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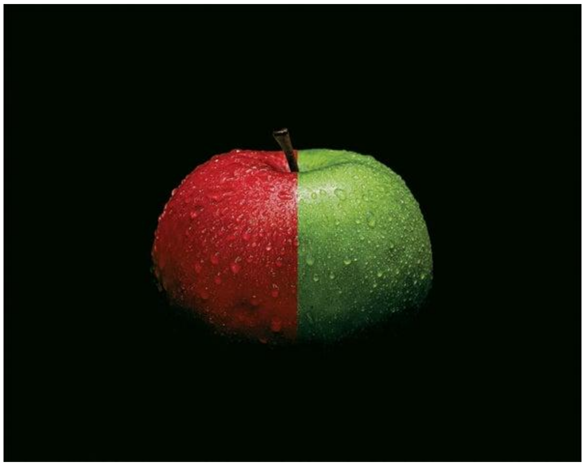
The Universe Is Not Locally Real, and the Physics Nobel Prize Winners Proved It

Elegant experiments with entangled light have laid bare a profound mystery at the heart of reality

By Dan Garisto edited by Lee Billings



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One of the more unsettling discoveries in the past half a century is that the universe is not locally real. In this context, “real” means that objects have definite properties independent of observation—an apple can be red even when no one is looking. “Local” means that objects can be influenced only by their surroundings and that any influence cannot travel faster than light. Investigations at the frontiers of quantum physics have found that these things cannot both be true. Instead the evidence shows that objects are *not* influenced solely by their surroundings, and they *may* also lack definite properties prior to measurement.

This is, of course, deeply contrary to our everyday experiences. As Albert Einstein once bemoaned to a friend, “Do you really believe the moon is not there when you are not looking at it?” To adapt a phrase from author Douglas Adams, the demise of local realism has made a lot of people very angry and has been widely regarded as a bad move.

Blame for this achievement has been laid squarely on the shoulders of three physicists: John Clauser, Alain Aspect and Anton Zeilinger. They equally split the 2022 Nobel Prize in Physics “for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science.” (“Bell inequalities” refers to the trailblazing work of physicist John Stewart Bell of Northern Ireland, who laid the foundations for the 2022 Physics Nobel in the early 1960s.) Colleagues agreed that the trio had it coming, deserving this reckoning for overthrowing reality as we know it. “It was long overdue,” says Sandu Popescu, a quantum physicist at the University of Bristol in England. “Without any doubt, the prize is well deserved.”

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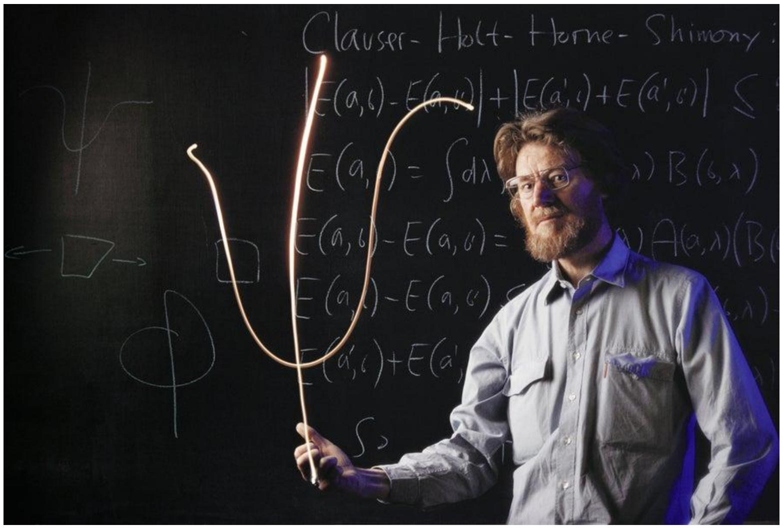
“The experiments beginning with the earliest one of Clauser and continuing along show that this stuff isn’t just philosophical, it’s real—and like other real things, potentially useful,” says Charles Bennett, an eminent quantum researcher at IBM. “Each year I thought, ‘Oh, maybe this is the year,’” says David Kaiser, a physicist and historian at the Massachusetts Institute of Technology. “[In 2022] it really was. It was very emotional—and very thrilling.”

