Does Nature Violate Local Realism?

A theoretical battle—asking whether quantum mechanics provides a complete description of nature—comes under experimental scrutiny

David Branning

Albert Einstein believed that physical measurements represent bona fide physical quantities. For instance, one can watch a spinning ball and measure the number of revolutions that it completes in a minute. This measurement represents information about the ball's physical characteristics, such as its angular momentum. Moreover, the ball spins at the same rate regardless of whether or not an observer counts its revolutions per minute. On the other hand, the prevailing theory of small-scale interactions, quantum mechanics, states that an object's physical characteristics can be affected—even created in some cases—by the process of measuring. For instance, the rotation of a subatomic particle may not exist until it is measured.

The theory of quantum mechanics emerged around the turn of the century and quickly became the cornerstone of modern physics, yielding predictions that have been confirmed to unprecedented levels of precision. In that regard, quantum mechanics is often hailed as the most successful physical theory ever devised. Such predictive power, however, demands a price: Quantum theory conflicts with some of our strongest intuitive notions about the way the universe ought to be. For instance, quantum mechanics posits that a physical characteristic, such as the location of an electron, can be fundamentally unpredictable and described only by probability. The probabilistic nature of quantum theory proved so unsatisfying to Einstein that he concluded that it could not be a complete description of nature. He insisted that quantum mechanics emerged from a more detailed and specific theory—one that had not been discovered.

More than 60 years after Einstein's challenge, new theoretical discoveries along with advanced electronic and optical devices have enabled us to experimentally confront one of nature's fundamental questions: Do physical quantities exist before being measured?

Quantum Mechanics

A *quantum* is a discrete amount of something—such as a single electron—that cannot be subdivided. All forms of electromagnetic radiation, including light, carry their energy in small amounts that cannot be split or reduced. The German physicist Max Planck first implied the existence of such tiny bundles of energy, which are now called *photons*.

It might be tempting to think of a photon as a particle, perhaps accompanied by a mental picture of a tiny billiard ball. Indeed, many of a photon's characteristics make it seem like a particle: It has a definite energy that cannot be reduced or increased, and it may interact with something else, such as an electron, at a specific point in space and time. These particle-like properties were essential for the correct description of some physical phenomena—including the photoelectric effect and blackbody radiation—that had defied understanding when light was viewed only as a wave. Nevertheless, the wave theory of light explains aspects of light's characteristics that cannot be explained by the particle theory. For instance, light exhibits diffraction and interference, two properties that are shared by all waves but are forbidden to particles.

This dilemma—whether to view light as a particle or a wave—cannot be resolved. Both the wave and the particle descriptions of light are necessary, each one revealing only some of light's properties. For this reason, physicists say that light possesses *wave-particle duality*, manifesting itself either as a wave or as a particle, but never as both. Astonishingly, this duality is not limited to photons; electrons, protons, subatomic particles and even whole atoms can be made to appear either as particles or waves in distinct experimental arrangements.

Quantum mechanics, then, is the physical theory that accurately describes the behavior of all objects saddled with this wave-particle duality. It does so by keeping track of the wave and particle attributes of the objects in a mutually exclusive fashion called *complementarity*. If two properties of an object are complementary in the quantum-mechanical sense, measuring one of them automatically destroys information about the other, or in some cases prevents the other from even existing.

Complementarity is commonly described through the German mathematical physicist Werner Karl Heisenberg's *uncertainty principle*, which states that complementary quantities cannot be measured simultaneously to arbitrary precision. For example, the momentum and position of an electron, which are complementary to each other, cannot both be determined with complete certainty at the same time. Measuring anelectron's momentum very precisely forces it into a nebulous *superposition state* of many possible positions. While the electron is in such a state, the property of its position can-

