P. A. Sandberg of the University of Illinois, Urbana-Champaign, pointed out that the carbonates precipitated from seawater without the assistance of living organisms had alternated between two crystalline forms. The observed variations in seawater Mg/Ca now explain that alternation, because abundant magnesium favors one form over the other. In 1999 Hardie and Johns Hopkins paleontologist Steven Stanley took the next step, proposing that the swings in the Mg/Ca ratio had acted as evolutionary gatekeepers. Corals and mollusks that build massive reefs came and went through the Phanerozoic, they said, depending on whether particular taxa were equipped to deal with a new Mg/Ca ratio.

Likewise, carbonate-producing nanoplankton that have been prevalent in the seas since 140 million years ago produced massive deposits of chalk—like the White Cliffs of Dover—only when the low Mg/Ca ratio favored them, 60 million to 100 million years ago. Hardie and Stanley also see signs of "evolutionary osteoporosis" setting in following the nanoplankton's heyday: Smaller, thinner, spindly carbonate encased the nanoplankton as the Mg/Ca ratio rose and calcium concentrations declined. High calcium might have had the reverse effect 545 million years ago, geochemist Sean Brennan of the U.S. Geological Survey in Reston, Virginia, Lowenstein, and Horita suggested last week at the Geological Society of America annual meeting in Denver. They reported a tripling of calcium as measured in fluid inclusions from the late Precambrian into the Cambrian, just when animals first began forming calcareous shells in the Cambrian explosion of life.

"It's a really interesting idea," says paleontologist David Jablonski of the University of Chicago, "that ocean changes could drive these major turnovers" of marine animals or even facilitate shelled animals' bursting on the scene. The trick, he says, will be refining the patterns of evolutionary and ocean change so that cause and effect can be firmly linked. Then geophysics and life might be joined for good. –RICHARD A. KERR

THEORETICAL PHYSICS

Constructing Spacetime—No Strings Attached

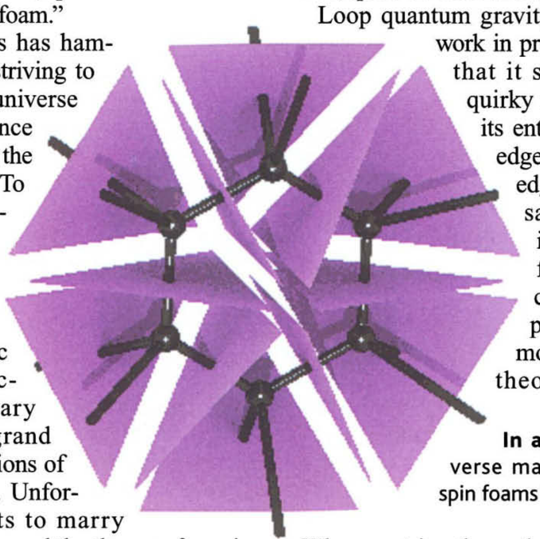
Move over, string theory. In the ongoing quest to meld quantum mechanics and gravity, an alternative theory aims to steal the stage

Space isn't smooth, and time doesn't flow. Regardless of what the rest of the world might think, physicists shed those illusions decades ago. To them, space and time are really two aspects of a single, stretchy thing called spacetime, which, thanks to the Uncertainty Principle of quantum mechanics, roils with tiny fluctuations measuring a few billion billion billion billionths of a meter. So when seen up close, spacetime resembles a frothy "quantum foam."

This foaminess has hamstrung physicists striving to explain how the universe sprang into existence and why it appears the way it does today. To tackle these questions, researchers need a single theory that accounts for everything from the frenetic quantum interactions of elementary particles to the grand gravity-driven motions of stars and galaxies. Unfortunately, attempts to marry quantum mechanics and the theory of gravity bog down in the foam, and even the leading candidate for a "theory of everything"—string theory—sidesteps the sticky froth.

Over the past 15 years, however, a few physicists have plowed headlong into the quantum foam. They've concocted a theory that precisely describes spacetime on the smallest length and time scales. Loop quantum gravity, as it is called, is the first theory that directly reconciles the minutiae of quantum mechanics with Einstein's general theory of relativity, which describes gravity as the warping of the very fabric of spacetime. It also predicts that space comes in discrete chunks, so that there is a smallest possible area and smallest possible volume. Just as matter is made of atoms and elementary particles, space consists of tiny indivisible bits.

