

# A Quantum Threat

Entanglement, like many quantum effects, violates some of our deepest intuitions about the world.

It may also undermine Einstein's special theory of relativity

By David Z Albert and Rivka Galchen

Our intuition, going back forever, is that to move, say, a rock, one has to touch that rock, or touch a stick that touches the rock, or give an order that travels via vibrations through the air to the ear of a man with a stick that can then push the rock—or some such sequence. This intuition, more generally, is that things can only directly affect other things that are right next to them. If A affects B *without* being right next to it, then the effect in question must be *indirect*—the effect in question must be something that gets transmitted by means of a chain of events in which each event brings about the next one directly, in a manner that smoothly spans the distance from A to B. Every time we think we can come up with an exception to this intuition—say, flipping a switch that turns on city street lights (but then we realize that this happens through wires) or listening to a BBC radio broadcast (but then we realize that radio waves propagate through the air)—it turns out that we have not, in fact, thought of an exception. Not, that is, in our everyday experience of the world.

We term this intuition “locality.”

Quantum mechanics has upended many an intuition, but none deeper than this one. And this particular upending carries with it a threat, as yet unresolved, to special relativity—a foundation stone of our 21st-century physics.

## The Thing from Outer Space

Let's back up a bit. Prior to the advent of quantum mechanics, and indeed back to the very beginnings of scientific investigations of nature, scholars believed that a complete description of

the physical world could in principle be had by describing, one by one, each of the world's smallest and most elementary physical constituents. The full story of the world could be expressed as the sum of the constituents' stories.

Quantum mechanics violates this belief.

Real, measurable, physical features of collections of particles can, in a perfectly concrete way, exceed or elude or have nothing to do with the sum of the features of the individual particles. For example, according to quantum mechanics one can arrange a pair of particles so that they are precisely two feet apart and yet neither particle on its own has a definite position. Furthermore, the standard approach to understanding quantum physics, the so-called Copenhagen interpretation—proclaimed by the great Danish physicist Niels Bohr early last century and handed down from professor to student for generations—insists that it is not that we do not know the facts about the individual particles' exact locations; it is that there simply *aren't* any such facts. To ask after the position of a single particle would be as meaningless as, say, asking after the marital status of the number five. The problem is not epistemological (about what we know) but ontological (about what is).

Physicists say that particles related in this fashion are quantum mechanically entangled with one another. The entangled property need not be location: Two particles might spin in opposite ways, yet with neither one definitely spinning clockwise. Or exactly one of the particles might be excited, but neither is definitely the excited one. Entanglement may connect particles irrespective of where they are, what they are and

## KEY CONCEPTS

- In the universe as we experience it, we can directly affect only objects we can touch; thus, the world seems local.
- Quantum mechanics, however, embraces action at a distance with a property called entanglement, in which two particles behave synchronously with no intermediary; it is nonlocal.
- This nonlocal effect is not merely counterintuitive: it presents a serious problem to Einstein's special theory of relativity, thus shaking the foundations of physics.

—The Editors

# to Special Relativity

[BASICS]

# The EPR Thought Experiment

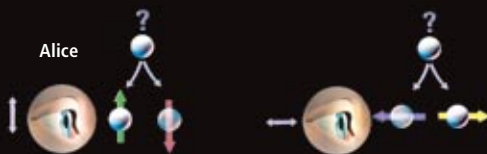
Albert Einstein, Boris Podolsky and Nathan Rosen ("EPR") pointed out that quantum entanglement of two particles produces inexplicable results if two people who are far apart (*here Alice and Buzz*) each examine one of the particles.

## Quantum spins



Electrons have a property called spin, represented here by arrows that may point in any direction. When Alice measures an electron's spin (*below*), she chooses an axis. Measuring along a vertical axis, she will find the electron in either the up or the down state, with some probability for each. Using an east-west axis, she will find east or west spin.