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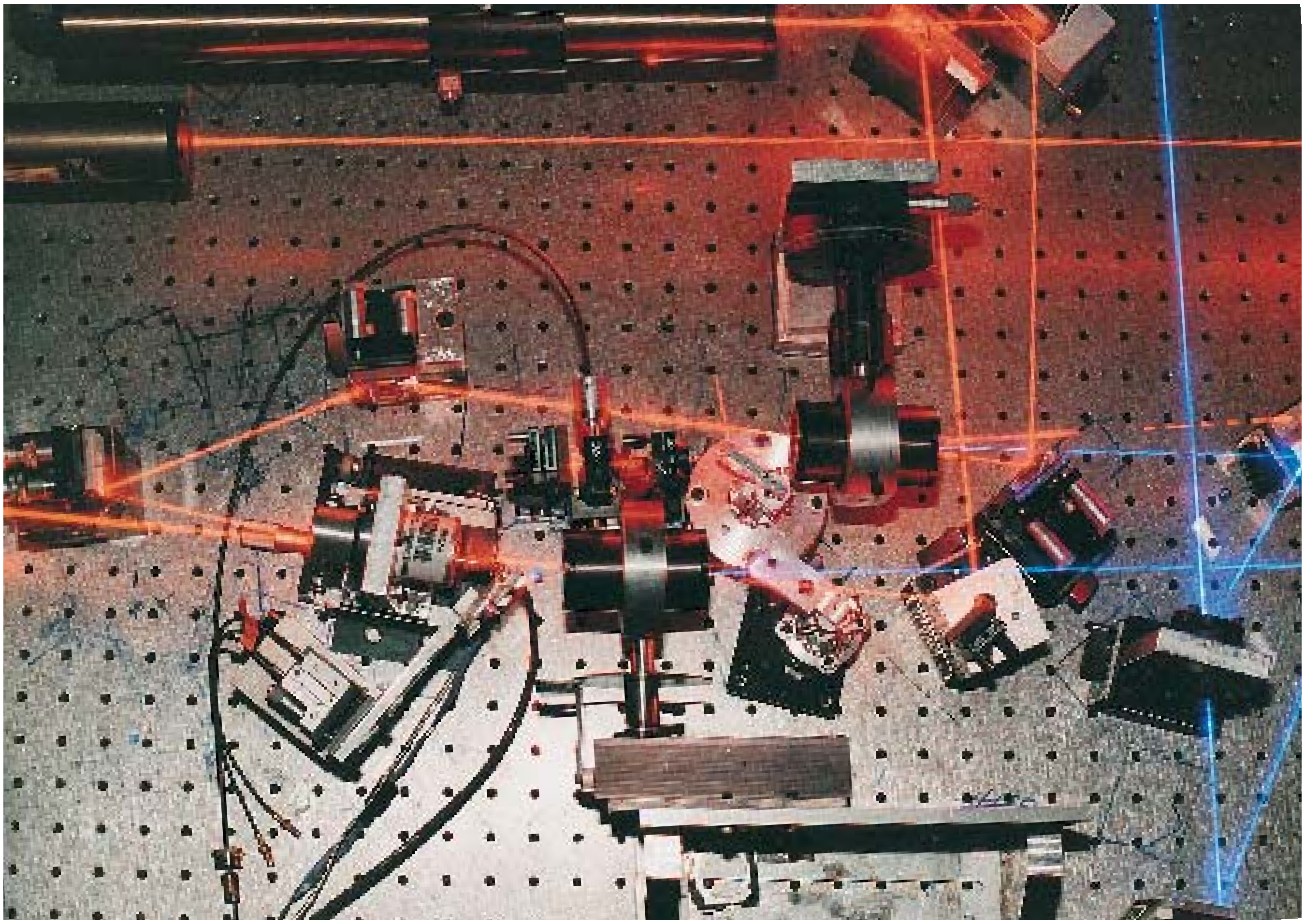

Figure 1. Quantum mechanics, the dominant theory of the physics of atomic-scale interactions, conflicts with our intuition in some cases. According to quantum mechanics, for example, some characteristics of a particle—such as it location, momentum and spin—may not be knowable beyond a given probability. In 1935, the uncertain nature of quantum mechanics triggered a disagreement between Niels Bohr, one of the founders of the theory, and Albert Einstein, who believed that quantum mechanics must be an incomplete theory. Recently, the author and his colleagues arranged an assortment of lenses, lasers and electronics in an experiment designed to solve the Bohr-Einstein disagreement. (Photograph courtesy of the author.)

not be well defined—it simply has no position. If the electron's position is measured subsequently, it assumes a definite location only at the moment of measurement; that location falls somewhere in the range of possibilities allowed by the superposition state, but it cannot be predicted with certainty.

According to quantum mechanics, only the probability of finding the electron in various locations can be calculated. The uncertainty about the electron's location does not arise from the imprecision of particular instruments, as we are accustomed to thinking. For example, we are comfortable with the everyday notion that a coin has a 50 percent chance to land "heads up" after being tossed, because we understand that the true outcome of the toss could be predicted if we knew enough details about the coin, the force of the flip and the air through which it travels. But quantum mechanics does not use probability in this comfortable fashion. It assigns a probability to an electron's position not because our knowledge is incomplete, but because, apparently, there are fundamental limits on what can be known in principle.

