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How Einstein Revealed the Universe's Strange "Nonlocality"

Our sense of the universe as an orderly expanse where events happen in absolute locations is an illusion

By George Musser | Oct 20, 2015 | 0

Adapted from Spooky Action at a Distance: The Phenomenon That Reimagines Space and Time—and What It Means for Black Holes, the Big Bang, and Theories of Everything, *by George Musser, by arrangement with Scientific American/Farrar, Straus and Giroux, LLC (US).*

Edward Kinsella III

When I first learned about the quantum phenomenon known as nonlocality in the early 1990s, I was a graduate student. But I didn't hear about it from my quantum-mechanics professor: he didn't see fit to so much as mention it. Browsing in a local bookshop, I picked up a newly published work, *The Conscious Universe*, which startled me with its claim that "no previous discovery has posed more challenges to our sense of everyday reality" than nonlocality. The phenomenon had the taste of forbidden fruit.

In everyday speech, "locality" is a slightly pretentious word for a neighborhood, town or other place. But its original meaning, dating to the 17th century, is about the very concept of "place." It means that everything *has* a place. You can always point to an object and say, "Here it is." If you can't, that thing must not really exist. If your teacher asks where your homework is, and you say it isn't anywhere, you have some explaining to do.

The world we experience possesses all the qualities of locality. We have a strong sense of place and of the relations among places. We feel the pain of separation from those we love and the impotence of being too far away from something we want to affect. And yet multiple branches of physics now suggest that, at a deeper level, there may be no such thing as place and no such thing as distance. Physics experiments can bind the fate of two particles together so that they behave like a pair of magic coins. If you flip them, each will land on heads or tails—but always on the same side as its partner. They act in a coordinated way even though no force passes through the space between them. Those particles might zip off to opposite sides of the universe, and still they act in unison. The particles violate locality—they transcend space.

Evidently nature has struck a peculiar and delicate balance: under most circumstances it obeys locality, and it *must* obey locality if we are to exist, yet it drops hints of being nonlocal at its foundations. For those who study it, nonlocality is the mother of all physics riddles, implicated in a broad cross section of the mysteries that physicists confront these days—not just the weirdness of quantum particles but also the fate of black holes, the origin of the cosmos and the essential unity of nature.

For most of the 20th century, quantum entanglement—the peculiar synchronicity of particles—was the only type of nonlocality that rated any mention. It was the phenomenon that Albert Einstein called "spooky action at a distance." But physicists gradually realized that other phenomena are suspiciously spooky, too.

For instance, Einstein created his general theory of relativity—which provides our modern understanding of gravity—with the express purpose of expunging nonlocality from physics. Isaac Newton's gravity acted at a distance, as if by magic, and general relativity snapped the wand in two by showing that the curvature of spacetime, and not an invisible force, gives rise to gravitational attraction. But whatever Einstein's intention may have been, his theory began to reveal a different side as physicists put it to use. The workings of gravity turn out to be sparkling with nonlocal phenomena.

What we mean by “here”

One day in autumn, Don Marolf, a physicist at the University of California, Santa Barbara, and I were talking about gravity while sitting in the student center of his campus, eating salads and looking out over the lagoon. But hang on. How did I really know I was sitting in the U.C.S.B. student center on a certain day in autumn? The principle of locality says that I had a position, the student center had a position, and when these two positions coincided, I was there. The GPS coordinates on my phone matched those of the center, and the date matched the calendar on the wall. But this seemingly straightforward procedure doesn't stand up on examination. “To ask a question about here, we should know what we mean by ‘here,’ and that's not so easy to do,” Marolf says.

One obvious complication is that California is tectonically active. The crustal plate on which Santa Barbara sits is moving northwest by a couple of inches per year relative to the rest of North America and to the national latitude and longitude grid. So the student center has no fixed position. If I come back some years from now and go to the same coordinates, I'll find myself sitting in that lagoon. Mapping companies must periodically resurvey tectonic zones to account for this motion.

You might suppose that the student center still has a position defined in an absolute sense by space itself. Yet space and time are no more stable than a tectonic plate. They can slide, heave and buckle. When a massive body shifts, it sends tremors through the spacetime continuum, resculpting it. The position of the cafeteria might change as a result, even if the tectonic plate stays put. This process, rather than Newton's mysterious action at a distance, is how gravity is communicated from one place to another, according to Einstein's general theory of relativity. Like geologic tremors, gravitational ripples propagate at a certain finite speed—namely that of light.

To grasp the reshaping of spacetime, our minds have to overcome a hurdle of abstraction. Spacetime is not as tangible as a geologic landscape. We can't see it, let alone discern its shape. Yet we catch indirect glimpses. Objects that are moving freely through space, unhindered by other objects, are like raindrops streaking across a car windshield, revealing the curve of the glass: they trace out the shape of space. For instance, astronomers routinely observe rays of starlight that begin as parallel, pass near a giant lump of mass such as the sun, then afterward intersect. Textbooks and articles describing this effect often say that the sun's gravity has bent the light rays, but that's not quite right. The rays are as straight as straight can be. What the sun has really done is to alter the rules of geometry—that is, to warp space—such that parallel lines can meet.

