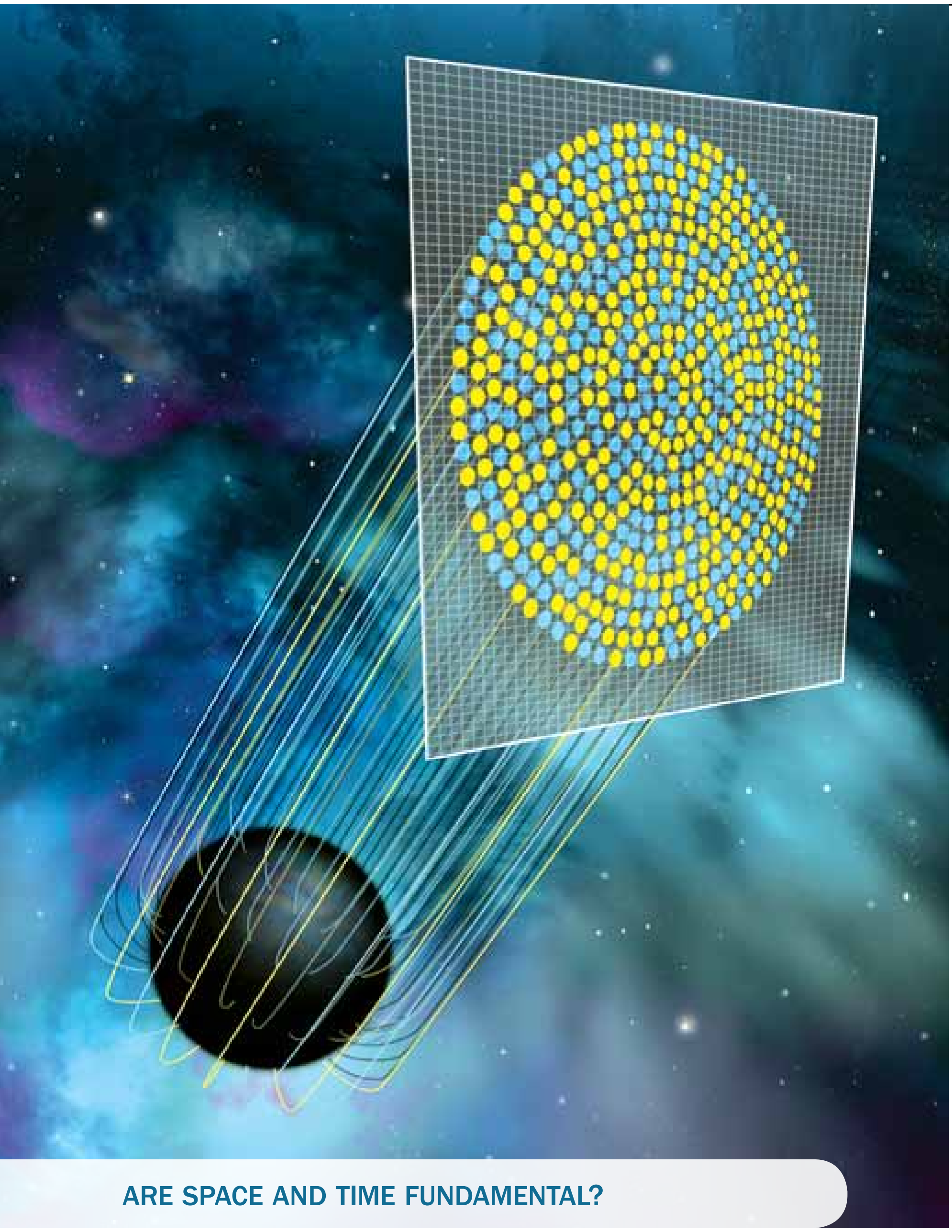

A 2-D projection contains all the details needed to map a 3-D black hole. Some physicists think space and time may emerge via a similar correspondence.

ARE SPACE AND TIME FUNDAMENTAL?

Out of the fabric

By Tom Siegfried ▪ Illustration by Nicolle Rager Fuller

Of all the mysteries of life and the universe, none resist the sleuthing of science's best private eyes more obstinately than the ultimate nature of space and time.

Every several centuries or so, profound insights do occur, immortalizing the names of the investigators who achieved them: Euclid (who cataloged the insights preceding him), Galileo, Newton, Einstein. Yet each advance left deeper questions unanswered. And now the 21st century's best brains still cannot say for sure whether space and time are fundamental building blocks of natural existence, or are themselves built from more primordial ingredients, so far unperceived.

Newton simply declared space and time as absolute and constant, providing a convenient arena for the operation of his laws of motion and gravity. Einstein saw, and showed, that space and time actually shift shape or speed as events unfold; mass and motion warp space and alter the flow of time.

Coping with these inconveniences required a merger, space and time becoming spacetime. From that merger emerged a bonus: a model for the evolution of the cosmos, from an initial speck of matter and energy to a gigantic ballooning multigalactic network.