A Quantum-Mechanical Challenge

In 1935, Einstein and two younger colleagues, Boris Podolsky and Nathan Rosen, published an article in *Physical Review* entitled, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" The authors said no. They based their conclusion on an ingenious thought experiment, which was later simplified by American theoretical physicist David Bohm.

The so-called Einstein-Podolsky-Rosen-Bohm *gedankenexperiment* begins with a single unstable subatomic particle—a pi meson—that decays into an electron and a positron. The new particles fly away from each other in opposite directions, toward separate observers who are prepared to measure an arriving particle's spin—essentially the way it rotates. In current discussions, the two observers are called Alice and Bob. Assume that the electron flies to the left, where Alice measures its spin, and that the positron flies to the right, where Bob measures its spin. More precisely, Alice and Bob measure spin along a chosen direction.

The spin of an electron or a positron can take two possible values—say, "up" or "down"—and a pi meson has zero spin. Because total spin must be conserved in the decay process, the electron and the positron must have opposite spins when they are measured along the same axis. So if Alice finds that her electron's spin along a direction called *x*—so-called *x*-spin—is up, then Bob's

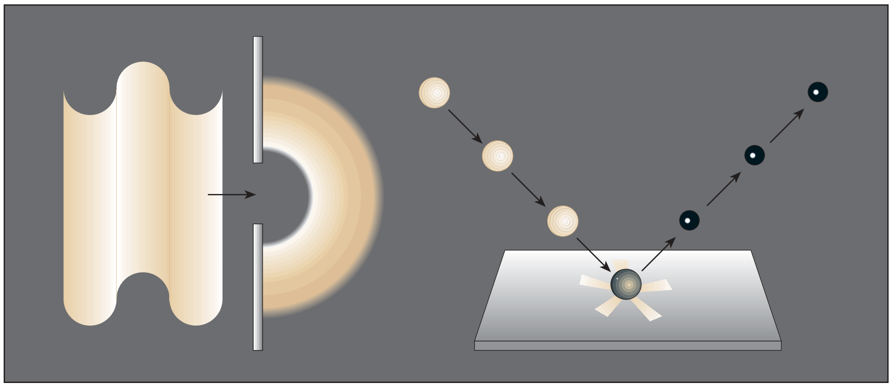

Figure 2. Light's properties illustrate a counterintuitive principle of quantum mechanics called *complementarity*. In some cases, light acts like a wave, as when parallel waves of light diffract into semicircular waves after passing through a slit *(left)*. Light acts like a particle in other situations, including the photoelectric effect *(right)*, where light quanta, or photons *(yellow)*, hitting a metal surface lead to the release of electrons *(black)*. The electrons have discrete energies that can only be explained if the photons are described as having discrete—particle-like—energies. This so-called wave-particle duality of light means that light can act like a wave or a particle, but never like both simultaneously. Any two properties that cannot exist simultaneously are called complementary.