## Measurements



Two particles may be entangled so that they have their spins pointing in opposite directions, even though neither has a definite direction of its own. Suppose that Alice and Buzz share such a pair and that Alice finds hers to have spin up (*below*). No matter how far away Buzz and his particle are from Alice, if he measures his particle along the vertical axis he will definitely see that his particle has spin down, the opposite of Alice's.

## Entangled spins



EPR argued that because Buzz can be 100 percent certain of measuring spin down, the spin of his particle must already be down, even prior to his measuring it. But Alice could equally well have measured along east-west and obtained, say, east spin, implying that Buzz's particle already has a west spin.

## EPR argument



Because no quantum state permits Buzz's particle to be certainly spin down *and* certainly spin west, EPR concluded that quantum mechanics must be an incomplete theory.

what forces they may exert on one another—in principle, they could perfectly well be an electron and a neutron on opposite sides of the galaxy. Thus, entanglement makes for a kind of intimacy amid matter previously undreamt of.

Entanglement lies behind the new and exceedingly promising fields of quantum computation and quantum cryptography, which could provide the ability to solve certain problems that are beyond the practical range of an ordinary computer and the ability to communicate with guaranteed security from eavesdropping [see "Quantum Computing with Ions," by Christopher R. Monroe and David J. Wineland; SCIENTIFIC AMERICAN, August 2008].

But entanglement also appears to entail the deeply spooky and radically counterintuitive phenomenon called nonlocality—the possibility of physically affecting something without touching it or touching any series of entities reaching from here to there. Nonlocality implies that a fist in Des Moines can break a nose in Dallas without affecting any other physical thing (not a molecule of air, not an electron in a wire, not a twinkle of light) anywhere in the heartland.

The greatest worry about nonlocality, aside from its overwhelming intrinsic strangeness, has been that it intimates a profound threat to special relativity as we know it. In the past few years this old worry—finally allowed inside the house of serious thinking about physics—has become the centerpiece of debates that may finally dismantle, distort, reimagine, solidify or seed decay into the very foundations of physics.

## Radical Revisions of Reality

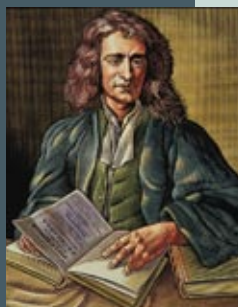
Albert Einstein had a number of worries about quantum mechanics. The overquoted concern about its chanciness ("God does not play dice") was just one. But the only objection he formally articulated, the only one he bothered to write a paper on, concerned the oddity of quantum-

B. SAMERSON Photo Researchers, Inc. (Newton); THE GRANGER COLLECTION (Coulomb apparatus); ALFRED T. KAMAHAJIAN (illustrations)

### NONLOCALITY THROUGH THE CENTURIES

## Changing Views of "Reality"

Our intuition is that the world is local: we can move a rock only by touching it directly, or by touching a stick that touches it, or by creating some unbroken chain of such direct, local connections. Yet since the beginnings of modern science in the 1600s, apparent nonlocalities have been challenging scientists.



**1687:** Isaac Newton's law of universal gravitation, the first modern scientific description of gravity, involves "action at a distance." Newton is sure there must be an account of gravity without this nonlocality and even tries an unsuccessful theory in which tiny invisible, jiggling particles fill all of seemingly empty space.

**1785:** Charles Coulomb introduces the inverse-square law for electrostatic forces, analogous to Newton's inverse-square law for gravity. Electric effects seem to involve action at a distance.



CORDELLA MOLLOY/Photo Researchers, Inc. (Faraday's magnetic repulsion); LAWRENCE MANNING/Corbis (Fizeau and Foucault's speed of light); SPL/PHOTO RESEARCHERS, INC. (Maxwell's equations); COURTESY OF DAVID Z ALBERT (Albert); COURTESY OF KEN GOEBEL (Galchen)

mechanical entanglement. This objection lies at the heart of what is now known as the EPR argument, named after its three authors, Einstein and his colleagues Boris Podolsky and Nathan Rosen [see box on opposite page]. In their 1935 paper “Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?”, they answer their own question with a tightly reasoned “no.”

