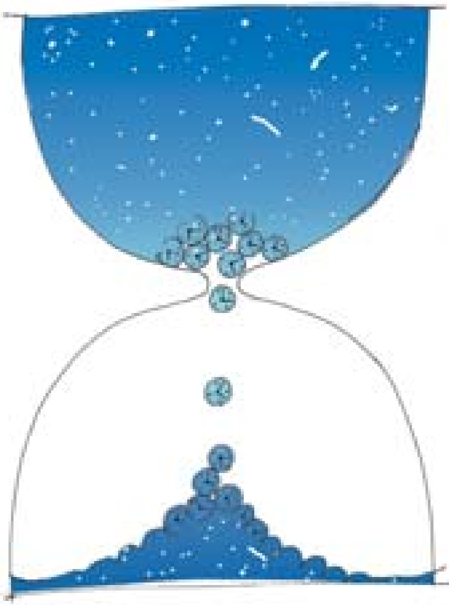
The individual nodes and edges of the diagrams represent extremely small regions of space: a node is typically a volume of about one cubic Planck length, and a line is typically an area of about one square Planck length. But in principle, nothing limits how big and complicated a spin network can be. If we could draw a detailed picture of the quantum state of our universe—the geometry of its space, as curved and warped by the gravitation of galaxies and black holes and everything else—it would be a gargantuan spin network of unimaginable complexity, with approximately 10^{184} nodes.

These spin networks describe the geometry of space. But what about all the matter and energy contained in that space? How do we represent particles and fields occupying positions and regions of space? Particles, such as electrons, correspond to certain types of nodes, which are represented by adding more labels on nodes. Fields, such as the electromagnetic field, are represented by additional labels on the lines of the graph. We represent particles and fields moving through space by these labels moving in discrete steps on the graphs.

Moves and Foams

PARTICLES AND FIELDS are not the only things that move around. According to general relativity, the geometry of space changes in time. The bends and curves of space change as matter and energy move, and waves can pass through it like ripples on a lake [see "Ripples in Space and Time," by W. Wayt Gibbs; SCIENTIFIC AMERICAN, April 2002]. In loop quantum gravity, these processes are represented by changes in the graphs. They evolve in time by a succession of certain "moves" in which the connectivity of the graphs changes [*see illustration on opposite page*].

When physicists describe phenomena quantum-mechanically, they compute probabilities for different processes. We do the same when we apply loop quantum gravity theory to describe phenomena, whether it be particles and fields moving on the spin networks or the geometry of space itself evolving in time. In particular, Thomas Thiemann of the Perimeter Institute for Theoretical Physics in Waterloo, Ontario, has derived precise quantum probabilities for the spin network moves. With these the theory is completely specified: we have a well-defined procedure for computing the probability of any process that can occur in a world that obeys the rules of our theory. It remains only to do the computations and work out predictions for what could be observed in experiments of one kind or another.


TIME ADVANCES by the discrete ticks of innumerable clocks.

Einstein's theories of special and general relativity join space and time together into the single, merged entity known as spacetime. The spin networks that represent space in loop quantum gravity theory accommodate the concept of spacetime by becoming what we call spin "foams." With the addition of another dimension—time—the lines of the spin networks grow to become two-dimensional surfaces, and the nodes grow to become lines. Transitions where the spin networks change (the moves discussed earlier) are now represented by nodes where the lines meet in the foam. The spin foam picture of spacetime was proposed by several people, including Carlo Rovelli, Mike Reisenberger (now of the University of Montevideo), John Barrett of the University of Nottingham, Louis Crane of Kansas State University, John Baez of the University of California at Riverside and Fotini Markopoulou of the Perimeter Institute for Theoretical Physics.