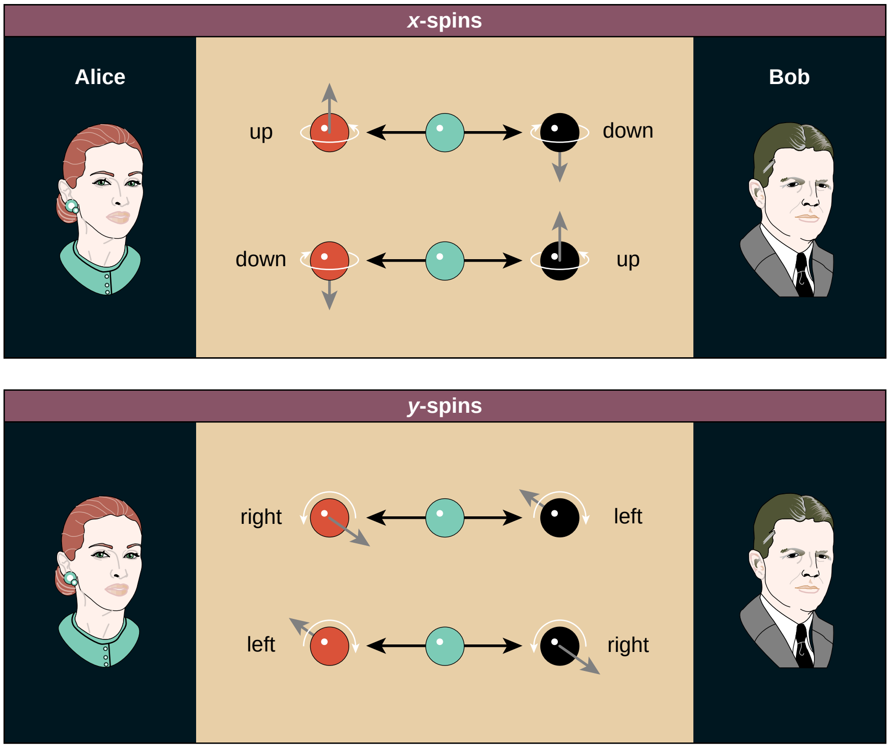

Figure 3. Local realism formed the foundation of the disagreement between Bohr and Einstein. It can be understood through the so-called Einstein-Podolsky-Rosen-Bohm *gedankenexperiment*, where a pi meson *(green)* splits into an electron *(black)* and a positron *(red)* that fly away in opposite directions where two observers, Alice and Bob, measure their spins. The original pi meson has no spin, so the resulting particles must have opposite spins to meet the requirements of spin conservation. If Alice and Bob measure spin along the *x* axis—so-called *x*-spin—and one measures "up," the other will measure "down" *(top)*. If Alice and Bob measure spin along the *y* axis—so-called *y*-spin—and one measures "right," the other will measure "left" (bottom). Once Alice makes her measurement along either axis, Bob's measurement is determined, because it will be the opposite. The constraint called local realism prohibits Alice's measurement from affecting Bob's, and also maintains that the measurements can only reveal pre-existing values of the spins. Therefore, because Alice and Bob have a free choice in which type of spin they will measure, Einstein and his colleagues believed that both the *x*- and *y*-spins of the particles must have had definite values all along. Nevertheless, *x*- and *y*-spins are complementary, so they cannot exists simultaneously according the quantum mechanical theory.

positron will have *x*-spin down, and vice versa. According to quantum mechanics, neither Alice nor Bob can know in advance what they will observe, because they are equally likely to measure up or down. However, Alice knows that whatever measurement she makes, Bob's must be the opposite.

Einstein, Podolsky and Rosen made the following assertion in their paper: "If, without in any way disturbing a system, we can predict with certainty the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity." This philosophical position, called *realism*, implies that at the instant that Alice measures the electron's *x*-spin, the *x*-spin of the positron becomes an element of physical reality—having an objective, real existence in the natural world, whether or not Bob decides to measure it.

Alternatively, Alice might decide to measure the electron's *y*-spin, which is perpendicular to *x*-spin. As before, the electron's spin could have only one of two possible values—called "left" or "right" for *y*-spin—and Bob's positron would then have the opposite value for its *y*-spin. In that case, Alice's measurement would make the *y*-spin of Bob's positron an element of physical reality.

Alice's measurement, however, cannot influence any of the properties of Bob's particle. Alice's electron cannot send an instantaneous signal to Bob's positron, telling it which value of *x*-spin or *y*-spin to adopt. So if Bob and Alice were to make their measurements simultaneously, the results of one cannot affect the other. Einstein and his colleagues insisted on that separate nature of the two systems—a property called *locality*. The combined principles of realism and locality are called *local realism*.

The above *gedankenexperiment* poses the so-called EPR (Einstein, Podolsky and Rosen) paradox: Although no signal can travel faster than light, Alice instantaneously makes either the *x*- or *y*-spin of Bob's positron an element of reality. Einstein, Podolsky, and Rosen believed that the only way to resolve that paradox was to accept that the particles had definite *x*- and *y*-spins all along, which Alice and Bob were merely uncovering. That is, the spins were elements of reality from the moment they were created.

According to quantum mechanics, however, *x*- and *y*-spin are complementary; both cannot have simultaneous reality. No wavefunction, or mathematical description of a particle's quantum-mechanical characteristics, can simultaneously specify both spin values of a particle. As a result, Einstein concluded that quantum mechanics must be an incomplete theory, because the EPR paradox showed that elements of physical reality could exist where quantum mechanics said they could not.

Niels Bohr, a Danish physicist and one of quantum mechanics' founders, raised the first objection to the EPR paper. He argued that the EPR definition of an "element of reality" was ambiguous and not "founded on a direct appeal to experiments and measurements." According to Bohr, the only "real" things are those that we can measure, and quantum mechanics reflects the fact that making some measurements precludes making others.

Nearly 30 years later, Irish physicist John S. Bell introduced another element to that debate when he discovered the so-called "Bell inequalities." In terms of the EPR-Bohm *gedankenexperiment*, a Bell inequality is a mathematical statement that places a fundamental upper limit on how well correlated Alice and Bob's measurements could be if the observers repeatedly measured *x*-spin, *y*-spin and spin components along several other axes, assuming that nature follows the principle of local realism. Bell's inequalities lead to another inconsistency between the expectations of quantum mechanics and locality: In some cases, quantum mechanics predicts a correlation between Alice and Bob's measurements that exceeds the limit imposed by the Bell inequalities.

