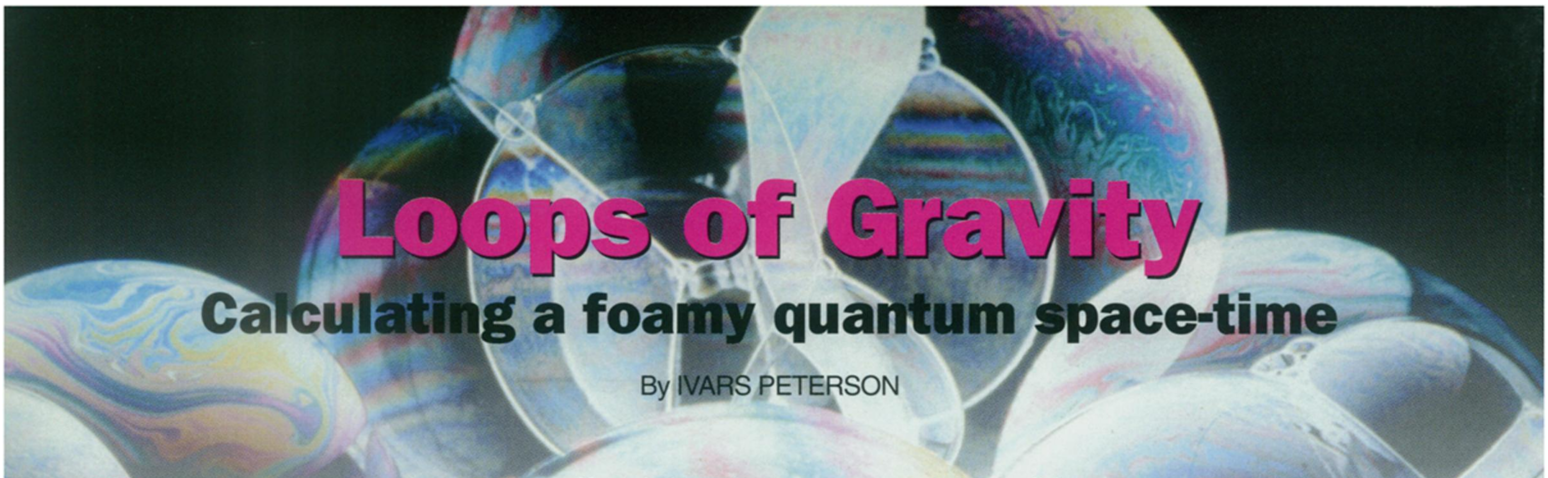


Loops of Gravity

Calculating a foamy quantum space-time

By IVARS PETERSON

Space devoid of matter isn't really empty. It's an arena of constant activity where force fields play out their complex interactions.

The electromagnetic field that pervades space, for instance, exhibits tiny vacuum fluctuations—unceasing, random variations in energy. According to quantum theory, such universal field fluctuations nonetheless have a measurable effect on microscopic objects. For instance, they influence the motion of an electron in a hydrogen atom.

Several decades ago, experimental verification of the influence of electromagnetic vacuum fluctuations on electron behavior prompted physicists to take seriously the possibility that similar quantum effects could occur in other situations. In particular, they became curious about quantum fluctuations associated with gravitational fields.

Einstein's general theory of relativity interprets the force of gravity as a geometric effect—the presence of matter warps a four-dimensional entity known as space-time. In the 1960s, John A. Wheeler of Princeton University argued that the classical picture of a smooth, featureless space-time continuum would not apply at the quantum level. He hypothesized that, on a sufficiently small scale, space-time itself could be described as a roiling geometric foam of constantly expanding and collapsing bubbles.

Wheeler didn't have the mathematical tools to turn his vision into a rigorous, coherent theory. In the last few years, however, theorists have discovered that just such a picture emerges naturally from a relatively new mathematical model known as loop quantum gravity (SN: 5/20/95, p. 311).

In this model, space itself comes packaged in discrete units. "The theory predicts that a physical measurement of an area or a volume will necessarily yield quantized results," says Carlo Rovelli of the University of Pittsburgh. It suggests there is no way of observing areas or volumes of space less than about 10^{-35} meter wide.

Testing such predictions, however, is at present well beyond the reach of experimental physics. The scales involved are considerably smaller than a proton's radius, roughly 10^{-15} m.

Nonetheless, loop quantum gravity provides an intriguing picture of the microstructure of physical space, Rovelli contends. It furnishes a mathematically well-defined realization of Wheeler's intuitive notion of a space-time foam.

Researchers highlighted recent developments in efforts to find a quantum theory of gravitational fields earlier this year at an American Mathematical Society meeting in Baltimore and at an American Physical Society meeting in Columbus, Ohio.

