

## How Is the Universe Built? Grain by Grain

---

By GEORGE JOHNSON

Slightly smaller than what Americans quaintly insist on calling half an inch, a centimeter (one-hundredth of a meter) is easy enough to see. Divide this small length into 10 equal slices and you are looking, or probably squinting, at a millimeter (one-thousandth, or  $10^{-3}$  meters). By the time you divide one of these tiny units into a thousand minuscule micrometers, you have far exceeded the limits of the finest bifocals.

But in the mind's eye, let the cutting continue, chopping the micrometer into a thousand nanometers and the nanometers into a thousand picometers, and those in steps of a thousandfold into femtometers, attometers, zeptometers, and yoctometers. At this point,  $10^{-24}$  meters, about one-billionth the radius of a proton, the roster of convenient Greek names runs out. But go ahead and keep dividing, again and again until you reach a length only a hundred-billionth as large as that tiny amount:  $10^{-35}$  meters, or a decimal point followed by 34 zeroes and then a one.

**You have finally hit rock bottom: a span called the Planck length, the shortest anything can get. According to recent developments in the quest to devise a so-called "theory of everything," space is not an infinitely divisible continuum. It is not smooth but granular, and the Planck length gives the size of its smallest possible grains.**

The time it takes for a light beam to zip across this ridiculously tiny distance (about  $10^{-43}$  seconds) is called the Planck time, the shortest possible tick of an imaginary clock. Combine these two ideas and the implication is that space and time have a structure. What is commonly thought of as the featureless void is built from tiny units, or quanta.

"We've long suspected that space-time had to be quantized," said Dr. Steven B. Giddings, a theorist at the University of California at Santa Barbara. "Recent developments have led to some exciting new proposals about how to make these ideas more concrete."

The hints of graininess come from attempts to unify general relativity, Einstein's theory of gravity, with quantum mechanics, which describes the workings of the three other forces: electromagnetism and the strong and weak nuclear interactions. The result would be a single framework -- sometimes called quantum gravity -- that explains all the universe's particles and forces.

The most prominent of these unification efforts, superstring theory, and a lesser-known approach called loop quantum gravity, both strongly suggest that space-time has a minute architecture. But just what the void might look like has physicists straining their imaginations.

As Dr. John Baez, a theorist at the University of California at Riverside put it: "There's a lot we don't know about nothing."

**Since the days of ancient Greece, some philosophers have insisted that reality must be perfectly smooth like the continuum of real numbers: pick any two points, no matter how close together, and there is an infinity of gradations in between. Others have argued that, on the smallest scale, everything is surely divided into irreducible units like the so-called natural or counting numbers, with nothing between, say, 3 and 4.**

The development of modern atomic theory, in the 19th century, pushed science toward viewing the universe as lumpy instead of smooth. At the beginning of this century, sentiments swung further in that direction when Max Planck found that even light was emitted in packets. From that unexpected discovery emerged quantum field theory, in which all the forces are carried by tiny particles, or quanta -- all, that is, except gravity.

This force continues to be explained, in entirely different terms, by general relativity: as the warping of a perfectly smooth continuum called space-time. A planet bends the surrounding space-time fabric causing other objects to move toward it like marbles rolling down a hill.

Scientists have long assumed that unification would reveal that gravity, like the other forces, is also quantum in nature, carried by messenger particles called gravitons. But while the other forces can be thought of as acting within an arena of space and time, gravity *is* space-time. Quantizing one is tantamount to quantizing the other.

**It is hardly surprising that space-time graininess has gone unnoticed here in the macroscopic realm. Even the tiny quarks that make up protons, neutrons and other particles are too big to feel the bumps that may exist on the Planck scale. More recently, though, physicists have suggested that quarks and everything else are made of far tinier objects: superstrings vibrating in 10 dimensions. At the Planck level, the weave of space-time would be as apparent as when the finest Egyptian cotton is viewed under a magnifying glass, exposing the warp and woof.**

It was Planck himself who first had an inkling of a smallest possible size. He noticed that he could start with three fundamental parameters of the universe -- the gravitational constant (which measures the strength of gravity), the speed of light, and his own Planck's constant (a gauge of quantum graininess) -- and combine them in such a way that the units canceled one another to yield a length. He was not sure about the meaning of this Planck length, as it came to be called, but he felt that it must be something very basic.