The journey from fringe to favor was a long one. From about 1940 until as late as 1990, studies of so-called quantum foundations were often treated as philosophy at best and crackpottery at worst. Many scientific journals refused to publish papers on the topic, and academic positions indulging such investigations were nearly impossible to come by. In 1985 Popescu’s adviser warned him against a Ph.D. in the subject. “He said, ‘Look, if you do that, you will have fun for five years, and then you will be jobless,’” Popescu says.

Today quantum information science is among the most vibrant subfields in all of physics. It links Einstein’s general theory of relativity with quantum mechanics via the still mysterious behavior of black holes. It dictates the design and function of quantum sensors, which are increasingly being used to study everything from earthquakes to dark matter. And it clarifies the often confusing nature of quantum entanglement, a phenomenon that is pivotal to modern materials science and that lies at the heart of quantum computing. “What even makes a quantum computer ‘quantum?’” Nicole Yunger Halpern, a physicist at the National Institute of Standards and Technology, asks rhetorically. “One of the most popular answers is entanglement, and the main reason why we understand entanglement is the grand work participated in by Bell and these Nobel Prize winners. Without that understanding of entanglement, we probably wouldn’t be able to realize quantum computers.”



Work by John Stewart Bell in the 1960s sparked a quiet revolution in quantum physics.

Peter Menzel/Science Source

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FOR WHOM THE BELL TOLLS

The trouble with quantum mechanics was never that it made the wrong predictions—in fact, the theory described the microscopic world splendidly right from the start when physicists devised it in the opening decades of the 20th century. What Einstein, Boris Podolsky and Nathan Rosen took issue with, as they explained in their iconic 1935 paper, was the theory's uncomfortable implications for reality. Their analysis, known by their initials EPR, centered on a thought experiment meant to illustrate the absurdity of quantum mechanics. The goal was to show how under certain conditions the theory can break—or at least deliver nonsensical results that conflict with our deepest assumptions about reality.

A simplified and modernized version of EPR goes something like this: Pairs of particles are sent off in different directions from a common source, targeted for two observers, Alice and Bob, each stationed at opposite ends of the solar system. Quantum mechanics dictates that it is impossible to know the spin, a quantum property of individual particles, prior to measurement. Once Alice measures one of her particles, she finds its spin to be either "up" or "down." Her results are random, and yet when she measures up, she instantly knows that Bob's corresponding particle—which had a random, indefinite spin—must now be down. At first glance, this is not so odd. Maybe the particles are like a pair of socks—if Alice gets the right sock, Bob must have the left.

But under quantum mechanics, particles are not like socks, and only when measured do they settle on a spin of up or down. This is EPR's key conundrum: If Alice's particles lack a spin until measurement, then how (as they whiz past Neptune) do they know what Bob's particles will do as they fly out of the solar system in the other direction? Each time Alice measures, she quizzes her particle on what Bob will get if he flips a coin: up or down? The odds of correctly predicting this even 200 times in a row are one in 10^{60}—a number greater than all the atoms in the solar system. Yet despite the billions of kilometers that separate the particle pairs, quantum mechanics says Alice's particles can keep correctly predicting, as though they were telepathically connected to Bob's particles.

Designed to reveal the incompleteness of quantum mechanics, EPR eventually led to experimental results that instead reinforce the theory's most mind-boggling tenets. Under quantum mechanics, nature is not locally real: particles may lack properties such as spin up or spin down prior to measurement, and they seem to talk to one another no matter the distance. (Because the outcomes of measurements are random, these correlations cannot be used for faster-than-light communication.)