Loop quantum gravity is very much a work in progress. Critics say that it sometimes gives quirky results, and even its enthusiasts acknowledge that many rough edges still need to be sanded down. But it's worth the effort, they say, because it takes them places where the more popular string theory doesn't go.



In a lather. Our universe may be a collage of spin foams like this one.

Whereas string theory begins by assuming how spacetime stretches and twists, loop quantum gravity builds the "geometry of spacetime" from scratch. That's a crucial feature of any fundamental theory of quantum gravity, says Lee Smolin of the Perimeter Institute for Theoretical Physics in Waterloo, Ontario. Come what may, he says, "it's hard to imagine that there could be a consistent formulation of quantum gravity that doesn't include these results."

Making a connection

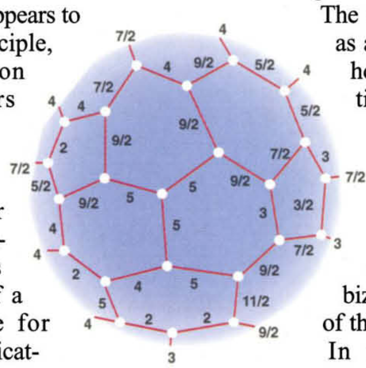
Since the 1950s physicists have struggled to develop a quantum-mechanical theory of gravity. In the quantum theories of all the other forces—electromagnetism, the strong force that binds the atomic nucleus, and the weak force that causes radioactive decay—physicists assume that infinitely smooth spacetime is filled with quantum fields that describe particles, such as photons or electrons. They imagine small ripples in these fields, calculate the interactions between them, and add up the results for ripples of all lengths. For gravity, however, the ripples are in spacetime itself, and when their length sinks below the size of the "bubbles" in the quantum foam, the standard approach starts churning out mathematical gibberish in the form of nonsensical infinities.

String theory provides a way around such blowups. First formulated in the 1980s, the theory assumes that every fundamental particle is really a tiny loop known as a superstring. Because the strings are long enough to stretch over the fluctuations in the spacetime foam, awkward infinities do not arise. To the strings, spacetime looks relatively smooth.

Yet string theory still suffers from a fundamental weakness. In the theory, the strings move in a spacetime whose shape has been chosen from the beginning, as if they were actors on a previously constructed stage. A truly fundamental theory of gravity, everyone agrees, would build the stage itself. In the vernacular, the theory should be "background independent," and string theory is not.

Loop quantum gravity, in contrast, takes dead aim at background independence. The theory got its start in 1986, when Abhay Ashtekar of Pennsylvania State University, University Park, found a novel way to write

Einstein's equations for gravity. Imagine an ant scurrying across the surface of an invisible apple. As it moves around to the far side of the fruit, its head appears to reverse direction. In principle, by tracking the direction of the ant as it wanders all over, a clever observer could determine the shape of the fruit. Thinking along similar lines, Ashtekar reformulated Einstein's equations for gravity in terms of a "connection": a recipe for transporting direction-indicating vectors through spacetime. "This transport encodes all the information about the physical geometry," Ashtekar says.



Spin network. In loop quantum gravity, area-conveying links connect little chunks of space.

With Ashtekar's formulation, theorists could write down quantum-mechanical gravity equations that did not require a background as an input. But researchers still had to solve the equations to determine the quantum states that would tell them what spacetime looked like. In the late 1980s Smolin, Ted Jacobson of the University of Maryland, College Park, and others discovered whole families of these solutions.

The solutions describe slices of space, each frozen at a fixed time. A single solution resembles a Cubist's dot-to-dot drawing. Each description, or state, consists of many nodes, interconnected by simple links (see figure, above). "You can view the nodes as chunks of space and the links as paths that tell you which chunks talk to each other," says Carlo Rovelli of the Center for Theoretical Physics in Marseille, France.