Dutch-Door Physics

In 1993, Lucien Hardy of the University of Durham in the United Kingdom devised another method of demonstrating the conflict between quantum mechanics and local realism. Later, the method was refined by Thomas Jordan of the University of Minnesota at Duluth. The so-called Hardy-Jordan approach, which does not involve Bell's inequalities, begins like the EPR-Bohm *gedankenexperiment*: Two particles fly toward separate observers who make spin measurements. Alice measures spin along direction "A1" or "A2," and Bob measures spin along "B1" or "B2." Unlike the EPR-Bohm arrangement, however, A1 and A2 are not orthogonal to each other, and neither are B1 and B2. Nevertheless, the spins can only be measured as up or down along any direction.

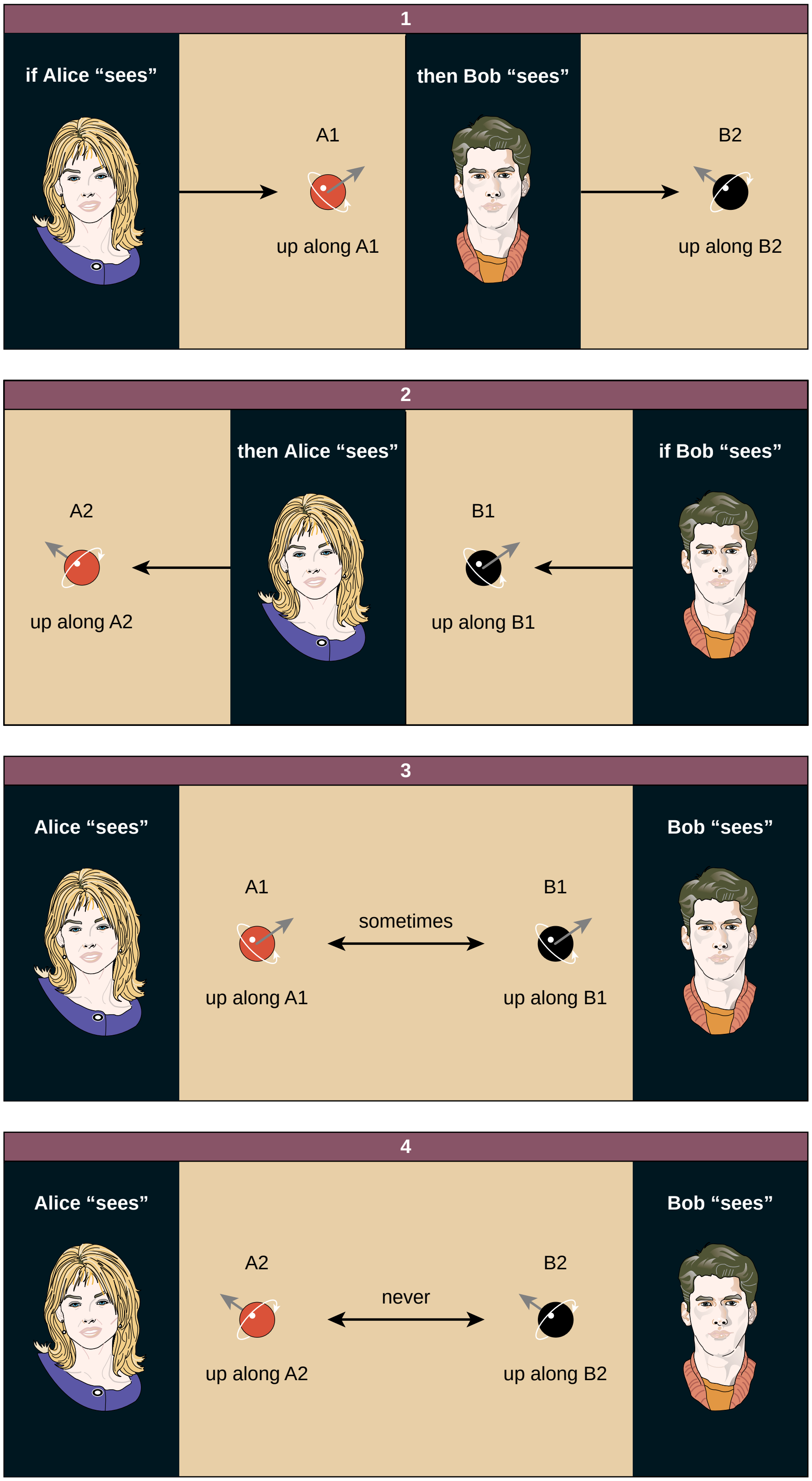

Figure 4. Hardy-Jordan *gedankenexperiment* also begins with a pi meson that splits into two particles. In this example, Alice and Bob measure along directions A1 or A2 and B1 or B2, respectively, and the spins can be only up or down. These axes can be carefully selected through quantum mechanics such that four propositions are true. If Alice measures up along A1, then Bob will measure up along B2 *(1)*. If Bob measures up along B1, then Alice will measure up along A2 *(2)*. Sometimes, Alice and Bob will simultaneously measure up along A1 and B1, respectively *(3)*. Alice and Bob will never simultaneously measure up along A2 and B2, respectively *(4)*.