Physicists have long sought a description of space and time at the quantum level. At present, the bulk of this theoretical activity focuses on two main approaches: string theory and loop quantum gravity.

In string theory, which developed out of particle physics, the point particles of relativity and quantum mechanics are replaced by extended objects called strings, which can be visualized as either closed loops or segments with two free ends (SN: 2/27/93, p. 136).

According to this model, gravity arises from one of the many possible excitations of a string. String theory, however, says nothing directly about the space in which strings vibrate and move.

Loop quantum gravity represents an alternative route in which the rules of quantum mechanics are applied directly to Einstein's description of space and time. To quantize space itself, theorists have to come up with discrete states analogous to the energy levels, or orbitals, of an atom.

About a decade ago, Abhay Ashtekar, now at Pennsylvania State University in State College, discovered that he could reformulate and drastically simplify the equations of general relativity by replacing a single variable, representing a unified, four-dimensional space-time continuum, with a pair of such variables. That mathematical transformation made the equations much more amenable to standard techniques for quantizing the theory.

In 1987, Rovelli and Lee Smolin, now at Penn State, developed a way of interpreting solutions to the quantized theory as patterns of closed loops—lines of force of the gravitational field somewhat analogous to the lines of magnetic force around a bar magnet. The quantum states of space depend on how these loops are knotted and linked.

In fact, the theory deals with networks of bundles of knotted threads—not to be confused with the vibrating entities of string theory. The crucial physical difference is that strings reside in space, whereas loops actually constitute space.

The loop networks can be pictured as sets of lines joining points in an array, with a definite number of threads running along each line, called an edge. These threads change course from one edge to another at each point, or vertex.

Each quantum state of space corresponds to a particular knotted network. For historical reasons, such structures are usually called spin networks. They were invented several decades ago by Roger Penrose of the University of Oxford in England to serve as mathematical devices for describing processes involving the interactions of elementary particles with different spins.

It took Rovelli and Smolin several years of intricate calculations involving spin networks to derive formulas showing that, according to this model, area and volume come only in certain discrete units.

These results indicate that the geometry of space is made out of quanta analogous to photons of light or an atom's energy levels. Theorists can even calculate the range, or spectrum, of sizes that pieces of space can have.

In effect, spin network states are excitations of space-time, Rovelli says.

Thus, according to loop quantum gravity, space "is actually woven from an enormous number of fundamental quantum knots," Smolin says. The familiar space around us looks smooth and featureless simply because the threads, loops, and knots of its constituent spin networks are so tiny.

Black holes—enormous concentrations of mass that strongly warp space-time—provide a useful testing ground for any theory of quantum gravity.

A black hole is surrounded by a surface called an event horizon. An object can pass through the horizon into a black hole, but it can never get out again. Such an escape would require traveling faster than the speed of light.

If a black hole absorbs even the tiniest amount of energy but never emits any, it acts like a body at the absolute zero of temperature. In the 1970s, however, Stephen W. Hawking of the University of Cambridge in England showed that a black hole isn't quite black. According to his calculations, a black hole should radiate energy at a temperature proportional to the gravity at its event horizon.

Hawking's surprising discovery both built on and helped explain an earlier finding from Jacob Bekenstein, then at Princeton and now at Hebrew University in Jerusalem, who had established that a black hole has a thermodynamic entropy proportional to the surface area of its event horizon.

In a quantum theory of gravity, it should be possible to derive the Bekenstein-Hawking formula linking a black hole's entropy, temperature, and area from more fundamental ideas. In loop quantum gravity, that means finding the right connection between microscopic quantum states of space, represented by spin networks, and the macroscopic surface area of a black hole's event horizon.

The trouble is that recognizing the presence of a piece of an event horizon crossing a small patch of space-time is a tricky business. In particular, one needs a way to describe the geometry of a black hole's event horizon and how it changes as time passes.

It took considerable mathematical ingenuity on the part of Rovelli, Kirill Krasnov of Penn State, and others to overcome the problem and finally develop an expression compatible with the Bekenstein-Hawking formula for black hole entropy. Those calculations represent a significant success for loop quantum gravity, Rovelli says.