In the spacetime way of looking at things, a snapshot at a specific time is like a slice cutting across the spacetime. Taking such a slice through a spin foam produces a spin network. But it would be wrong to think of such a slice as moving continuously, like a smooth flow of time. Instead, just as space is defined by a spin network's discrete geometry, time is defined by the sequence of distinct moves that rearrange the network, as shown in the illustration on the opposite page. In this way time also becomes discrete. Time flows not like a river but like the ticking of a clock, with "ticks" that are about as long as the Planck time: 10^{-43} second. Or, more precisely, time in our universe flows by the ticking of innumerable clocks—in a sense, at every location in the spin foam where a quantum "move" takes place, a clock at that location has ticked once.

Predictions and Tests

I HAVE OUTLINED what loop quantum gravity has to say about space and time at the Planck scale, but we cannot verify the theory directly by examining spacetime on that scale. It is too small. So how can we test the theory? An important test is whether one can derive classical general relativity as an approximation to loop quantum gravity. In other words, if the spin networks are like the threads woven into a piece of cloth, this is analogous to asking whether we can compute the right elastic properties for a sheet of the material by averaging over thousands of threads. Similarly, when averaged over many Planck lengths, do spin networks describe the geometry of space and its evolution in a way that agrees roughly with the "smooth cloth" of Einstein's classical theory? This is a difficult problem, but recently researchers have made progress for some cases, for certain configurations of the material, so to speak. For example, long-wavelength gravitational waves propagating on otherwise flat (uncurved) space can be described as excitations of specific quantum states described by the loop quantum gravity theory.

Another fruitful test is to see what loop quantum gravity has to say about one of the long-standing mysteries of

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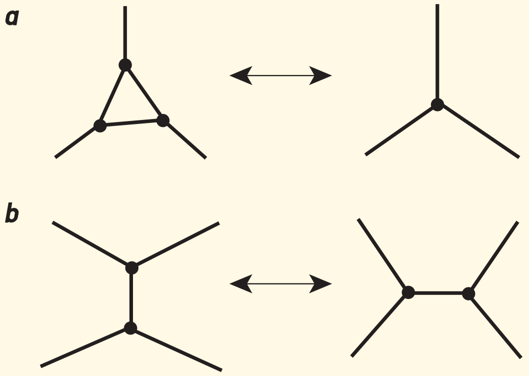
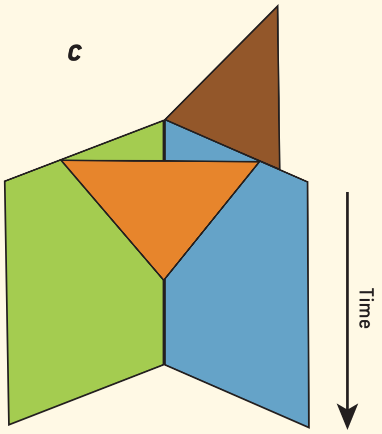
gravitational physics and quantum theory: the thermodynamics of black holes, in particular their entropy, which is related to disorder. Physicists have computed predictions regarding black hole thermodynamics using a hybrid, approximate theory in which matter is treated quantum-mechanically but spacetime is not. A full quantum theory of gravity, such as loop quantum gravity, should be able to reproduce these predictions. Specifically, in the 1970s Jacob D. Bekenstein, now at the Hebrew University of Jerusalem, inferred that black holes must be ascribed an entropy proportional to their surface area [see "Information in a Holographic Universe," by Jacob D. Bekenstein; Scientific American, August 2003]. Shortly after, Stephen Hawking deduced that black holes, particularly small ones, must emit radiation. These predictions are