Their argument made pivotal use of one particular instruction in the quantum-mechanical recipe, or mathematical algorithm, for predicting the outcomes of experiments. Suppose that we measure the position of a particle that is quantum mechanically entangled with a second particle so that neither individually has a precise position, as we mentioned above. Naturally, when we learn the outcome of the measurement, we change our description of the first particle because we now know where it was for a moment. But the algorithm also instructs us to alter our description of the second particle—and to alter it instantaneously, no matter how far away it may be or what may lie between the two particles.

Entanglement was an uncontroversial fact of the picture of the world that quantum mechanics presented to physicists, but it was a fact whose implications no one prior to Einstein had thought much about. He saw in entanglement something not merely strange but dubious. It struck him as spooky. It seemed, in particular, nonlocal.

Nobody at that time was ready to entertain the possibility that there were genuine physical nonlocalities in the world—not Einstein, not Bohr, not anybody. Einstein, Podolsky and Rosen took it for granted in their paper that the apparent nonlocality of quantum mechanics must be apparent only, that it must be some kind of mathematical anomaly or notational infelicity or, at any rate, that it must be a disposable artifact of the algorithm—surely one could cook up quantum mechanics’s predictions for ex-

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periments without needing any nonlocal steps.

And in their paper they presented an argument to the effect that if (as everybody supposed) no genuine physical nonlocality exists in the world and if the experimental predictions of quantum mechanics are correct, then quantum mechanics must leave aspects of the world out of its account. There must be parts of the world’s story that it fails to mention.

Bohr responded to the EPR paper practically overnight. His feverishly composed letter of refutation engaged none of the paper’s concrete scientific arguments but instead took issue—in an opaque and sometimes downright oracular fashion—with its use of the word “reality” and its definition of “elements of physical reality.” He talked at length about the distinction between subject and object, about the conditions under which it makes sense to ask questions and about the nature of human language. What science needed, according to Bohr, was a “radical revision of our attitude as regards physical reality.”

Bohr did go out of his way to agree with the EPR paper on one point: that of course there can be no question of a genuine physical nonlocality. The apparent nonlocality, he argued, was just one more reason why we must abandon the quaint and outdated aspiration, so manifest in the EPR paper, of being able to read from the equations of quantum mechanics a realistic picture of the world—a picture of what actually exists before us from moment to moment. Bohr insisted, in effect, that not only do we see the world through a glass darkly but that this shadowy and indefinite view is as real as anything gets.

Bohr’s was a curiously philosophical response to an explicitly scientific concern. More curious still was the enshrinement of Bohr’s response as the official gospel of theoretical physics. To spend any more time on these matters became, thereafter, apostasy. The physics community thus turned away from its old aspirations to uncover what the

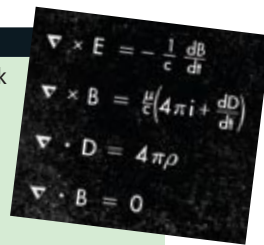


**1831:** Michael Faraday introduces the idea of magnetic lines of force. Physicists at this time use a notation involving electric and magnetic fields that fill space. The forces on a particle become, at least formally, a local action of the fields on them. But these fields are viewed as convenient calculational tools, not as things that are real.

**1849:** Hippolyte Fizeau and Jean-Bernard Foucault measure the speed of light to be 186,000 miles per second, or 298,000 kilometers per second, but no one knows what light really is.



**1865:** James Clerk Maxwell’s equations reveal that electromagnetic fields have a rich dynamical life of their own, pushing and pulling each other, and crossing empty space at 298,000 km/s. Electromagnetism is local and light is an electromagnetic wave!



