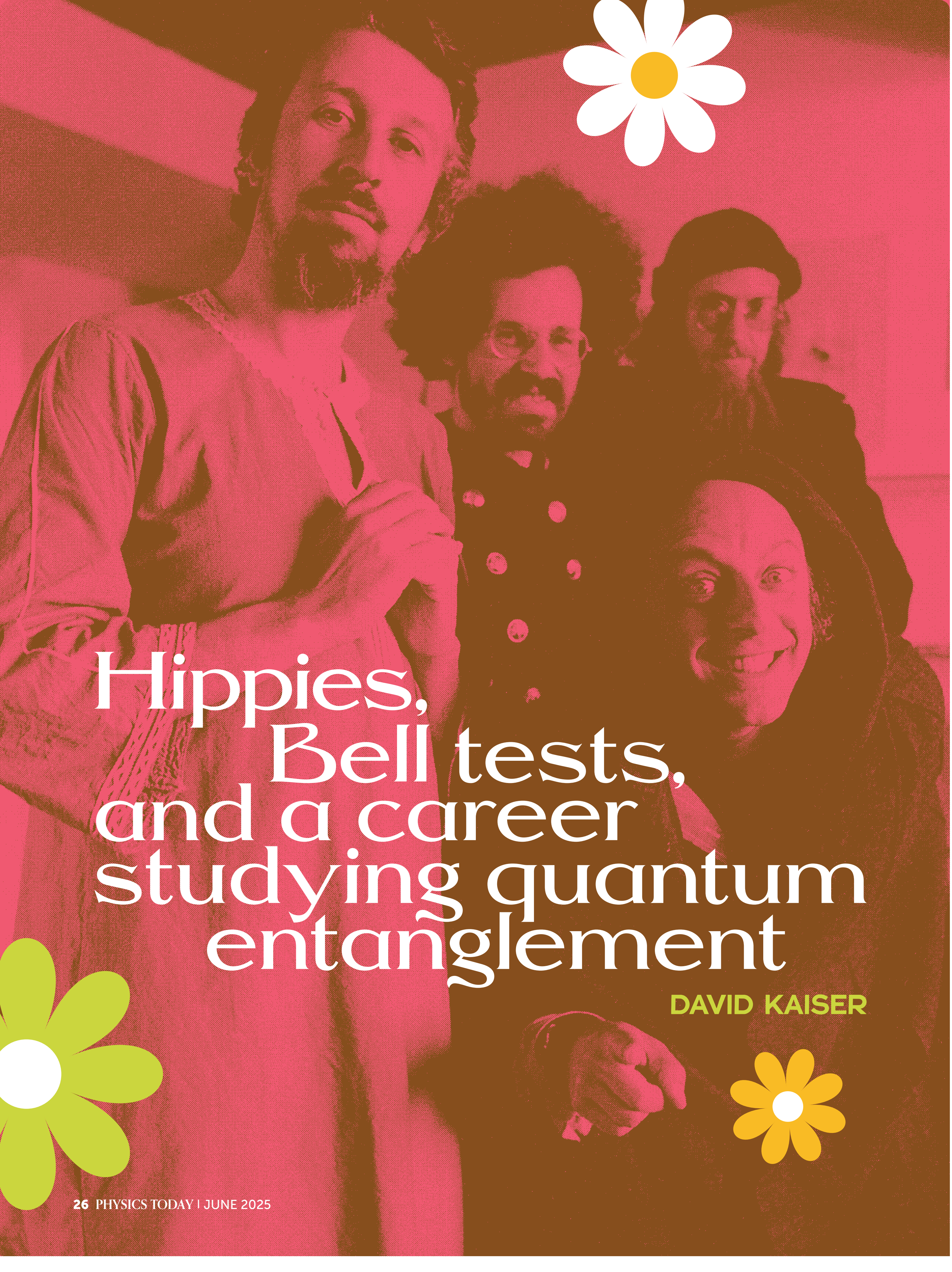

Hippies, Bell tests, and a career studying quantum entanglement

DAVID KAISER

INTERNATIONAL YEAR OF
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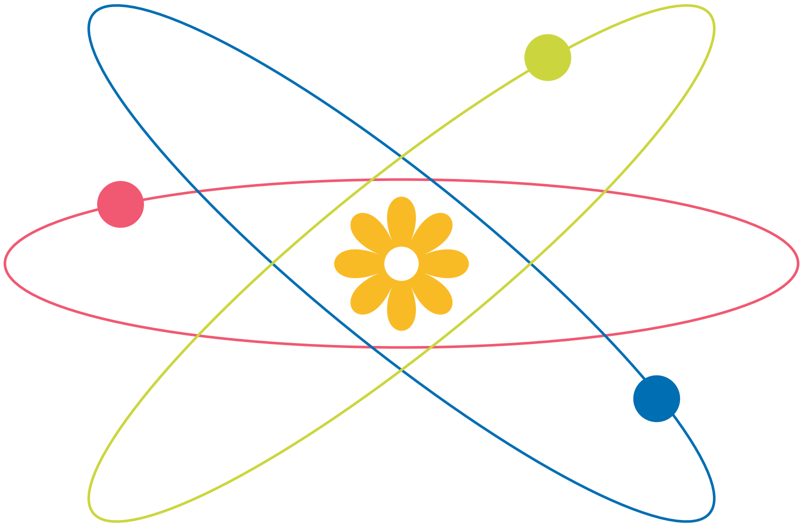


Investigating a group of maverick physicists who studied the foundations of quantum mechanics in the 1970s led one physicist-historian to help create a new test of entanglement.