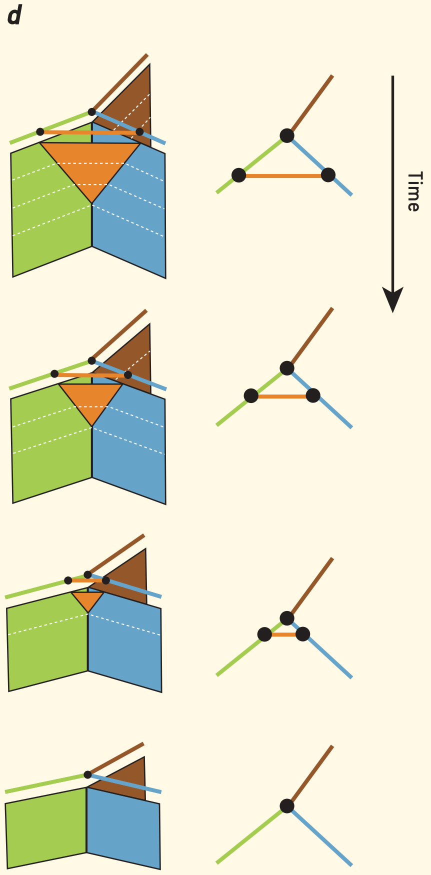
EVOLUTION OF GEOMETRY IN TIME

CHANGES IN THE SHAPE of space—such as those occurring when matter and energy move around within it and when gravitational waves flow by—are represented by discrete rearrangements, or moves, of the spin network. In *a,* a connected group of three volume quanta merge to become a single volume quantum; the reverse process can also occur. In *b,* two volumes divide up space and connect to adjoining volumes in a different way. Represented as polyhedra, the two polyhedra would merge on their common face and then split like a crystal cleaving on a different plane. These spin-network moves take place not only when large-scale changes in the geometry of space occur but also incessantly as quantum fluctuations at the Planck scale.



ANOTHER WAY to represent moves is to add the time dimension to a spin network—the result is called a spin foam (*c*). The lines of the spin network become planes, and the nodes become lines. Taking a slice through a spin foam at a particular time yields a spin network; taking a series of slices at different times produces frames of a movie showing the spin network evolving in time (*d*). But notice that the evolution, which at first glance appears to be smooth and continuous, is in fact discontinuous. All the spin networks that include the orange line (*first three frames shown*) represent exactly the same geometry of space. The length of the orange line doesn't matter—all that matters for the geometry is how the lines are connected and what number labels each line. Those are what define how the quanta of volume and area are arranged and how big they are. Thus, in *d,* the geometry remains constant during the first three frames, with 3 quanta of volume and 6 quanta of surface area. Then the geometry changes discontinuously, becoming a single quantum of volume and 3 quanta of surface area, as shown in the last frame. In this way, time as defined by a spin foam evolves by a series of abrupt, discrete moves, not by a continuous flow.



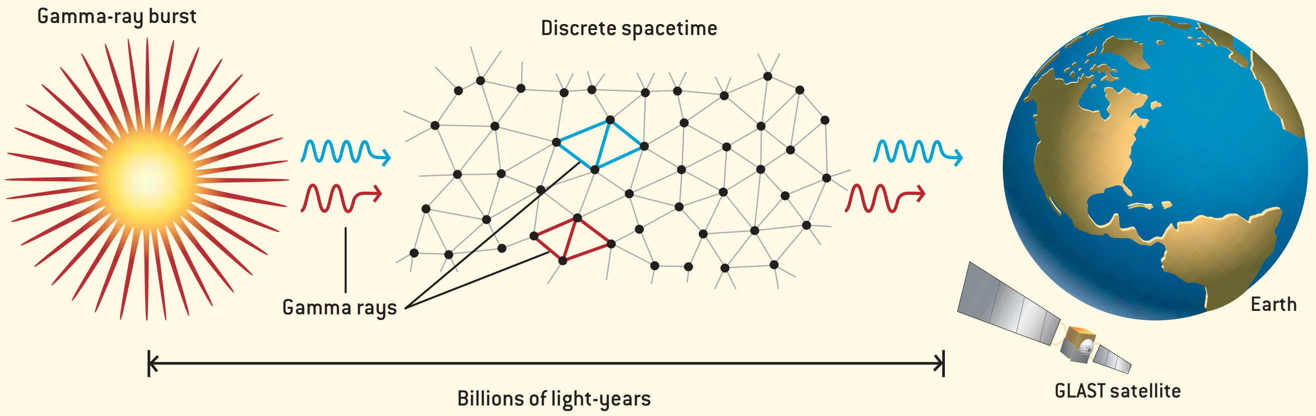


Although speaking of such sequences as frames of a movie is helpful for visualization, the more correct way to understand the evolution of the geometry is as discrete ticks of a clock. At one tick the orange quantum of area is present; at the next tick it is gone—in fact, the disappearance of the orange quantum of area *defines* the tick. The difference in time from one tick to the next is approximately the Planck time, 10^{-43} second. But time *does not exist* in between the ticks; there is no "in between," in the same way that there is no water in between two adjacent molecules of water.