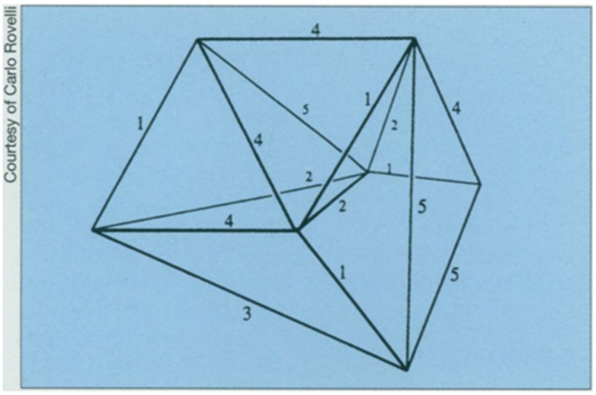
Interestingly, theorists have also recently derived the formula for black hole entropy on the basis of string theory. That result hints that loop quantum gravity and string theory share certain features.

At present, the loop approach offers an incomplete theoretical picture of quantum gravity. In particular, the spin networks of loop quantum gravity turn out to be more suitable for describing three-dimensional space than four-dimensional space-time.

As one attempt at a quantum description of the geometry of space-time, Rovelli, John C. Baez of the University of California, Riverside, and others have been exploring mathematical structures called spin foams. Slicing through a four-dimensional spin foam reveals a spin network—just as a cross section through a mass of soapsuds unveils a collection of curved lines and vertices of adjoining soap films.

Spin networks are used in quantum loop gravity to describe the geometry of space at a given time, Baez says, so it's natural to hope that they're the slice of something that describes the geometry of space-time.

Some researchers are trying out different sorts of spin foam structures and various rules for specifying the number of faces that meet along an edge. One promising model builds space-time from four-dimensional analogs of tetrahedra. Applying appropriate numerical labels to such a spin foam's edges and faces turns it into a quantized four-dimensional geometry.



Courtesy of Carlo Rovelli

This example of a spin network corresponds to a possible quantum state of the geometry of space. Roughly speaking, the number along an edge counts the units, or quanta, of area of a surface associated with that edge.

Theorists are now busy debating the merits of different approaches to drawing and labeling such spin foams. Their goal is to find a structure that not only corresponds to a four-dimensional quantum geometry but also represents a process that evolves over time.

"We need to show that some such model gives results that are well approximated by general relativity . . . on distance scales about the size of an atom as well as a planet," Baez says.

Spin foams "offer the prospect of a simple and beautiful picture of the microstructure of space-time which takes both general relativity and quantum mechanics into account," he concludes. "This is what we need, and any step in that direction, no matter how flawed, is a good thing."

The problem of understanding the quantum properties of space-time is today at the core of fundamental physics, Rovelli said at a quantum gravity conference held last year in Poona, India.

"The recent explosion of interest in quantum gravity has led to some progress and *might* have taken us much closer to the solution of the puzzle," he commented. "The main approaches . . . have produced predictions that are at least testable in principle and whose indirect consequences are being explored."

Both loop quantum gravity and string theory, however, are highly tentative models with no experimental evidence to support them, Rovelli warned. No one knows whether either theory correctly describes the universe.

In the face of such uncertainty, "the only way to make serious progress is for different people to push on different fronts simultaneously," Baez says.

The spin-network picture of quantum geometry is still developing, and major problems remain, Smolin notes.

It is possible that loop quantum gravity and string theory have uncovered complementary aspects of quantum gravity. Baez favors combining the best elements of both approaches, despite their vast differences. "Maybe we are just seeing two faces of the same theory," he says.

Smolin speculates that a loop in an enormous, complex network could turn out to be a close-up of the same phenomenon that string theory describes as a string moving in a smooth space-time geometry.

Or maybe not. The search for the next level of understanding goes on. □

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Many of the lessons we learned from Apollo are pertinent to Mars, and what was not learned there can be suitably tested using Earth-based methods (airdrops of containers, laboratory studies, and so on), so a new lunar mission is unnecessary.

"There are two problems with using the Space Station as a laboratory. First, one of the reasons for having the Space Station is to understand the adaptation of life to microgravity and to use microgravity as a probe to study organisms in a novel way. The requisite controlled studies for a sample's biological effects cannot be done on the Space Station until we have extensive knowledge of microgravity physiology—a process that could take decades (to be optimistic).

"Second, the Space Station is preferable to Earth's surface only if you believe that containment might be breached and, if so, you would be prepared to sacrifice the crew in the event of an 'unknown or adverse reaction' to the sample. Similar concerns obtain in a Space Shuttle recovery of samples while in orbit. Moreover, a Shuttle recovery might be less safe, overall, than direct entry.

"As to our ability to sterilize a sample, there is no doubt that high temperatures will be able to break carbon bonds and eliminate a threat posed by carbon-based life. The trick is learning how to sterilize such a sample without destroying the scientific information that led you to collect it in the first place. Between containment, corrosives, and heat, there should be ample margin for a safe analysis of materials returned from Mars."

—R. Cowen