## Bell's Theorem and the Physical World

The nonlocality of our physical world follows from a combination of a theorem proved by John S. Bell in 1964 and experimental results obtained since the early 1980s. His theorem builds on the puzzle about entangled particles pointed out by Einstein, Podolsky and Rosen in 1935 [see box on page 34]. The EPR argument assumes that nature is local so that in particular a measurement (by, say, Alice) on one particle of a widely separated entangled pair cannot instantaneously alter the physical state of the faraway partner particle (which, say, Buzz can measure). They conclude that Buzz's particle must already have determinate values for spins in every direction. Thus, quantum mechanics must be incomplete because it does not determine those values except to guarantee they will be consistent with whatever result Alice gets when she measures her particle.

Bell asked: supposing that Alice's and Buzz's entangled particles have determinate values, can such particles reproduce the results predicted by quantum mechanics for all the ways that Alice and Buzz might measure their particles? Recall that for particles with entangled spins, Alice and Buzz must each choose an axis to measure the spin along. Bell proved mathematically that if Alice and Buzz chose to measure along axes at angles such as 45 and 90 degrees from each other, their measurements from numerous runs of the experiment would produce a statistical distribution of results that disagreed with that predicted by quantum mechanics—no matter what distribution of determinate values the particles had.

Researchers carried out experiments using entangled photons instead of electrons (which alters the angles to use but makes the experiment technically much less difficult) and found results that conformed with quantum mechanics's predictions. And so by Bell's theorem there must not be any determinate values carried by those photons. And because that contradicts EPR's conclusion, the assumption that nature is local is also wrong. And so the universe we live in cannot be local.

—D.Z.A. and R.G.

world is really like and for a long time thereafter it relegated metaphysical questions to the literature of fantasy.

Even today this crucial part of Einstein's legacy remains very much obscured. The best-selling 2007 Walter Isaacson biography of Einstein simply assures the reader that Einstein's criticism of quantum mechanics has since been resolved. And this is not true.

### Return of the Repressed

The first serious scientific engagement with the EPR argument came (after 30 years of more or less complete neglect) in a famous 1964 paper by the extraordinary Irish physicist John S. Bell.

From Bell's work it emerged that Bohr was wrong that nothing was wrong with his understanding of quantum mechanics and that Einstein was wrong about *what* was wrong with Bohr's understanding. To take in what was actually wrong involves abandoning the idea of locality.

The crucial question is whether the nonlocalities that at least appear to be present in the quantum-mechanical algorithm are merely apparent or something more. Bell seems to have been the first person to ask himself precisely what that question means. What could make genuine physical nonlocalities distinct from merely apparent ones? He reasoned that if any manifestly and completely local algorithm existed that made the same predictions for the outcomes of experiments as the quantum-mechanical algorithm does, then Einstein and Bohr would have been right to dismiss the nonlocalities in quantum mechanics as merely an artifact of that particular formalism. Conversely, if no algorithm could avoid nonlocalities, then they must be genuine physical phenomena. Bell then analyzed a specific entanglement scenario and concluded that no such local algorithm was mathematically possible.

And so the actual physical world is nonlocal. Period.

This conclusion turns everything upside down. Einstein, Bohr and everyone else had always taken it for granted that any genuine incompatibility between quantum mechanics and the principle of locality would be bad news for quantum mechanics. But Bell had now shown that locality was incompatible not merely with the abstract theoretical apparatus of quantum mechanics but with certain of its empirical predictions as well. Experimenters—in particular work by Alain Aspect of the Institute of Optics in Palaiseau, France, and his co-workers in 1981 and later—have left no doubt that those predictions are indeed correct. The bad news, then, was not for

### [NONLOCALITY THROUGH THE CENTURIES]

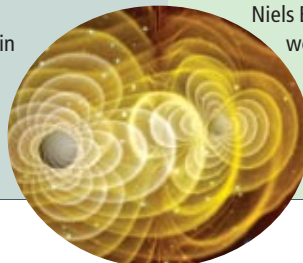
**1905:** Einstein's special theory of relativity reconciles Maxwell's equations with the principle

that observers moving at a constant relative velocity should see identical laws of physics. But it destroys the possibility of distant events being simultaneous in any absolute sense.