My fascination with quantum entanglement began in high school, when I stumbled upon a cheap paperback of physicist Fritjof Capra's *The Tao of Physics*.[1] The book had first been published in 1975; by the time I found the copy in a used bookstore about a decade later, it had long since become an international bestseller. I was immediately captivated by the book's discussion of bizarre-sounding features of quantum theory and the subtle dance of subatomic particles. Capra's earnest discussions of various Eastern spiritual traditions—and what struck him as parallel suggestions, comparable to those from modern physics, about the nature of physical reality—left less of an impression on me. But few could miss his passion for quantum strangeness.

Inspired by some marvelous high school teachers and books like Capra's, I entered college determined to study physics. Soon, other books grabbed me—I can still picture the tiny cubicle in the library where I spent hours tightly gripping a copy of Bernard d'Espagnat's *Conceptual Foundations of Quantum Mechanics*.[2] Meanwhile, my academic adviser, an expert in general relativity whose diverse reading habits included literature, art, and history, sparked my interest in the history of science. Before long, I was delving into classes in both physics and history. I became fascinated by the history of quantum entanglement and contemporary physicists' efforts to grapple with it. I decided to pursue doctoral studies in both theoretical physics and the history of science.

During my doctoral studies, my physics department stipulated that PhD students in theoretical physics had to complete one semester of an undergraduate laboratory course. I grumbled the whole time, except when my long-suffering lab partner and I worked on a benchtop experiment to test entanglement. We were clumsily redoing a classic experiment, first conducted in 1972 by John Clauser and Stuart Freedman, that

A GROUP OF OFFBEAT BERKELEY PHYSICISTS began meeting during the 1970s to discuss foundational questions in physics, such as quantum entanglement, that were then considered passé. Pictured here are four members of the self-proclaimed Fundamental Fysiks Group. Standing, left to right, are Jack Sarfatti, Saul-Paul Sirag, and Nick Herbert; kneeling is Fred Alan Wolf. (Photo courtesy of Fred Alan Wolf.)

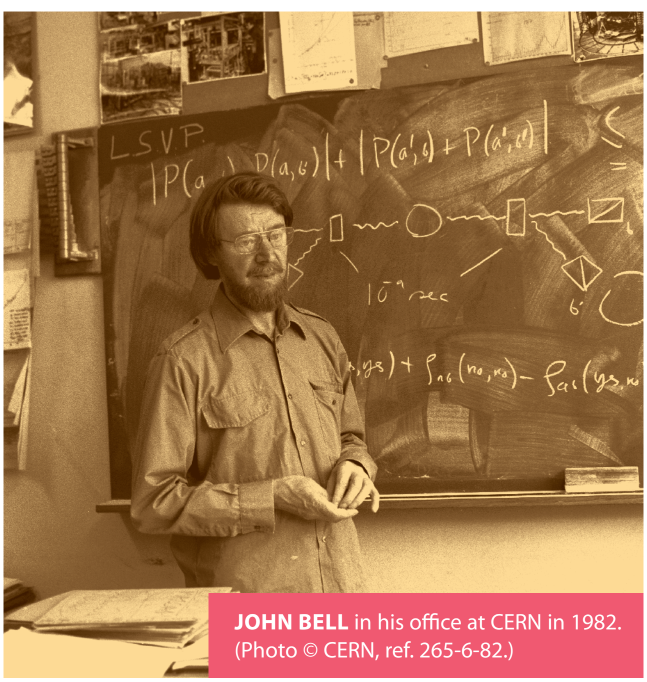
attempts to measure correlations in the polarizations of pairs of photons.[3] (Clauser shared the 2022 Nobel Prize in Physics for his pioneering efforts to test entanglement.) Freedman had been a graduate student at the time and Clauser a young postdoc, newly arrived at Lawrence Berkeley Laboratory.

About 10 years after stumbling through that experiment, I learned that during the 1970s, Clauser had been one of the founding members of a spirited, informal discussion group in Berkeley whose members called themselves the Fundamental Fysiks Group. Capra had also been a member, right around the time he published *The Tao of Physics*. Between Capra's book and Clauser's experiment, I was hooked, and I wanted to know more. The exploration led to my 2011 book, *How the Hippies Saved Physics*.[4] And then, in a wonderful twist, my *Hippies* book helped catalyze one of the most memorable adventures of my career: working with an international collaboration to design and conduct novel tests of entanglement, which we dubbed the cosmic Bell experiments.

The International Year of Quantum Science and Technology offers opportunities to ask how some of the most central ideas of quantum theory were introduced, debated, tested, and ultimately accepted (see Physics Today, April 2025, page 38). As I found while working on my *Hippies* book and the cosmic Bell tests, physicists' decades-long efforts to discern whether entanglement is a robust feature of the world have been anything but straightforward.

Articulating entanglement

Erwin Schrödinger, Albert Einstein, and several other architects of quantum theory identified entanglement as a prediction of the still-new quantum formalism back in the 1930s. Tickle a particle here, the equations seemed to suggest, and somehow the measured properties of its distant twin would be affected, no matter how far apart the particles had traveled. To Schrödinger and Einstein alike, that hypothetical behavior seemed too strange to be true. Surely, they convinced themselves, real bits of matter in the real world could not behave that way.



JOHN BELL in his office at CERN in 1982. (Photo © CERN, ref. 265-6-82.)