SOURCE: *A* AND *B* ADAPTED FROM FOTINI MARKOPOULOU (http://arxiv.org/abs/gr-qc/9704013/); *C* ADAPTED FROM CARLO ROVELLI (http://arxiv.org/abs/gr-qc/9806121/); NADIA STRASSER

AN EXPERIMENTAL TEST

RADIATION from distant cosmic explosions called gamma-ray bursts might provide a way to test whether the theory of loop quantum gravity is correct. Gamma-ray bursts occur billions of light-years away and emit a huge amount of gamma rays within a short span. According to loop quantum gravity, each photon occupies a region of lines at each instant as it moves through the spin network that is space (in reality a very large number of lines, not just the five depicted here). The discrete nature of space causes higher-energy gamma rays to travel slightly faster than lower-energy ones. The difference is tiny, but its effect steadily accumulates during the rays' billion-year voyage. If a burst's gamma rays arrive at Earth at slightly different times according to their energy, that would be evidence for loop quantum gravity. The GLAST satellite, which is scheduled to be launched in 2006, will have the required sensitivity for this experiment.



among the greatest results of theoretical physics in the past 30 years.

To do the calculation in loop quantum gravity, we pick the boundary B to be the event horizon of a black hole. When we analyze the entropy of the relevant quantum states, we get *precisely* the prediction of Bekenstein. Similarly, the theory reproduces Hawking's prediction of black hole radiation. In fact, it makes further predictions for the fine structure of Hawking radiation. If a microscopic black hole is ever observed, this prediction could be tested by studying the spectrum of radiation it emits. That may be far off in time, however, because we have no technology to make black holes, small or otherwise.

Indeed, any experimental test of loop quantum gravity would appear at first to be an immense technological challenge. The problem is that the characteristic effects described by the theory become significant only at the Planck scale, the very tiny size of the quanta of area and volume. The Planck scale is 16 orders of magnitude below the scale probed in the highest-energy particle accelerators currently planned (higher energy is needed to probe shorter distance scales). Because we cannot reach the Planck scale with an accelerator, many people have held out little hope for the confirmation of quantum gravity theories.

In the past several years, however, a few imaginative young researchers have thought up new ways to test the predictions of loop quantum gravity that can be done now. These methods depend on the propagation of light across the universe. When light moves through a medium, its wavelength suffers some distortions, leading to effects such as bending in water and the separation of different wavelengths, or colors. These effects also occur for light and particles moving through the discrete space described by a spin network.

Unfortunately, the magnitude of the effects is proportional to the ratio of the Planck length to the wavelength. For visible light, this ratio is smaller than 10^{-28}; even for the most powerful cosmic rays ever observed, it is about one billionth. For any radiation we can observe, the effects of the granular structure of space are very small. What the young researchers spotted is that these effects accumulate when light travels a long distance. And we detect light and particles that come from billions of light years away, from events such as gamma-ray bursts [see "The Brightest Explosions in the Universe," by Neil Gehrels, Luigi Piro and Peter J. T. Leonard; SCIENTIFIC AMERICAN, December 2002].

A gamma-ray burst spews out photons in a range of energies in a very brief explosion. Calculations in loop quantum gravity, by Rodolfo Gambini of the University of the Republic in Uruguay, Jorge Pullin of Louisiana State University and others, predict that photons of different energies should travel at slightly different speeds and therefore arrive at slightly different times [*see illustration above*]. We can look for this effect in data from satellite observations of gamma-ray bursts. So far the precision is about a factor of 1,000 below what is needed, but a new satellite observatory called GLAST, planned for 2006, will have the precision required.