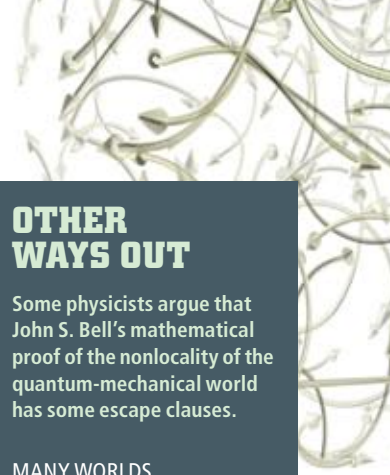
**1915:** In Einstein's general theory of relativity, the curvature of spacetime plays the role that electromagnetic fields play for electromagnetic forces. Gravity is local: if a mass is jiggled, ripples in the curvature travel out at the speed of light.

**1935:** Einstein, Boris Podolsky and Nathan Rosen argue that because quantum-mechanical calculations involve nonlocal steps, quantum mechanics cannot be the full story.

Niels Bohr (*far right*) insists we must accept quantum mechanics and instead give up old notions of "reality."



HULTON-DEUTSCH (Einstein); C. HENZE/NASA (curvature of spacetime); PAUL EHRENFEST, COURTESY OF EMILIO SEGRE VISUAL ARCHIVES, EHRENFEST COLLECTION (Einstein and Bohr)



## OTHER WAYS OUT

Some physicists argue that John S. Bell's mathematical proof of the nonlocality of the quantum-mechanical world has some escape clauses.

### MANY WORLDS

Bell innocently assumes that quantum experiments have unique outcomes. The many-worlds interpretation, however, asserts that quantum measurements in effect split the universe into branches where all the different outcomes occur in parallel [see "The Many Worlds of Hugh Everett," by Peter Byrne; SCIENTIFIC AMERICAN, December 2007]. So your universe can be "local" if copies of you inhabit myriad unseen parallel universes. This approach, however, is beset by many difficult problems.

### REALISM?

Many believe that because Bell starts by assuming the world conforms to what is called local realism, he therefore proved that *either* locality or realism is violated. Thus, the world could be local if it violates "realism." But this idea overlooks—or misunderstands—that the original "EPR" argument of Albert Einstein, Boris Podolsky and Nathan Rosen rules out the possibility of quantum locality without the realism Bell uses.

—D.Z.A. and R.G.

quantum mechanics but for the principle of locality—and thus, presumably, for special relativity, because it at least appears to rely on a presumption of locality [see box on next page].

## Metaphysical Mystery Tour

The main reaction to Bell's work—one that persists in many quarters even today—was still more obfuscation. Bell had shown that any theory capable of reproducing the empirical predictions of quantum mechanics for entangled pairs of particles—including quantum mechanics itself—had to be genuinely physically nonlocal.

This message has been virtually ignored. Instead almost everyone says that what Bell showed is that any attempt at replacing the orthodox quantum-mechanical picture of the world with something more in tune with our classical metaphysical expectations—any so-called hidden-variable, deterministic or philosophically realist theory—would have to be nonlocal if it could reproduce the quantum-mechanical predictions for EPR systems [for a couple of proposed escape clauses from Bell's conclusion, see box at right]. People were at least reading Bell's work but as if through a convex looking glass.

Only a very small minority of physicists managed to avoid this particular misunderstanding and grasp that Bell's proof and Aspect's experiments meant the world itself had been discovered to be nonlocal, but even they almost universally believed that the nonlocality in question here posed no particular threat to special relativity.