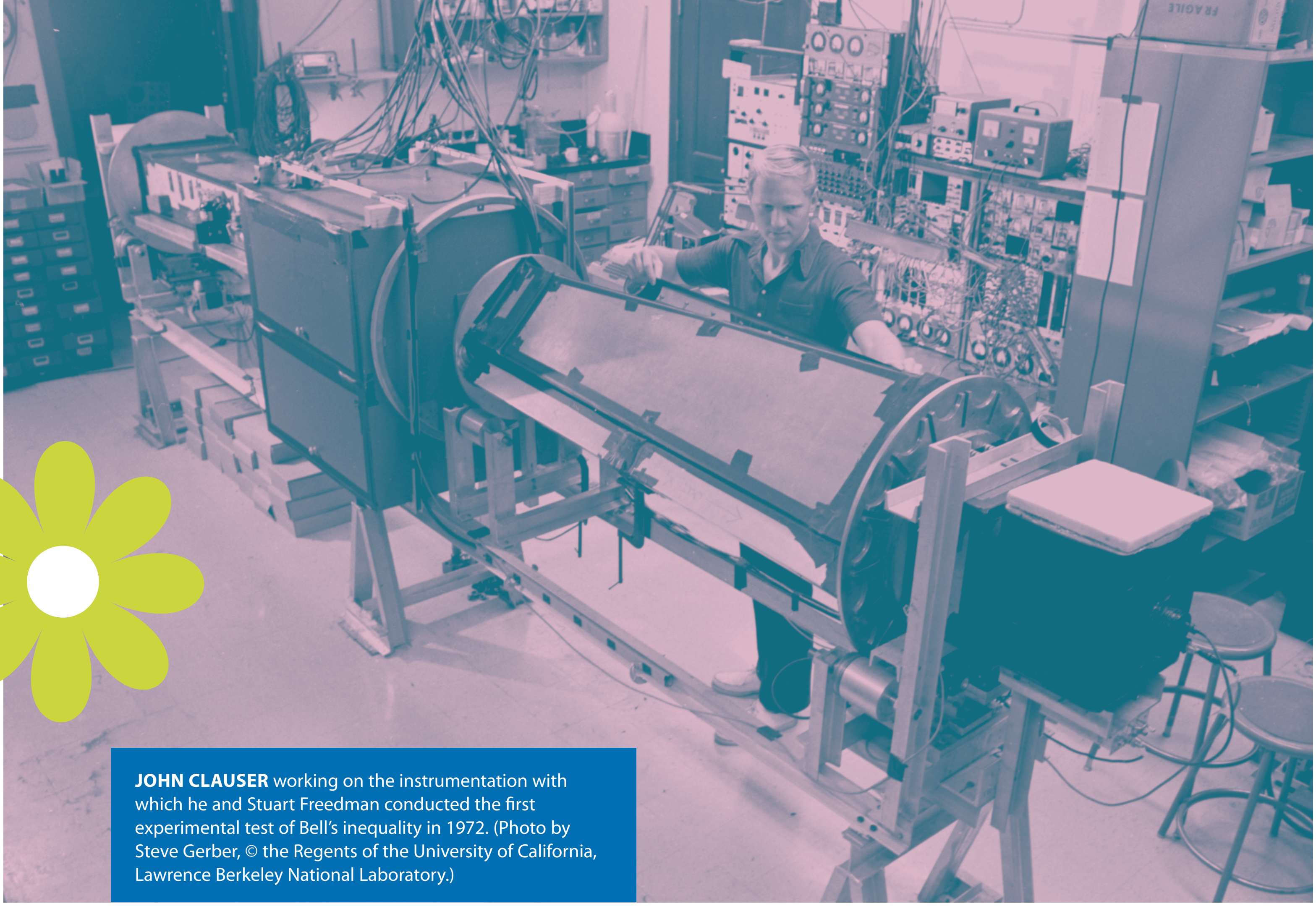
In a now-famous article published in May 1935, Einstein, Boris Podolsky, and Nathan Rosen asserted that predictions like entanglement revealed that quantum mechanics must be incomplete.[5] A more proper theory, they concluded, would enable physicists to specify properties of each particle rather than imagining that one particle's properties somehow depended on something that happened to its distant partner (see the article by David Mermin, Physics Today, January 2025, page 28). If such spooky connectedness were a prediction of quantum mechanics, perhaps it was time to search for another theory.[6]

Niels Bohr's 1935 defense of the new quantum theory and its strange-sounding predictions like entanglement,[7] a paper he wrote in response to Einstein, Podolsky, and Rosen, seemed to satisfy many physicists at the time. Their relief came not necessarily because Bohr's arguments seemed clear but because another giant of the field had stepped into the fray and declared that all was well in the quantum realm.

Nearly 30 years elapsed before the stalemate over entanglement began to shift. In 1964, physicist John Bell published his now-famous inequality[8] (see the box on page 30). In an elegant, six-page article, Bell derived a constraint on the behavior of any physical system that obeyed the two reasonable postulates that Einstein, Podolsky, and Rosen had introduced in their analysis—namely, that a particle should possess definite values for various properties even when no one tries to measure those properties and that no force or signal could travel faster than the speed of light. Given those postulates, Bell demonstrated that there must exist an upper limit to how strongly correlated the outcomes of measurements could be on pairs of particles that had once interacted and then traveled arbitrarily far apart.

In just a few more lines, Bell demonstrated that according to quantum mechanics, the outcomes of measurements on such particle pairs could be more strongly correlated than the Einstein-like limit would allow. Bell's work thus identified a measurable difference between predictions from Einstein-like theories and those from quantum mechanics—a difference that, in principle, might be testable in a laboratory. Near the conclusion of his landmark paper, Bell emphasized that the strong correlations predicted by quantum theory sit rather uneasily with Einstein's relativity: For entangled systems, quantum theory seemed to suggest, local causes need not yield only local effects.