The reader may ask if this result would mean that Einstein's theory of special relativity is wrong when it predicts a universal speed of light. Several people, including Giovanni Amelino-Camelia of the University of Rome "La Sapienza"

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and João Magueijo of Imperial College London, as well as myself, have developed modified versions of Einstein's theory that will accommodate high-energy photons traveling at different speeds. Our theories propose that the universal speed is the speed of very low energy photons or, equivalently, long-wavelength light.

Another possible effect of discrete spacetime involves very high energy cosmic rays. More than 30 years ago researchers predicted that cosmic-ray protons with an energy greater than 3×10^{19} electron volts would scatter off the cosmic microwave background that fills space and should therefore never reach the earth. Puzzlingly, a Japanese experiment called AGASA has detected more than 10 cosmic rays with an energy over this limit. But it turns out that the discrete structure of space can raise the energy required for the scattering reaction, allowing higher-energy cosmic-ray protons to reach the earth. If the AGASA observations hold up, and if no other explanation is found, then it may turn out that we have already detected the discreteness of space.

The Cosmos

IN ADDITION to making predictions about specific phenomena such as high-energy cosmic rays, loop quantum gravity has opened up a new window through which we can study deep cosmological questions such as those relating to the origins of our universe. We can use the theory to study the earliest moments of time just after the big bang. General relativity predicts that there was a first moment of time, but this conclusion ignores quantum physics (because general relativity is not a quantum theory). Recent loop quantum gravity calculations by Martin Bojowald of the Max Planck Institute for Gravitational Physics in Golm, Germany, indicate that the big bang is actually a big bounce; before the bounce the universe was rapidly contracting. Theorists are now hard at work developing predictions for the early universe that may be testable in future cosmological observations. It is not impossible that in our lifetime we could see evidence of the time before the big bang.

HOW CLASSICAL REALITY arises from quantum spacetime is still being worked out.

A question of similar profundity concerns the cosmological constant—a positive or negative energy density that could permeate "empty" space. Recent observations of distant supernovae and the cosmic microwave background strongly indicate that this energy does exist and is positive, which accelerates the universe's expansion [see "The Quintessential Universe," by Jeremiah P. Ostriker and Paul J. Steinhardt; SCIENTIFIC AMERICAN, January 2001]. Loop quantum gravity has no trouble incorporating the positive energy density. This fact was demonstrated in 1990, when Hideo Kodama of Kyoto University wrote down equations describing an exact quantum state of a universe having a positive cosmological constant.

Many open questions remain to be answered in loop quantum gravity. Some are technical matters that need to be clarified. We would also like to understand how, if at all, special relativity must be modified at extremely high energies. So far our speculations on this topic are not solidly linked to loop quantum gravity calculations. In addition, we would like to know that classical general relativity is a good approximate description of the theory for distances much larger than the Planck length, in all circumstances. (At present we know only that the approximation is good for certain states that describe rather weak gravitational waves propagating on an otherwise flat spacetime.) Finally, we would like to understand whether or not loop quantum gravity has anything to say about unification: Are the different forces, including gravity, all aspects of a single, fundamental force? String theory is based on a particular idea about unification, but we also have ideas for achieving unification with loop quantum gravity.

Loop quantum gravity occupies a very important place in the development of physics. It is arguably *the* quantum theory of general relativity, because it makes no extra assumptions beyond the basic principles of quantum theory and relativity theory. The remarkable departure that it makes—proposing a discontinuous spacetime described by spin networks and spin foams—emerges from the mathematics of the theory itself, rather than being inserted as an ad hoc postulate.

Still, everything I have discussed is theoretical. It could be that in spite of all I have described here, space really is continuous, no matter how small the scale we probe. Then physicists would have to turn to more radical postulates, such as those of string theory. Because this is science, in the end experiment will decide. The good news is that the decision may come soon. SA

MORE TO EXPLORE

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