This belief arises out of the idea that special relativity is inextricably bound up with the impossibility of transmitting messages faster than the speed of light. After all, if special relativity is true, one can argue that no material carrier of a message can be accelerated from rest to speeds greater than that of light. And one can argue that a message transmitted faster than light would, according to some clocks, be a message that ar-

rived before it was sent, potentially unleashing all the paradoxes of time travel.

As long ago as 1932 the brilliant Hungarian mathematician John von Neumann proved that the nonlocality of quantum mechanics cannot ever be parlayed into a mechanism to transmit messages instantaneously. For many decades, virtually the entire theoretical physics community regarded von Neumann's proof as an assurance that quantum-mechanical nonlocality and special relativity can perfectly peacefully coexist.

## Varieties of Nonlocal Experience

It took yet another 30 years after the publication of Bell's paper for physicists to finally look these issues squarely in the face. The first clear, sustained, logically flawless and uncompromisingly frank discussion of quantum nonlocality and relativity appeared in 1994, in a book with precisely that title by Tim Maudlin of Rutgers University. His work highlighted how the compatibility of nonlocality and special relativity was a much more subtle question than the traditional platitudes based on instantaneous messages would have us believe.

Maudlin's work occurred against the backdrop of a new and profound shift in the intellectual environment. From the early 1980s onward, the grip of Bohr's conviction—that there could be no old-fashioned, philosophically realistic account of the subatomic world—was everywhere palpably beginning to weaken. By then a number of promising concrete scientific proposals seemed to provide a good account of that kind, at least in the approximation that neglects the effects of special relativity. These proposals included the Bohmian mechanics of David Bohm in England (developed in the early 1950s and an inspiration for Bell's work but otherwise largely ignored) and the GRW model of GianCarlo Ghirardi, Alberto Rimini and Tullio Weber in Italy [see "Bohm's Alternative to Quantum Mechanics," by David

CERN, COURTESY OF AIP EMILIO SEGRE VISUAL ARCHIVES (Bell); PAUL KWIAK AND MICHAEL RECK University of Vienna (entanglement)

**1964:** John S. Bell (*right*) extends the "EPR" reasoning to cases in which spins are measured along nonparallel axes and shows that no local theory can possibly reproduce all of quantum mechanics's predictions for experimental results. The predictions of any local theory must always satisfy mathematical relations known as Bell's inequalities.



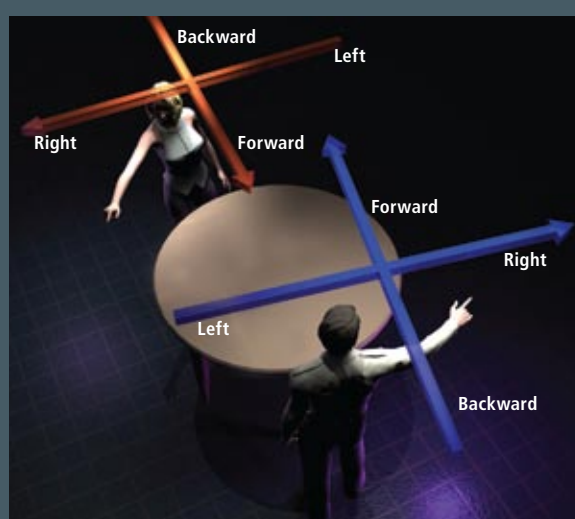
**1981–present:** Experiments using entangled states of light (*right*), in particular by Alain Aspect and his co-workers, verify that the world follows the predictions of quantum mechanics even in those situations in which quantum mechanics violates Bell's inequalities. The world is nonlocal after all.