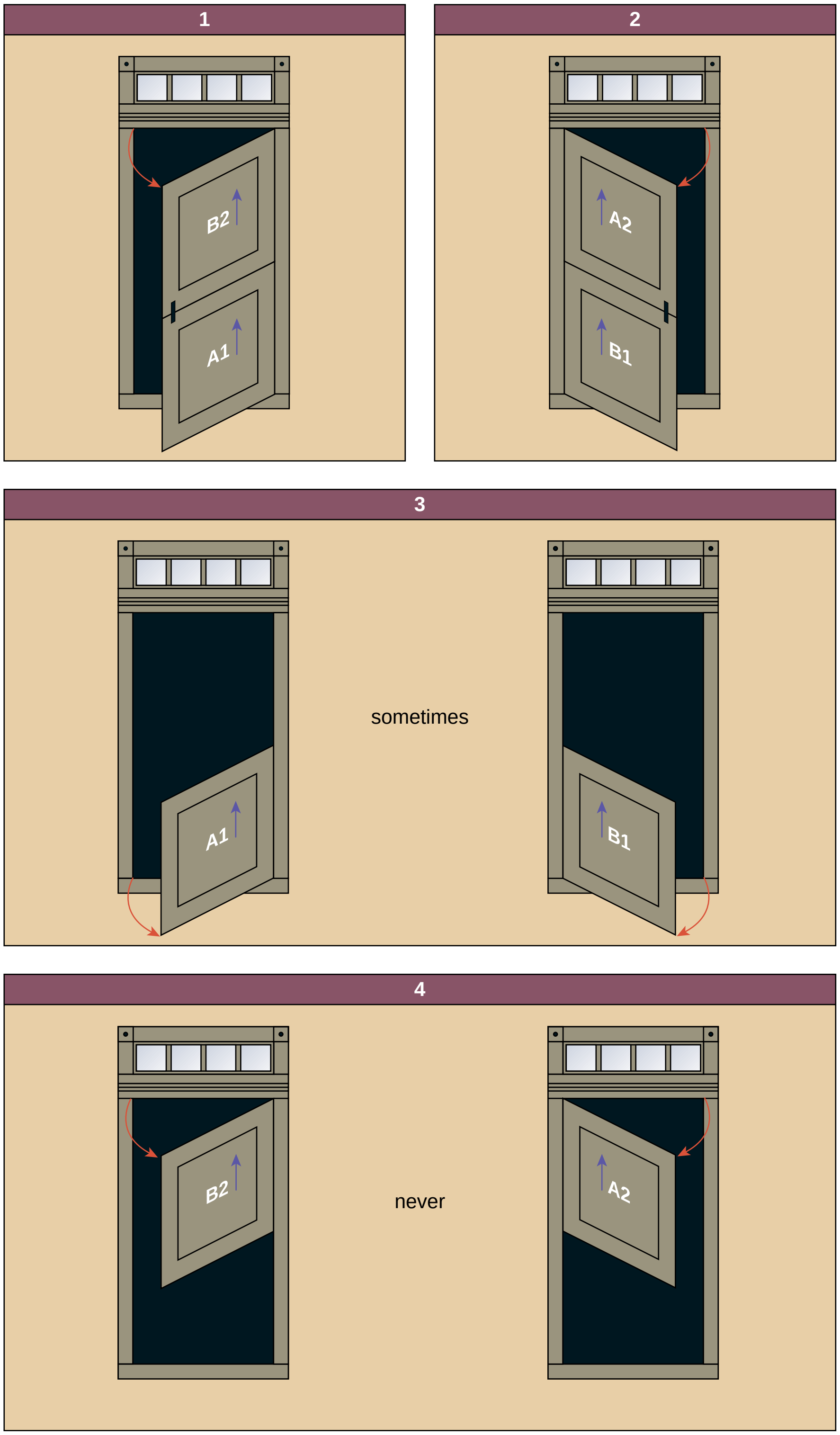

Figure 5. Dutch-door analogy shows how the Hardy-Jordan approach conflicts with local realism. Imagine two Dutch doors that are latched, so that the upper and lower sections move together. Open and closed doors represent up and down spins, respectively. The first and second Hardy-Jordan propositions can be used to label and open the two doors *(1* and *2)*. According to the third Hardy-Jordan proposition, the two bottom doors can open together sometimes *(3)*. The fourth Hardy-Jordan proposition says that the two top doors can never open together *(4)*. No latched Dutch doors could meet all four propositions at once, because if both bottom doors are open, both top doors would be open, which violates the fourth proposition. Nevertheless, Hardy found quantum-mechanical systems that satisfy all of the statements, because quantum mechanics can violate local realism. In terms of this analogy, quantum mechanics only determines the state of any two doors that are actually observed, and says nothing about the two that are not.

In the Hardy-Jordan approach, the directions A1, A2, B1 and B2 can be carefully arranged according to the theory of quantum mechanics such that the following four statements must be true:

1. If Alice measures spin up along direction A1, then Bob will measure spin up along B2.
2. If Bob measures spin up along B1, then Alice will measure spin up along A2.
3. If Alice measures along A1 and Bob measures along B1, sometimes they will both observe spin up.
4. If Alice measures along A2 and Bob measures along B2, they will never both observe spin up.

If we adhere to local realism, the Hardy-Jordan propositions generate a contradiction, because all four of them cannot be true simultaneously. The first proposition says that when Alice measures spin up along axis A1, Bob will measure spin up if he chooses axis B2. The fact that Bob's value can be predicted with certainty in this case means that his particle's spin along B2 is an element of reality, which exists whether or not he decides to measure it. Furthermore, locality demands that this element of reality is independent of Alice's axis choice, and must have existed from the moment Bob's particle was created. Similarly, proposition two says that for the trials in which Bob measures up along B1, Alice's particle must have possessed a spin-up element of reality along A2 from the moment it was created. According to proposition three, Alice and Bob may sometimes measure spin up along the axes A1 and B1, respectively. In these cases, according to the first two propositions, both Alice and Bob's particles must have left the source with definite elements of reality for the A2 and B2 spins. So if Alice and Bob had chosen to measure along A2 and B2 on those occasions, they would certainly have found both spins to be up. This violates the fourth proposition.