Today, entanglement and Bell's inequality are at the heart of quantum computing, quantum teleportation, quantum encryption, and more. Yet all that lay far in the future when Bell published his remarkable analysis. His paper was published in the first volume of an obscure journal, *Physics Physique Fizika*, which folded a few years later. The article garnered one citation in the worldwide scientific literature over the next three years, and that was a self-citation in one of Bell's other papers.[4]



JOHN CLAUSER working on the instrumentation with which he and Stuart Freedman conducted the first experimental test of Bell's inequality in 1972. (Photo by Steve Gerber, © the Regents of the University of California, Lawrence Berkeley National Laboratory.)

Around that time, Clauser stumbled across Bell's article in a library at Columbia University, where Clauser was working on his PhD. Clauser's dissertation adviser urged him to stay away from such "philosophy."[4,9] Disappointed, Clauser made a mental note of Bell's work. A few years later, as he was completing his dissertation and getting ready to start his postdoc at Berkeley Lab, Clauser reached out to Bell to see if any physicists had conducted the type of experiment that he had proposed. As Bell later recalled, Clauser's letter from February 1969 was the first response he had received about his work. Delighted that an experimentalist was showing interest, Bell dashed off his reply: No one else seemed to have noticed the work, and if Clauser could manage to measure a deviation from the quantum predictions, that would "shake the world!"[4,9]

Quantum carnivalesque

By the time Clauser had made his way to Berkeley, he had struck up a new collaboration with Abner Shimony and Michael Horne. Shimony was then a professor of both physics and philosophy at Boston University, and Horne was his curious physics PhD student. Shimony had also stumbled on Bell's 1964 paper and become intrigued. Before long, Shimony and Horne spotted a brief abstract that Clauser had submitted to the *Bulletin of the American Physical Society*. Taking into account details like finite apertures and limited detector efficiencies, Clauser proposed to translate Bell's pristine algebra into quantities that could be measured in a real experiment. Shimony tracked Clauser down by telephone in early 1969, and they arranged to chat at a meeting of the American Physical Society that spring. Horne, Clauser, and Shimony became fast friends, and they delved into the intricacies of entanglement and Bell's inequality in collaboration with experimentalist Richard Holt.

Clauser soon picked up other discussion mates in Berkeley. Some, including Elizabeth Rauscher and George Weissmann, were PhD students studying nuclear and particle physics at the University of California, Berkeley; others, like Capra, Nick Herbert, Jack Sarfatti, and Fred Alan Wolf, were a few years past their doctorates; another, Saul-Paul Sirag, had taken a detour from his physics studies to pursue theater and other passions. A few more senior researchers—staff scientists at Berkeley Lab like Henry Stapp and Philippe Eberhard—rounded out the group.

Each member of the group had entered graduate school in the years after the Soviets launched the *Sputnik 1* satellite, a time when generous federal funding drove skyrocketing physics enrollments. Each, in turn, found that their broad curiosity about the foundations of physics and the nature of reality had been stunted amid the overcrowded classrooms and narrow research agendas of their professors—much as Clauser had felt the sting when his Columbia adviser had steered him away from Bell's work.

FRITJOF CAPRA, author of *The Tao of Physics*, in November 1977. (Photo by Roger Ressmeyer/Corbis/VCG via Getty Images.)

The group members' main misfortune was to be seeking careers in physics during the early 1970s, just as the discipline was undergoing the steepest decline in its history (see "Physics Today ads track employment boom and bust," Physics Today online, 7 May 2018). As late as 1963, even amid exponential growth in the number of physics PhD students across the US, jobs for young physicists had been outpacing the number of graduates. Then a series of rapid-fire developments sent the physics profession into a tailspin: the escalation of fighting in Vietnam and the subsequent removal of draft deferments for students; widespread economic uncertainty compounded by oil shocks and stagflation; and a sharp reversal of funding priorities in the US Department of Defense and related federal agencies, which until the late 1960s had underwritten research and training in physics even for open-ended, basic research. By 1971, the number of PhD-holding physicists in the US seeking jobs outstripped the number of jobs on offer by a factor of 20.[4]

With newfound time on their hands and a rekindled passion to engage with the kinds of questions that had attracted them to physics in the first place, the ragtag collection of Berkeley physicists formed the Fundamental Fysiks Group, which met on Friday afternoons in a spare classroom on UC Berkeley's campus. They threw themselves with gusto into such topics as quantum entanglement, even as several of them struggled to make ends meet. In fact, during a time when few physicists paid much attention to Bell's work, nearly 90% of the research articles on Bell's inequality published through 1980 and written by US-based physicists came from members of the group or from authors who thanked group members for introducing them to the topic or clarifying various subtleties.[4]

TESTING BELL'S INEQUALITY

In his 1964 article, John Bell derives an inequality that limits how strongly correlated the outcomes of measurements on two or more particles can be if the outcomes of each measurement are independent of actions undertaken at arbitrarily distant locations. Further, he confirms that quantum mechanics predicts that measurements on particles in entangled states can be more strongly correlated than his new inequality would allow.[8,13]

Incorporating an earlier suggestion by David Bohm, Bell focuses on dichotomic observables—that is, observables for which the measured outcomes can be only one of two values. Such is the case for an electron's spin. To measure it, a physicist must select a basis—namely, they must choose to measure the electron's spin along the *x*-direction, along the *y*-direction, or along any orientation in between. No matter which basis is selected, a measurement of the electron's spin along that direction yields only spin up (labeled +1) or spin down (−1).