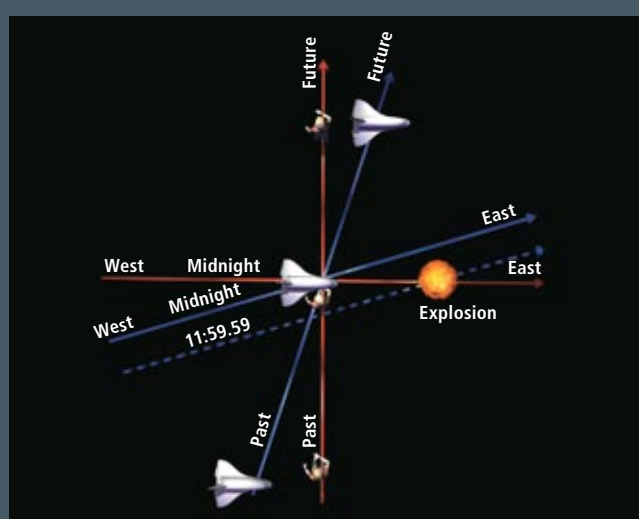
## Why Special Relativity Dislikes Nonlocality

The special theory of relativity reveals an essential geometric relation between space and time that had never previously been imagined. The relation makes the concept of "instantaneous action at a distance" not merely strange but downright unintelligible.

Here, Alice and Buzz cannot agree about which distant events are simultaneous, nor can they agree about a theory involving action at a distance, such as one in which Alice causes the distant explosion "instantaneously" by pressing a button at midnight.



Alice and Buzz, who are standing at different places around a table, disagree about the spatial directions "right," "left," "forward" and "backward." Special relativity shows that people in relative motion disagree about time as well as space.



Alice's space and time axes (red) are centered on where she stands at precisely midnight. Buzz flies over Alice, heading east at nearly the speed of light. His motion tilts his space and time axes (blue) relative to Alice's. The duo disagree about when a bomb exploded several kilometers away: Alice insists it happened at midnight, but Buzz says it happened a second earlier (blue dashed line).

Z Albert; SCIENTIFIC AMERICAN, May 1994]. The old aspirations of physics to be a guide to metaphysics, to tell us literally and straightforwardly how the world actually is—aspirations that had lain dormant and neglected for more than 50 years—began, slowly, to reawaken.

Maudlin's book focused on three important points. First, the special theory of relativity is a claim about the geometric structure of space and time. The impossibility of transmitting mass or energy or information or causal influences faster than light—none of these requirements are even remotely, in and of themselves, sufficient to guarantee that the theory's claim about geometry is correct. Thus, von Neumann's proof about message transmission, in and of itself, offers us no assurance that quantum-mechanical nonlocality and special relativity can peacefully coexist.

Second, the truth of special relativity is (as a matter of fact) perfectly compatible with an enormous variety of hypothetical mechanisms for faster-than-light transmission of mass and energy and information and causal influence. In the 1960s, for example, Gerald Feinberg of Columbia published an internally consistent and fully relativistic theory of a hypothetical species

of particle—tachyons—for which it is physically impossible ever to travel *slower* than light. Maudlin invented other examples.

Thus, the mere existence of a nonlocality in quantum mechanics, in and of itself, does not mean that quantum mechanics cannot coexist with special relativity. So perhaps there is hope.

As Maudlin emphasized in his third point, however, the particular variety of action at a distance that we encounter in quantum mechanics is an entirely different animal from the kind exemplified by Feinberg's tachyons or Maudlin's other examples. What is uncanny about the way that quantum-mechanical particles can nonlocally influence one another is that it does not depend on the particles' spatial arrangements or their intrinsic physical characteristics—as all the relativistic influences alluded to in the preceding paragraphs do—but only on whether or not the particles in question are quantum mechanically entangled with one another.

The kind of nonlocality one encounters in quantum mechanics seems to call for an absolute simultaneity, which would pose a very real and ominous threat to special relativity.

That's the rub.