The potential physical contradiction may become more apparent through the following Dutch-door analogy. Imagine two Dutch doors in which the upper and lower sections are latched so that if the bottom door opens the top must open as well. In this analogy, an open door represents a measurement of spin up and a closed door represents spin down. Using the first Hardy-Jordan proposition, label the lower section of one door as A1.

When that door is open (spin up), its upper section, labeled B2, is also open (spin up). The second Hardy-Jordan proposition can be used to label the other door's lower section as B1 and its upper one as A2, which also open and close together. The third Hardy-Jordan proposition applies to the two bottom sections, A1 and B1, which can open together on some occasions. When the two bottom sections are open, however, the two top sections—B2 and A2—would also be open, but the fourth Hardy-Jordan proposition says that can never happen.

In other words, the Hardy-Jordan propositions seem to present an inescapable paradox: No everyday system of "Dutch doors" could meet the necessary requirements, because everyday systems are bound by realism and locality. A local-realism perspective demands that all four statements must not be capable of arising simultaneously. Nevertheless, Hardy demonstrated the existence of quantum-mechanical systems that do satisfy all four statements. That is, a quantum-mechanical system of particles or Dutch doors can meet the constraints of the Hardy-Jordan propositions because such systems are not bound by local realism. Something that can be observed in a quantum-mechanical system takes on a value only when it has been measured. Along the lines of the Dutch-door analogy, Bohr might have said that the only doors that exist at any moment are the ones being observed. A conundrum arises only if one insists that all four of them must exist no matter which ones are being examined.

The Rochester Experiment

The above *gedankenexperimente* relied on subatomic particles, but laboratory experiments in this area of physics often use photons as the "correlated particles," because they are easier to make and measure. In such experiments, measurements of a photon's polarization—the direction in which the light's electric field vibrates—replace the spin measurements. As is the case with spin, a photon's polarization can take only one of two possible states—say *x* and *y*—that are orthogonal to each other. So rather than spin up and down, one can imagine, for example, horizontal and vertical polarization.