Physicists skeptical of quantum mechanics proposed that this puzzle could be explained by hidden variables, factors that existed in some imperceptible level of reality, under the subatomic realm, that contained information about a particle's future state. They hoped that in hidden variable theories, nature could recover the local realism denied it by quantum mechanics. "One would have thought that the arguments of Einstein, Podolsky and Rosen would produce a revolution at that moment, and everybody would have started working on hidden variables," Popescu says.

Einstein's "attack" on quantum mechanics, however, did not catch on among physicists, who by and large accepted quantum mechanics as is. This was less a thoughtful embrace of nonlocal reality than a desire not to think too hard—a head-in-the-sand sentiment later summarized by American physicist N. David Mermin as a demand to "shut up and calculate." The lack of interest was driven in part because John von Neumann, a highly regarded scientist, had in 1932 published a mathematical proof ruling out hidden variable theories. Von Neumann's proof, it must be said, was refuted just three years later by a young female mathematician, Grete Hermann, but at the time no one seemed to notice.

The problem of nonlocal realism would languish for another three decades before being shattered by Bell. From the start of his career, Bell was bothered by quantum orthodoxy and sympathetic toward hidden variable theories. Inspiration struck him in 1952, when he learned that American physicist David Bohm had formulated a viable nonlocal hidden variable interpretation of quantum mechanics—something von Neumann had claimed was impossible.

Bell mulled the ideas for years, as a side project to his job working as a particle physicist at CERN near Geneva. In 1964 he rediscovered the same flaws in von Neumann's argument that Hermann had. And then, in a triumph of rigorous thinking, Bell concocted a theorem that dragged the question of local hidden variables from its metaphysical quagmire onto the concrete ground of experiment.

Typically local hidden variable theories and quantum mechanics predict indistinguishable experimental outcomes. What Bell realized is that under precise circumstances, an empirical discrepancy between the two can emerge. In the eponymous Bell test (an evolution of the EPR thought experiment), Alice and Bob receive the same paired particles, but now they each have two different detector settings—A and a, B and b. These detector settings are an additional trick to throw off Alice and Bob's apparent telepathy. In local hidden variable theories, one particle cannot know which question the other is asked. Their correlation is secretly set ahead of time and is not sensitive to updated detector settings. But according to quantum mechanics, when Alice and Bob use the same settings (both uppercase or both lowercase), each particle is aware of the question the other is posed, and the two will correlate perfectly—in sync in a way no local theory can account for. They are, in a word, entangled.

Measuring the correlation multiple times for many particle pairs, therefore, could prove which theory was correct. If the correlation remained below a limit derived from Bell's theorem, this would suggest hidden variables were real; if it exceeded Bell's limit, then the mind-boggling tenets of quantum mechanics would reign supreme. And yet, in spite of its potential to help determine the nature of reality, Bell's theorem languished unnoticed in a relatively obscure journal for years.

THE BELL TOLLS FOR THEE

In 1967 a graduate student at Columbia University named John Clauser accidentally stumbled across a library copy of Bell's paper and became enthralled by the possibility of proving hidden variable theories correct. When Clauser wrote to Bell two years later, asking if anyone had performed the test, it was among the first feedback Bell had received.

Three years after that, with Bell's encouragement, Clauser and his graduate student Stuart Freedman performed the first Bell test. Clauser had secured permission from his supervisors but little in the way of funds, so he became, as he said in a later interview, adept at "dumpster diving" to obtain equipment—some of which he and Freedman then duct-taped together. In Clauser's setup—a kayak-size apparatus requiring careful tuning by hand—pairs of photons were sent in opposite directions toward detectors that could measure their state, or polarization.

Unfortunately for Clauser and his infatuation with hidden variables, once he and Freedman completed their analysis, they had to conclude that they had found strong evidence against them. Still, the result was hardly conclusive because of various "loopholes" in the experiment that conceivably could allow the influence of hidden variables to slip through undetected. The most concerning of these was the locality loophole: if either the photon source or the detectors could have somehow shared information (which was plausible within an object the size of a kayak), the resulting measured correlations could still emerge from hidden variables. As M.I.T.'s Kaiser explained, if Alice tweets at Bob to tell him her detector setting, that interference makes ruling out hidden variables impossible.