Bell then sketches how an idealized version of an experiment to test his new inequality might go: A source σ emits pairs of particles that travel away from it in opposite directions, as seen in the figure. At each detector, a physicist selects a basis ($\mathbf{a}$ for detector A, on the left, and $\mathbf{b}$ for detector B, on the right) in which to perform a measurement; once each particle has reached its respective detector, the detector yields a measurement outcome (A, B). For spin, A and B could be only ± 1, no matter which of the two bases the physicist had selected.

Bell then introduces correlation functions $E(\mathbf{a}, \mathbf{b}) = \langle A(\mathbf{a})\, B(\mathbf{b})\rangle$, where the brackets indicate averaging over many experimental runs in which pairs of particles were measured in the bases $(\mathbf{a}, \mathbf{b})$. Given the fact that each measurement outcome $A(\mathbf{a})$ and $B(\mathbf{b})$ could be only ± 1, the correlation function for any pair of bases $(\mathbf{a}, \mathbf{b})$ would satisfy $-1 \le E(\mathbf{a}, \mathbf{b}) \le +1$.

Next, Bell constructs a conditional probability $p(A, B|\mathbf{a}, \mathbf{b})$ to find the pair of measurement outcomes A and B given the selection of bases $\mathbf{a}$ and $\mathbf{b}$. He defines it in terms of the conditional probability for detector A to yield measurement outcome A when performing a measurement in basis $\mathbf{a}$ and the conditional probability for detector B to yield measurement

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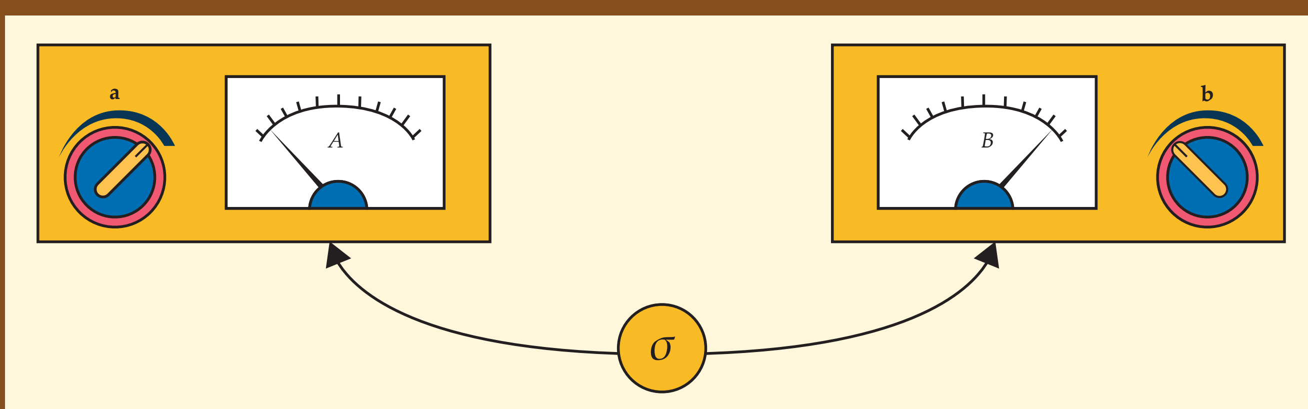
Members of the Fundamental Fysiks Group pored over entanglement and Bell's work while immersed in a burgeoning counterculture. Mainstream newspapers like the *San Francisco Chronicle* were reporting on such unorthodox topics as mind-reading experiments and tests of extrasensory perception, or ESP. Some group members began to wonder whether quantum entanglement—with its spooky, long-range connections between particles—might help to explain the latest reports. After Israeli stage magician and self-proclaimed ESP aficionado Uri Geller underwent testing at Birkbeck College in London in 1974 under physicist David Bohm's direction,[10] group member Sarfatti announced that entanglement, with its intrinsically nonlocal character, left "ample room for the possibility of psychokinetic and telepathic effects."[11]

To pursue their unusual research topics, some group members sought cash from unlikely sources, including the Central Intelligence Agency and the self-made entrepreneurs in California who had become fascinated by such subjects as the nature of human consciousness and whether quantum theory could help unlock human potential. The physicists became regulars at the Esalen Institute, the central gathering spot for New Age enthusiasts, nestled among the seaside cliffs in Big Sur, California. With help from an eccentric supporter named Ira Einhorn—a counterculture gadfly who was famous for hanging out with such flower-power advocates as Abbie Hoffman and was later convicted for the grisly murder of his girlfriend—they shared preprints across an underground network, even as Capra and a few others became bestselling authors.

Along the way, the group members inspired some fascinating work that, stripped of its original packaging, has since entered the physics mainstream. Take the no-cloning theorem, for example. A fundamental feature of quantum theory, the theorem was discovered in 1982 independently by Wojciech Zurek and Bill Wootters, by Dennis Dieks, and by GianCarlo Ghirardi and Tullio Weber. It stipulates that it is impossible to make exact copies, referred to as clones, of an unknown quantum state (see the Quick Study by Bill Wootters and Wojciech Zurek, Physics Today, April 2025, page 46). It quickly became the linchpin for the first quantum encryption protocol.[4]

The physicists arrived at the theorem in the process of refuting a particularly clever entanglement-related thought experiment published by Fundamental Fysiks Group member Herbert earlier in 1982. As physicist Asher Peres wrote many years later—unmasking himself as having been one of the referees for Herbert's paper and thus as having missed a subtle flaw in Herbert's proposal that the no-cloning pioneers identified—Herbert's "erroneous paper was a spark that generated immense progress."[12]

By the time the Fundamental Fysiks Group had disbanded



outcome B when performing a measurement in basis $\mathbf{b}$:

$$p(A, B|\mathbf{a}, \mathbf{b}) = \int d\lambda\, p(\lambda)\, p(A|\mathbf{a}, \lambda)\, p(B|\mathbf{b}, \lambda).$$

Here, λ represents some shared properties of a given particle pair (often dubbed hidden variables) that could help determine the measurement outcomes at each detector. Bell assumes that there would be some probability distribution $p(\lambda)$ for a given value of λ to be selected each time a new pair of particles is created.