The morphing of space and time is not just the stuff of exotic physics. It governs the motion of any falling object. Baseballs, wineglasses, expensive smartphones: things that slip out of your hand accelerate toward the floor because Earth's mass warps time. (The warping of space plays only a minor role in these cases.) “Down” is defined by the direction in which time passes more slowly. Clocks at sea level tick more slowly than clocks on the summit of Denali; a watch strapped to your ankle will fall behind one on your wrist. In human terms, the deviations are small—parts in a trillion at most—but enough to account for the rate at which falling objects pick up speed. When you see an apple fall from a tree, you are watching it roll across the contours of time.

Relativity's revelation

Although the shape shiftiness of spacetime explains away the kind of nonlocality that Newton talked about, it produces a new variety. It comes out of relativity theory's core innovation: that there's no such thing as a place outside spacetime, no external or absolute standard to judge it by. This seemingly self-evident proposition has remarkable consequences. It means that spacetime not only warps but also loses many of the qualities we associate with it, including the ability to define locations.

Disavowing a god's-eye perspective, Marolf says, “is very subtle, and, honestly, Einstein didn't understand it for a long time.” Previous conceptions of space, including Newton's and even Einstein's own earlier thinking, supposed that space had a fixed geometry, which would let you imagine rising above space and looking down on it. In fact, at one point, Einstein argued there *had* to be an absolute reference point or else the shape of space would become ambiguous.

For a sense of why the ambiguity arises, consider how we experience geography in everyday life. We might suppose there is a unique "real" shape to the landscape—what Google Earth shows—but in practice the shape is defined by the experience of being embedded within that landscape, and that experience can vary. A student running late to an exam, an athlete hobbling on a sprained ankle, a professor walking with a colleague while deep in conversation and a cyclist yelling at pedestrians to get out of the way will perceive very different campuses. A short distance for one may seem an interminable crossing to another. When we eschew the view from on high, we can no longer make definitive statements about what is where.

In an epiphany in 1915, Einstein realized that the ambiguity is not a bug but a feature. He noted that we never observe places to have absolute locations, anyway. Instead we assign positions based on how objects are arranged relative to one another, and—crucially—those relative locations are objective. Everyone wandering around the college campus will recognize the basic ordering of places. They will juxtapose the U.C. student center with the lagoon rather than putting them on opposite sides of campus. If the landscape buckled or flowed while preserving these relations, the denizens would never know. So it is for spacetime. Different observers may ascribe different locations to a place but will agree on the relations that places bear to one another. These relations are what determine the events that occur. "If George and Don met in a certain café at noon in the first spacetime," Marolf tells me, "they would also do so in the reshuffled spacetime. It's just that in the first case this would have occurred at point B, and in the reshuffled case it occurs at point A."

The cafeteria, then, is situated at A or B or C or D or E—an infinity of possible positions. When we say it's located at such and such a place, we're really using a shorthand for its relations to other landmarks. Lacking definitive coordinates, the cafeteria must be situated by the things within and around it. To locate it, you'd need to search the world over for a place where the tables, chairs and salad bar are arranged just so and where a patio overlooks a lagoon bathed in the golden sunlight of southern California. The position of the student center is a property not of the center but of the entire system to which it belongs. "The question you asked in principle refers to the whole spacetime," Marolf says.

The ambiguity of localized measurements is a form of nonlocality. To begin with, quantities such as energy can't be situated in any specific place, for the simple reason that there is no such thing as a specific place. You can no sooner pin down a position than you can plant a flag on the sea. Points in space are indistinguishable and interchangeable. Because they lack any differentiating attributes, whatever the world consists of must not reside at points; space is unable to support any localized structure. Gravitational quantities must instead be holistic—properties of spacetime in its entirety.

Furthermore, the multiple equivalent shapes of space are described by different configurations of the gravitational field. In one configuration, the field might exert a stronger force in one place than it would in another configuration, with compensating changes elsewhere to maintain the relative arrangement of objects. Points in the gravitational field must be interlinked with one another so that they can flop around while collectively still producing the same internal arrangement of objects. These linkages violate the principle that individual locations in space have an autonomous existence. Marolf has put it this way: "Any theory of gravity is not a local field theory. Even classically there are important constraint equations. The field at *this* point in spacetime and the field at *this* point in spacetime are not independent."

Under most circumstances, we can ignore this nonlocality. You can designate some available chunk of matter as a reference point and use it to anchor a coordinate grid. You can, to the chagrin of Santa Barbarans, take Los Angeles as the center of the universe and define every other place with respect to it. In this framework, you can go about your business in blissful ignorance of space's fundamental inability to demarcate locations. "Once you've done that, the physics looks like it's local," Marolf says. "The dynamics of gravity is completely local. Things move in a continuous way, limited by the speed of light." But the properties of gravity are still only "pseudo local." The nonlocality is always there, lurking beneath the surface, emerging under extreme circumstances such as black holes.

In short, Einstein's theory is nonlocal in a more subtle and insidious way than Newton's theory of gravity was. Newtonian gravity acted at a distance, but at least it operated within a framework of absolute space. Einsteinian gravity has no such element of wizardry; its effects ripple through the universe at the speed of light. Yet it demolishes the framework, violating locality in what was, for Einstein, its most basic sense: the stipulation that all things have a location. General relativity confounds our intuitive picture of space as a kind of container in which material objects reside and forces us to search for an entirely new conception of place.

ABOUT THE AUTHOR(S)

George Musser is a contributing editor at Scientific American and author of The Complete Idiot's Guide to String Theory (Alpha Books, 2008).

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