Closing the locality loophole is easier said than done. The detector setting must be quickly changed while photons are on the fly—"quickly" meaning in a matter of mere nanoseconds. In 1976 a young French expert in optics, Alain Aspect, proposed a way to carry out this ultraspeedy switch. His group's experimental results, published in 1982, only bolstered Clauser's results: local hidden variables looked extremely unlikely. "Perhaps Nature is not so queer as quantum mechanics," Bell wrote in response to Aspect's test. "But the experimental situation is not very encouraging from this point of view."

Other loopholes remained, however, and Bell died in 1990 without witnessing their closure. Even Aspect's experiment had not fully ruled out local effects, because it took place over too small a distance. Similarly, as Clauser and others had realized, if Alice and Bob detected an unrepresentative sample of particles—like a survey that contacted only right-handed people—their experiments could reach the wrong conclusions.

No one pounced to close these loopholes with more gusto than Anton Zeilinger, an ambitious, gregarious Austrian physicist. In 1997 he and his team improved on Aspect's earlier work by conducting a Bell test over a then unprecedented distance of nearly half a kilometer. The era of divining reality's nonlocality from kayak-size experiments had drawn to a close. Finally, in 2013, Zeilinger's group took the next logical step, tackling multiple loopholes at the same time.

"Before quantum mechanics, I actually was interested in engineering. I like building things with my hands," says Marissa Giustina, a quantum researcher at Google who worked with Zeilinger. "In retrospect, a loophole-free Bell experiment is a giant systems-engineering project." One requirement for creating an experiment closing multiple loopholes was finding a perfectly straight, unoccupied 60-meter tunnel with access to fiber-optic cables. As it turned out, the dungeon of Vienna's Hofburg palace was an almost ideal setting—aside from being caked with a century's worth of dust. Their results, published in 2015, coincided with similar tests from two other groups that also found quantum mechanics as flawless as ever.

BELL'S TEST REACHES THE STARS

One great final loophole remained to be closed—or at least narrowed. Any prior physical connection between components, no matter how distant in the past, has the potential to interfere with the validity of a Bell test's results. If Alice shakes Bob's hand prior to departing on a spaceship, they share a past. It is seemingly implausible that a local hidden variable theory would exploit these kinds of loopholes, but it was still possible.

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In 2016 a team that included Kaiser and Zeilinger performed a cosmic Bell test. Using telescopes in the Canary Islands, the researchers sourced random decisions for detector settings from stars sufficiently far apart in the sky that light from one would not reach the other for hundreds of years, ensuring a centuries-spanning gap in their shared cosmic past. Yet even then, quantum mechanics again proved triumphant.

One of the principal difficulties in explaining the importance of Bell tests to the public—as well as to skeptical physicists—is the perception that the veracity of quantum mechanics was a foregone conclusion. After all, researchers have measured many key aspects of quantum mechanics to a precision of greater than 10 parts in a billion. "I actually didn't want to work on it," Giustina says. "I thought, like, 'Come on, this is old physics. We all know what's going to happen.'" But the accuracy of quantum mechanics could not rule out the possibility of local hidden variables; only Bell tests could do that.

"What drew each of these Nobel recipients to the topic, and what drew John Bell himself to the topic, was indeed [the question], 'Can the world work that way?'" Kaiser says. "And how do we really know with confidence?" What Bell tests allow physicists to do is remove the bias of anthropocentric aesthetic judgments from the equation. They purge from their work the parts of human cognition that recoil at the possibility of eerily inexplicable entanglement or that scoff at hidden variable theories as just more debates over how many angels may dance on the head of a pin.

The 2022 award honors Clauser, Aspect and Zeilinger, but it is testament to all the researchers who were unsatisfied with superficial explanations about quantum mechanics and who asked their questions even when doing so was unpopular. "Bell tests," Giustina concludes, "are a very useful way of looking at reality."

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