Nowadays, though, spacetime's ability to accommodate nature's phenomena has begun to fade as physicists push their probes to the limits of distance and duration. Below a certain very tiny distance, the dimension of length can no longer be explored, or even defined. Time faces a similar limit when durations approach the very brief.

Today's leading theories for answering the greatest cosmic questions suggest that neither time nor space appear in reality's ultimate recipe. Somewhere between the stove and the table, space and time emerge, cooked up out of equations underlying an existence without rulers and clocks. At least that is "the widespread current belief," says physicist Joe Polchinski of the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara.

Space as society

To illustrate this, Fotini Markopoulou of the Perimeter Institute for Theoretical Physics in Waterloo, Canada, compares space to society. Space, like society, has features that can be described — geometry textbooks catalog space's properties and their implications. But space as reflected in geometry need not have been present at the beginning. It could have emerged from the interactions of matter and forces, just as society materializes from interactions among people.

"We have capitalist societies, agricultural societies, totalitarian societies," Markopoulou wrote in a 2008 paper (arXiv.org/abs/0909.1861). Nobody is confused by phrases such as "our society is addicted to credit." But that doesn't mean society is a fundamental feature of existence.

"A society does not exist independent of its members," Markopoulou pointed out. "We can see spacetime geometry as the analog to society, with the role of individuals played by matter and its dynamics."

As Polchinski notes, specifying spacetime's status in relation to matter is part of the quest for a theory of quantum gravity — the math that would unify Einstein's relativity theory, which describes spacetime in bulk, with the quantum physics that governs the microworld (see Page 26). A key clue in that quest is a correspondence between the surface of a black hole, a gravitational bottomless pit from which nothing can escape, and the space within it. It turns out that a mathematical description of the black hole's outer boundary (the point of no return for objects falling in) contains all the information needed to specify the three-dimensional interior. In essence, that means the 3-D space inside somehow emerges from the physics of the 2-D surface.

Time materialized

Generalizing the peculiarities of black holes to ordinary space and time remains a research challenge for quantum gravity physicists. But most agree that sooner or later space and time will have to go. String theory — the most-studied approach to quantum gravity — offers several examples of how space, rather than being fundamental, emerges into existence, as physicist Nathan Seiberg of the Institute for Advanced Study in Princeton, N.J., outlined in a 2006 paper (arXiv.org/abs/hep-th/0601234).

If matter at its most basic is made of tiny vibrating strings, for instance, it becomes impossible to probe space to any arbitrarily short distance, Seiberg observes. That's another way of saying that at distances less than some (very short) length, the idea of space becomes meaningless.

Further study of spaceless theories may help solve serious problems confronting physicists today, Seiberg believes. String theory implies countless possible vacuum states — that is, spaces of differing physical properties — with no obvious method for determining which one the visible universe should have chosen. Knowing how space emerges from spacelessness might help explain why humans exist in one particular space from among the countless possibilities.

Doing away with time poses more difficult problems, Seiberg acknowledges. Basic notions in physics, such as that of causes preceding effects, or predicting the outcome of experiments before the experiment is done, seem to lose their meaning if there is no time to define before and after. So some physicists, Markopoulou for one, have suggested that even if space is emergent, time may remain fundamental. In fact, she conjectures, time is needed to allow quantum processes to create the illusion of space. Space may not have been around at the beginning, but that beginning would be stillborn without time to get reality going.

Seiberg, though, believes time and space will both go down the cosmic drain together.

"My personal prejudice is that these objections and questions are not obstacles to emergent time," Seiberg writes. "Instead, they should be viewed as challenges and perhaps even clues to the answers."

More intriguingly, he observes, space and time's ultimate status in nature may have something to say about the practice of science. Much of modern science is based on the concept of reductionism — explaining large-scale phenomena from laws operating at smaller scales. That notion will eventually break down if there's a smallest scale below which space no longer exists.

"Therefore, once we understand how spacetime emerges, we could still look for more basic fundamental laws, but these laws will not operate at shorter distances," he writes. "This follows from the simple fact that the notion of 'shorter distances' will no longer make sense. This might mean the end of standard reductionism." And the beginning of a new view of not only space and time, but of science itself. ■

As small as it gets

Current theories are unable to describe space and time below certain limits defined by what are called "natural units." These units, proposed by the German physicist Max Planck, are derived from fundamental quantities such as the speed of light. A theory uniting quantum mechanics with gravity will be needed to reveal whether space and time are meaningful concepts at smaller scales.

Planck length: 1.616×10^{-35} meters

The Planck length is derived from Newton's gravitational constant, the speed of light and Planck's own constant from quantum theory. It is unfathomably small: Comparing its size to a bacterium is like comparing the size of a bacterium to the visible universe. Many physicists believe that at shorter lengths space cannot be probed and the concept of distance becomes no longer meaningful.

Planck time: 5.391×10^{-44} seconds

The Planck time is also calculated from the gravitational constant, the speed of light and Planck's constant in such a way that moving at one Planck length per one Planck time would be equal to the speed of light. Current theories are unable to describe the universe at an age younger than the Planck time; physicists hope that a theory of quantum gravity could illuminate that epoch.