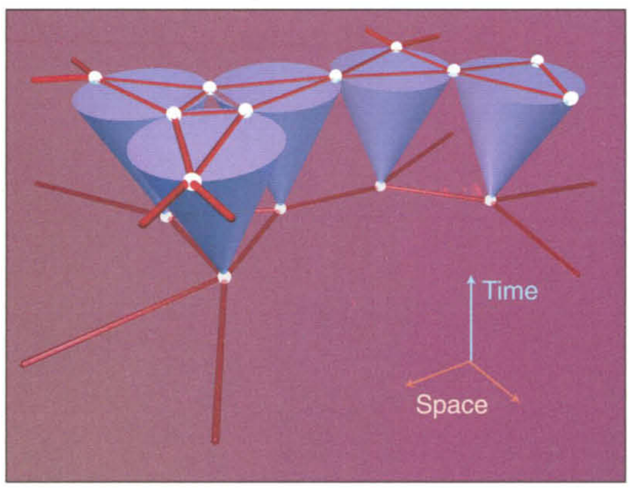
The lengths of the lines mean nothing. What matters are numerical weights attached to each line. Multiples of 1/2, the numbers add up at the nodes according to certain arcane rules—for example, 1 and 3/2 can add to 1/2, 3/2, or 5/2. Because the same peculiar arithmetic applies to angular momenta of particles in ordinary quantum mechanics, physicists call the arrangements spin networks. But in loop quantum gravity, the numbers actually denote the area separating different bits of space, Rovelli says. As a result, area can come only in discrete amounts, just as any sum of money can be counted out in a whole number of pennies. Thus, the spin networks tell theorists how to put space together, one little patch at a time.

Trouble on the horizon?

With this detailed description of space in hand, loop quantum gravity researchers decided to put their theory to a grueling test: calculating the amount of information trapped inside a celestial phantom known as a black hole.

An ultradense object can warp spacetime so severely that it creates a hole from which nothing—not even light—can escape. The edge of this abyss is known as an event horizon. As a black hole slurps matter and radiation, it also consumes information about the universe. Physicists know from general thermodynamic principles that the amount of lost information—or entropy—should, quite bizarrely, equal 1/4 of the area of the black hole's event horizon. In the past few years, researchers have shown that loop quantum gravity also predicts this equality—a signal success for the theory.

Or is it? Ironically, string theorists point to just this calculation as a sign that loop quantum gravity isn't quite complete. Loop quantum gravity researchers have to adjust a particular physical quantity to get the 1/4, they point out, whereas string theory predicts it without any fiddling. That precise agreement represents string theory's biggest success so far, says Brian Greene of Columbia University in New York City, because it strongly suggests that string theory contains the right physical variables to be the true theory of quantum gravity. "There's a damn good chance that it's all there," Greene says.



Cause and effect. To put the "time" into spacetime, researchers must show how one spin network evolves into another.

Loop quantum gravity researchers counter, however, that their calculations apply to any type of black hole—always with the same value of the adjustable parameter—whereas the string theory calculations employ weird hypothetical black holes unlike any found in our universe. "That's what string theorists never tell you," says John Baez of the University of California, Riverside, "just as people working on loop quantum gravity don't go out of their way to say that you need to worry about this free parameter."

Meeting in the middle

Despite their differences, both string theorists and loop quantum gravity researchers say they hope that their two approaches will merge someday to the benefit of all. But which will absorb which? String theorists, who outnumber their loop-quantum-gravity counterparts roughly 10 to 1, say that their theory's potential to unify all the forces of nature in a single quantum theory gives it the edge. "String theory is a much more ambitious project, so I don't see all of string theory being incorporated into loop quantum gravity," says Gary Horowitz of the University of California, Santa Barbara. Loop-quantum-gravity researchers, however, hold that string theory can only be an approximation to a more fundamental background-independent theory like their own. "There is a plausible background-independent approach to string theory, and that grows out of loop quantum gravity," Smolin says.

But loop-quantum-gravity researchers must still solve some fundamental problems. Because spin networks describe only space, researchers have to expand the theory to describe full four-dimensional spacetime. To do that, they're studying spin foams, latherlike objects that extend spin networks into another dimension. But no one is sure exactly which foams are the right ones, or how to superimpose them to produce our frothy, uncertain universe.

Meanwhile, researchers are looking for ways to put the theory to an experimental test. If loop quantum gravity is correct, then as light rattles through chunky spacetime, its speed might depend on its wavelength—contrary to Einstein's dictum that the speed of light is constant. The tiny effect might show up in observations of bursts of gamma rays coming from the farthest reaches of the cosmos, because the more energetic gamma rays would arrive first. If it's there, the difference should be observable with NASA's Gamma-ray Large Area Space Telescope, a satellite scheduled for launch in 2006. If so, our first indirect glimpse of the building blocks of spacetime could be right around the corner.

–ADRIAN CHO

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