By design, Bell's construction incorporates locality: The probability of finding measurement outcome A at detector A, written in the late 1970s, it had left some remarkable legacies, given its humble platform. During their playful, creative romps, group members applied their disciplined physics training outside the usual institutions and remained open to out-of-left-field curiosities. In the process, they nurtured a focus on entanglement and Bell's inequality before many other physicists took notice.

> In an ironic twist, given my grumbling in grad school about needing to complete a lab course, we soon set to work designing a new type of experiment that could test Bell's inequality.

Chasing loopholes

While writing my *Hippies* book, I learned about the early experimental tests of Bell's inequality. In a typical Bell test, a source emits pairs of entangled particles that move in opposite directions; physicists decide to perform a particular type of measurement on each particle, and then they identify correlations in the outcomes of those measurements. Learning more about Bell tests also introduced me to a series of loopholes that physicists, including Bell, Clauser, Shimony, and Horne, had identified over the course of the 1960s and 1970s—circumstances that, in principle, could account for the strong correlations measured in tests of Bell's inequality, even if the particles obeyed a model consistent with the postulates put forward in the 1935 paper by Einstein, Podolsky, and Rosen.

In their correspondence during 1969, for example, Bell and Clauser zeroed in on the timing of when various events should occur in a Bell test. They concluded that, ideally, the type of measurement to be performed at each detector should be selected such that no information about the selections could reach either the particle source or the distant detector until after each measurement had been completed. Otherwise, any correlations among the measurement outcomes could be attributed to the local flow of information during a given experimental run, all consistent with Einstein's postulates and with no need to invoke quantum entanglement.[9] That scenario was soon termed the locality loophole. Implementing fast switching of measurement selections proved too difficult in the early 1970s when Clauser and Freedman conducted their first experiment, but 10 years later, Alain Aspect led a team in France that accomplished just such a feat.[13] (Aspect shared the 2022 Nobel Prize with Clauser and Anton Zeilinger.)

As described in the box, within a few years, Clauser, Shimony, and Horne identified another possible flaw in a Bell test, one that is now known as the freedom-of-choice loophole. Unlike the locality loophole, which deals with the flow of information during a given experimental run, the freedom-of-choice loophole concerns whether some common cause might have nudged or previewed in advance the sequence of measurements to be performed. If that were the case, the common cause could have shared that information with the particle source before any particles were emitted, without requiring any direct communication among parts of the experimental apparatus.[13]

I began thinking about the freedom-of-choice loophole in

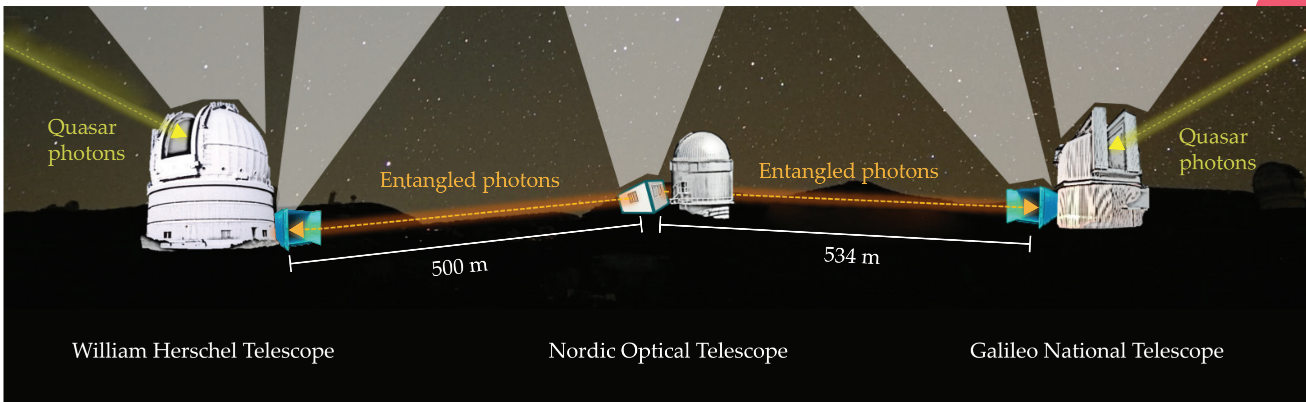
as $p(A|\mathbf{a}, \lambda)$, depends on the local properties carried by each particle (λ) and on the basis $\mathbf{a}$ at detector A, in which the measurement would be performed. The probability does not depend, however, on either the basis $\mathbf{b}$ or the measurement outcome B at the distant detector. Similarly, the converse is true for the probability of finding measurement outcome B at detector B: It does not depend on basis $\mathbf{a}$ or the measurement outcome A at the other detector.