In the 1950's, the physicist John Wheeler suggested that the Planck length marked the boundary where the random roil of quantum mechanics scrambled space and time so violently that ordinary notions of measurement stopped making sense. He called the result "quantum foam."

"So great would be the fluctuations that there would literally be no left and right, no before and no after," Dr. Wheeler recently wrote in his memoir, "Geons, Black Holes and Quantum Foam" (Norton, 1998). "Ordinary ideas of length would disappear. Ordinary ideas of time would evaporate."

**Half a century later, physicists are still trying to work out the bizarre implications of a minimum length.** In superstring theory, a mathematical relationship called T duality suggests that one can shrink a circle only so far. As the radius contracts, the circle gets smaller and smaller and then bottoms out, suddenly acting as though it is getting bigger and bigger.

"This behavior implies that there is a minimum 'true size' to the circle," Dr. Giddings said. Many believe this will turn out to be roughly comparable to the Planck scale.

There are other indications of graininess. According to the Heisenberg uncertainty principle, certain pairs of quantities are "noncommutative": you cannot simultaneously measure a particle's position and momentum, for example, or its energy and life span. The more precisely you know one, the fuzzier your knowledge of the other becomes.

In string theory, the very geometry of space may turn out to be noncommutative, making it impossible to measure simultaneously the horizontal and vertical position of a particle to perfect precision. The graininess of space itself would get in the way.

Not everyone in the unification business is a string theorist. Coming from an entirely different direction, researchers in a discipline called loop quantum gravity have devised a theory in which space is constructed from abstract mathematical objects called spin nets.

Imagine a tiny particle spinning like a top on its axis. Now send it on a roundtrip journey, a loop through space. Depending on the Einsteinian shape of the space the particle traverses, it will return home with its axis tilted in a different direction. This change then provides a clue about how the space is curved.

Using particles with various spins, theorists can probe space in more detail. The different trajectories can then be combined into a web, called a spin network, that captures everything you need to know about how the space is curved -- what physicists call its geometry.

"Our space in which we live is just this enormously complicated spin network," said Dr. Carlo Rovelli of the University of Pittsburgh. He and Dr. Lee Smolin of the Center for Gravitational Physics and Geometry at Pennsylvania State University have figured out how to use spin nets to calculate area and volume -- all this information is encoded within the weblike structure.

Suppose you are sitting at a table. To calculate its area you would add up the spins of all the links of the spin net that are passing through it, and multiply by the square of the Planck length. A table with an area of about one square meter would be impinged by some 10 to the 65th of these trajectories. The implication is that the very idea of a surface is an illusion generated by the spin network.

The picture gets even weirder. In quantum mechanics, an electron orbiting an atomic nucleus is thought of as a cloud of probability: a "superposition" in which all the electron's possible locations hover together. In the view of Dr. Rovelli, Dr. Smolin and their colleagues, the universe itself is a superposition of every conceivable spin net -- all the possible ways that it can be curved.

Where does time fit into the picture? A spin net provides a snapshot of the geometry of three-dimensional space at a particular instant. To describe space-time, Dr. Baez and other theorists have stretched spin nets into the fourth dimension, devising what they call spin foam. Slice it and each infinitely thin cross section is a spin net.

Most perplexing of all, spin nets and spin foam cannot be thought of as existing in space and time. They reside on a more fundamental level, as a deep structure that underlies and gives rise to space-time.

"That is the core of the matter," Dr. Rovelli said. "They don't *live* somewhere. They *are* the quantum space-time."

The universe, in this view, is conjured up from pure mathematics. And the old idea of space and time as the stage on which everything happens no longer seems to apply.

"If we believe what we really have discovered about the world with quantum mechanics and general relativity, then the *stage* fiction has to be abandoned," Dr. Rovelli said, "and we have to learn to do physics and to think about the world in a profoundly new way. Our notions of what are space and time are completely altered. In fact, in a sense, we have to learn to think without them."

---

Copyright 1999 The New York Times Company



Return to PHIL 320 [Home Page](#)