### ON THE WEB

For a narrative on nonlocality from Newton to Maxwell by Rivka Galchen and David Z Albert, go to [www.SciAm.com/mar2009](http://www.SciAm.com/mar2009)



## Hope for Special Relativity?

Two new results—pulling in curiously different directions—have emerged from this discussion in just the past few years. The first suggests a way that quantum-mechanical nonlocality could be compatible with special relativity; the other reveals a new blow that the combination of quantum mechanics and special relativity strikes against our deepest intuitions of the world.

The first result appeared in an astonishing 2006 paper by Roderich Tumulka, a young German mathematician now at Rutgers. Tumulka showed how all the empirical predictions of quantum mechanics for entangled pairs of particles could be reproduced by a clever modification of the GRW theory (recall that this theory proposes a philosophically realist way to get the predictions of quantum mechanics under many circumstances). The modification is nonlocal, and yet it is fully compatible with the spacetime geometry of special relativity.

This work is still very much in its infancy. No one has yet been able to write down a satisfactory version of Tumulka's theory that can be applied to particles that attract or repel one another. Moreover, his theory introduces a new variety of nonlocality into the laws of nature—a nonlocality not merely in space but in time! To use his theory to determine the probabilities of what happens next, one must plug in not only the world's current complete physical state (as is customary in a physical theory) but also certain facts about the past. That feature and some others are worrying, but Tumulka has certainly taken away some of the grounds for Maudlin's fear that quantum-mechanical nonlocality cannot be made to peacefully coexist with special relativity.

The other recent result, discovered by one of us (Albert), showed that combining quantum mechanics and special relativity requires that we give up another of our primordial convictions. We believe that everything there is to say about the world can in principle be put into the form of a narrative, or story. Or, in more precise and technical terms: everything there is to say can be packed into an infinite set of propositions of the form "at  $t_1$  *this* is the exact physical condition of the world" and "at  $t_2$  *that* is the exact physical condition of the world," and so on. But the phenomenon of quantum-mechanical entanglement and the spacetime geometry of special relativity—taken together—imply that the physical history of the world is infinitely too rich for that.

The trouble is that special relativity tends to mix up space and time in a way that transforms

quantum-mechanical entanglement among distinct physical systems into something along the lines of an entanglement among physical situations at different times—something that in a perfectly concrete way exceeds or eludes or has nothing to do with any sum of situations at distinct temporal instants.

That result, like most theoretical results in quantum mechanics, involves manipulating and analyzing a mathematical entity called a wave function, a concept Erwin Schrödinger introduced eight decades ago to define quantum states. It is from wave functions that physicists infer the possibility (indeed, the necessity) of entanglement, of particles having indefinite positions, and so forth. And it is the wave function that lies at the heart of puzzles about the nonlocal effects of quantum mechanics.

But what *is* it, exactly? Investigators of the foundations of physics are now vigorously debating that question. Is the wave function a concrete physical object, or is it something like a law of motion or an internal property of particles or a relation among spatial points? Or is it merely our current information about the particles? Or *what*?

Quantum-mechanical wave functions cannot be represented mathematically in anything smaller than a mind-bogglingly high-dimensional space called a configuration space. If, as some argue, wave functions need to be thought of as concrete physical objects, then we need to take seriously the idea that the world's history plays itself out not in the three-dimensional space of our everyday experience or the four-dimensional spacetime of special relativity but rather this gigantic and unfamiliar configuration space, out of which the illusion of three-dimensionality somehow emerges. Our three-dimensional idea of locality would need to be understood as emergent as well. The nonlocality of quantum physics might be our window into this deeper level of reality.

The status of special relativity, just more than a century after it was presented to the world, is suddenly a radically open and rapidly developing question. This situation has come about because physicists and philosophers have finally followed through on the loose ends of Einstein's long-neglected argument with quantum mechanics—an irony-laden further proof of Einstein's genius. The diminished guru may very well have been wrong just where we thought he was right and right just where we thought he was wrong. We may, in fact, see the universe through a glass not quite so darkly as has too long been insisted. ■

### ➔ MORE TO EXPLORE

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