In 1969, soon after they began collaborating, John Clauser, Michael Horne, Abner Shimony, and Richard Holt cast Bell's inequality in a simpler form. In what was later termed the CHSH paper, they consider experiments in which each particle would be subjected to measurement in one of two bases: either $\mathbf{a}_1$ or $\mathbf{a}_2$ at detector A and either $\mathbf{b}_1$ or $\mathbf{b}_2$ at detector B. Then they consider a particular combination S of correlation functions, as one toggles the bases at each detector:[18]

$$S = |E(\mathbf{a}_1, \mathbf{b}_1) + E(\mathbf{a}_2, \mathbf{b}_1) - E(\mathbf{a}_1, \mathbf{b}_2) + E(\mathbf{a}_2, \mathbf{b}_2)|.$$

The innocent-looking minus sign in front of the third correlation function makes all the difference. In just a few lines of algebra, Clauser and colleagues—much like Bell before them—demonstrate that for any model of the particles' behavior that could be put in the form of Bell's conditional probability $p(A, B|\mathbf{a}, \mathbf{b})$, the Bell–CHSH parameter S must obey the inequality $S \leq 2$.

Again following Bell's lead, Clauser and his colleagues demonstrate with a brief calculation that quantum mechanics predicts violations of the inequality $S \leq 2$. They considered two-particle quantum states, such as $|\psi\rangle = (|{+1}\rangle_A |{-1}\rangle_B \pm |{-1}\rangle_A |{+1}\rangle_B)/\sqrt{2}$, which represents a superposition of two possible outcomes: Particle A will be measured as spin up (in a particular basis) and particle B as spin down (in that same basis), or particle A will be measured as spin down and particle B as spin up. (The factor of $1/\sqrt{2}$ comes from normalization: The quantum state needs to satisfy $\langle\psi|\psi\rangle = 1$.) For specific choices of the angles between measurement bases $\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{b}_1$, and $\mathbf{b}_2$, measurements on pairs of particles prepared in that quantum state should exceed the limit $S \leq 2$; in



A SCHEMATIC OF THE COSMIC BELL EXPERIMENT conducted in January 2018 at the Roque de los Muchachos Observatory on the island of La Palma in the Canary Islands. A team in a makeshift laboratory next to the Nordic Optical Telescope generated polarization-entangled particles that were emitted in opposite directions toward detector stations at the William Herschel Telescope and the Galileo National Telescope. Teams at those two telescopes also performed rapid measurements of the color of distant quasars. The result of each color measurement determined which one of two polarization bases an entangled particle would be measured in. The findings revealed a substantial violation of Bell's inequality and confirmed that the predictions of quantum mechanics are correct.

2012, about a year after my *Hippies* book had been published. Andy Friedman, then a new postdoc at MIT, had planned to work with me on research projects in early-universe cosmology. Perhaps intrigued by the funny-sounding title, he read my book on a lark and began brainstorming with Jason Gallicchio, his good friend from graduate school. As Andy and Jason recognized, cosmologists had learned a remarkable amount since the 1970s about the expansion history and large-scale structure of our universe, stretching all the way back to the Big Bang. With a fuller understanding of the varying rate at which the universe has expanded over time, astrophysicists and cosmologists could now map causal relationships across the vast sweep of cosmic history—determining, for example, which discrete events in space and time could possibly have exchanged a single light signal with other spacetime events and which could not.

Andy and Jason shared their early ideas with me, and in an ironic twist, given my grumbling in grad school about needing to complete a lab course, we soon set to work designing a new type of experiment that could test Bell's inequality while shielding against both the locality and freedom-of-choice loopholes. Our basic idea: Turn the universe itself into a pair of rapid-cadence random-number generators. We proposed to use the results of real-time astronomical observations of distant objects, such as high-redshift quasars, to select

fact, the maximum value, according to quantum theory, is $2\sqrt{2}$.

A dozen years after Bell derived his inequality, Shimony, Horne, and Clauser pointed out a subtlety that Bell had overlooked: something known to statisticians as the law of total probability, which is similar to the chain rule in ordinary calculus.[13] In constructing $p(A, B|\mathbf{a}, \mathbf{b})$, Bell had integrated the λ parameters over a probability distribution $p(\lambda)$ rather than over a conditional probability $p(\lambda|\mathbf{a}, \mathbf{b})$—that is, the probability for parameters λ given the selection of measurement bases $(\mathbf{a}, \mathbf{b})$. The conditional probability would account for any statistical correlations between the selection of measurement bases $(\mathbf{a}, \mathbf{b})$ on a given experimental run and the properties of the emitted particles λ. Such correlations could arise, in principle, from some shared common cause without any direct communication between parts of the experimental apparatus.

The possibility that $p(\lambda|\mathbf{a}, \mathbf{b}) \neq p(\lambda)$ has been dubbed the measurement-dependence loophole, also known as the freedom-of-choice loophole. Additional recent theoretical work has demonstrated that only a minuscule amount of statistical correlation between λ and the bases $(\mathbf{a}, \mathbf{b})$ would enable a local, Einstein-like model to mimic all the correlations predicted by quantum mechanics for measurements on an entangled quantum state. (See reference 13 and references therein.)

To get an intuitive feel for Bell's inequality, one may simplify a bit and replace the averaged correlation functions with the products of measurement outcomes for a single experimental run. In their 1935 paper, Albert Einstein, Boris Podolsky, and Nathan Rosen had insisted that (at least in some situations) particles carry definite values for various properties prior to and independent of their measurement.[5] So the three physicists might have imagined that the particle heading toward detector A had specific values for spin measurements to perform on each member of a pair of entangled particles. By carefully arranging the spatial alignment of our Bell-test instrumentation on the ground, we could ensure that information about which measurement would be performed on each particle would be inaccessible to both the particle source and the detector for the other particle until both particles had been measured.[14]

As we were finalizing our proposal for the new "cosmic Bell" tests, we had good luck: None other than Anton Zeilinger, a renowned expert in experimental quantum optics and a leading figure in the long history of experimental tests of Bell's inequality, visited MIT to give a colloquium at the physics department. I secured time on Zeilinger's busy schedule, and at our appointed hour, Andy and I pitched to him our idea of using uncorrelated, astronomical sources of randomness for Bell tests. Within a few minutes, Zeilinger's smile was as broad as Andy's and mine. He and his group in Vienna had recently completed a major project related to the freedom-of-choice loophole, and he appreciated the novel twist that Andy, Jason, and I had in mind. In the meantime, Andy and I convinced cosmologist Alan Guth, my MIT friend and colleague, to join our project. And so our international cosmic Bell collaboration was born.

After we conducted a successful pilot test in Vienna in April 2016 using small-scale telescopes trained on bright Milky Way stars,[15] Zeilinger managed to secure telescope time for our group at the Roque de los Muchachos Observatory, on the island of La Palma in the Canary Islands. At the observatory during January 2018, one team set up at the William Herschel Telescope while another team took over the Galileo National Telescope—both world-class optical telescopes with roughly 4-meter mirrors. A third team worked near the Nordic Optical Telescope in a makeshift laboratory, placed about 500 meters from each of the other telescopes, in which the members used a pump laser and a nonlinear crystal shipped from Zeilinger's lab to generate about 1 million polarization-entangled photons per second. The entangled particles were beamed through the night sky, in opposite directions, toward detectors at the Herschel and Galileo Telescopes.

Within a few minutes, Zeilinger's smile was as broad as Andy's and mine.

While a pair of entangled photons was in flight, the Galileo Telescope team would perform a rapid measurement of the color of a distant quasar, whose light had been traveling toward Earth for the past 8 billion years. If, during a microsecond-long window, the quasar light happened to be redder than its average color, that would trigger the neighboring equipment to prepare to measure the incoming entangled photon (still zooming across the island) in one polarization basis. If the quasar measurement instead had been bluer than its average color, then the entangled particle would be measured in a second polarization basis. Meanwhile, the same procedure—triggering off a different quasar, on the opposite side of the sky, whose light had been traveling toward Earth for 12 billion years—unfolded at the Herschel Telescope.

We measured about 30 000 pairs of entangled particles that night on the mountaintop, each time selecting new measurement bases, predicated on updated inputs from the quasars, at each detector (see the box). Our results yielded a significant violation of Bell's inequality—exactly as predicted by quantum theory—even as our experiment addressed both the locality and freedom-of-choice loopholes. To account for those results, any Einstein-like mechanism that could have exploited a modest statistical correlation among detector settings and particle properties would need to have been set in motion at least 8 billion years ago, long before any physicists were around to ponder such wonderful topics as quantum entanglement.[16]

Entanglement today

Since 2015, several groups around the world have tested Bell's inequality while addressing various pairs of loopholes

along both orientations $\mathbf{a}_1$ and $\mathbf{a}_2$, even if a given measurement revealed only one of those values. If we denote A_1 as the value of the particle's spin in basis $\mathbf{a}_1$, then $E(\mathbf{a}_1, \mathbf{b}_1)$ becomes simply A_1B_1, and so on. Then the Bell–CHSH factor S would take the form:

$$|A_1B_1 + A_2B_1 - A_1B_2 + A_2B_2| = |(A_1 + A_2)B_1 - (A_1 - A_2)B_2|.$$

Since each spin value can only equal ±1, then either $(A_1 + A_2) = \pm 2$ while $(A_1 - A_2) = 0$ or vice versa. And since B_1 and B_2 likewise only equal ±1, the parameter S should obey $S \leq 2$.

A violation of the Bell–CHSH inequality implies that particles do not carry definite values of all relevant properties prior to measurement or that measurement outcomes at one detector are not independent of actions taken (such as the selection of a particular measurement basis) at a distant detector. Even though both of those postulates seem quite reasonable—we can go about our daily routines confidently assuming that the objects we encounter have definite properties on their own and that information obeys Einstein's relativistic speed limit—they do not both hold in quantum mechanics. And thanks to more than 50 years of experimental tests of Bell's inequality, we now know that the quantum prediction holds up: The Bell–CHSH inequality is routinely violated in careful experiments, which means that we indeed live in an entangled quantum world.[13]

THE COSMIC BELL COLLABORATION, nourished by a lunch near MIT, takes form in October 2014. From left to right are Andy Friedman, Jason Gallicchio, Anton Zeilinger, and David Kaiser.

(see PHYSICS TODAY, January 2016, page 14). Like our cosmic Bell tests, each of those experiments has measured significant violations of Bell's inequality, exactly as predicted by quantum theory. Over the past decade, the new generation of multi-loophole-closing experiments has demonstrated beyond dispute that quantum entanglement is a basic fact of our world.[13]

Some of the most ambitious and audacious Bell tests—including a breathtaking experiment by Jian-Wei Pan and his group that involved measuring, at detector stations roughly 1200 km apart, pairs of entangled photons emitted from a satellite in low Earth orbit[17]—have been central to testing quantum encryption infrastructure.

Efforts to understand quantum entanglement and to test or constrain various alternatives have enabled generations of physicists to explore the fundamental strangeness of quantum theory. At the same time, as topics like entanglement and Bell's inequality have wandered into and out of the mainstream, they enable us to chart the changing boundaries in the field of physics and the shifting place that physicists have occupied in our wider cultures—an evolution that we can ponder from many perspectives as we celebrate the International Year of Quantum Science and Technology in 2025.

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