A correlated pair of photons can be made through a process called *parametric downconversion*, where a nonlinear

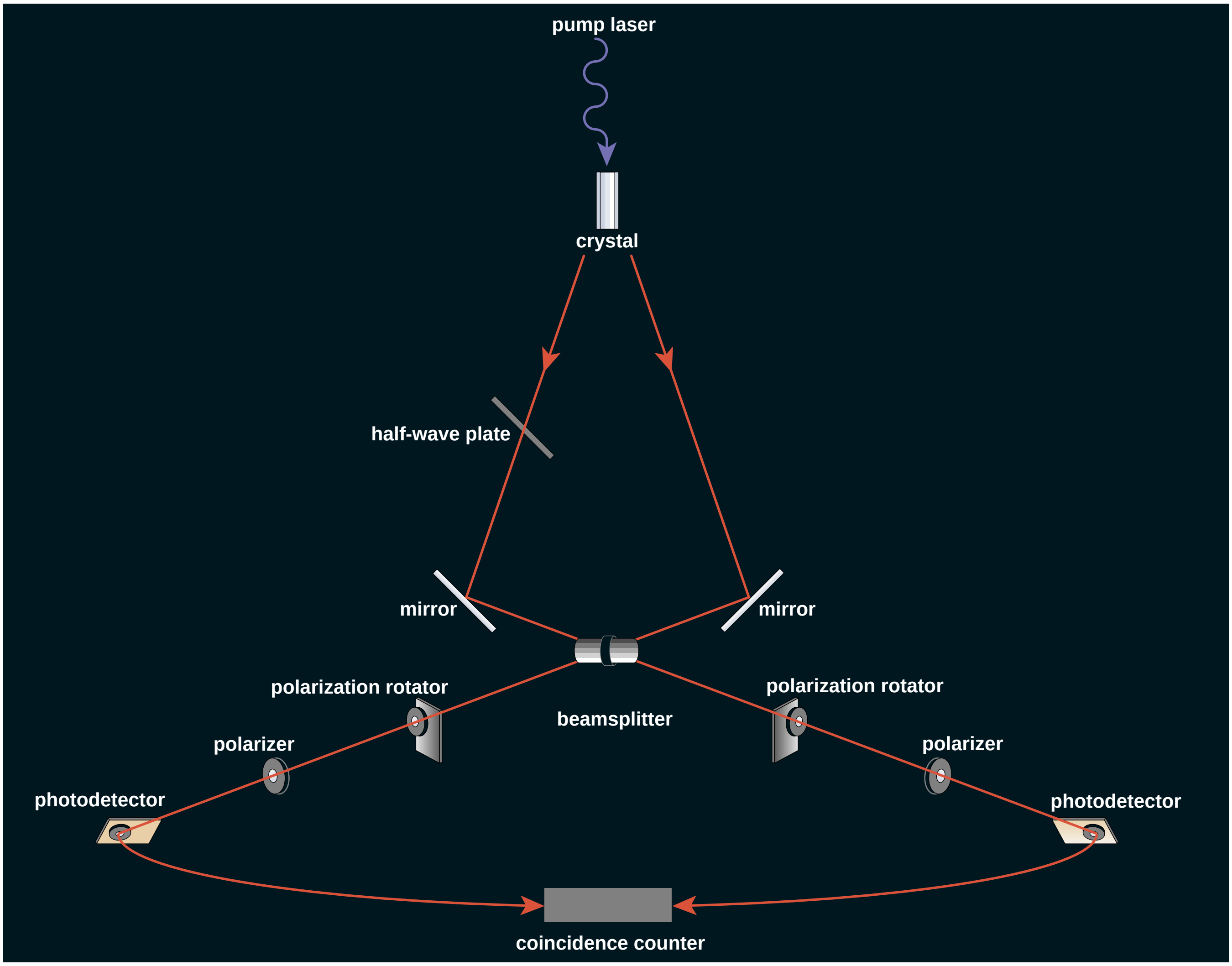

Figure 6. Rochester experiment was designed to test the Hardy-Jordan propositions. The author and his colleagues used a argon-ion pump laser and a crystal to make two beams with identical polarizations. A half-wave plate then rotated the left beam's polarization by 90 degrees. Mirrors reflected both beams to a beamsplitter that either reflected or transmitted each photon. These experiments only examined cases in which a photon emerged from each side of the beamsplitter, meaning that both photons were either reflected or transmitted. Next, each photon traveled through an adjustable polarization rotator, which could change the angle of polarization, and then through a polarizer that transmitted only photons with a specific polarization. Photons that passed all of the devices hit a photodetector, and a coincidence counter determined when both photodetectors received photons simultaneously.

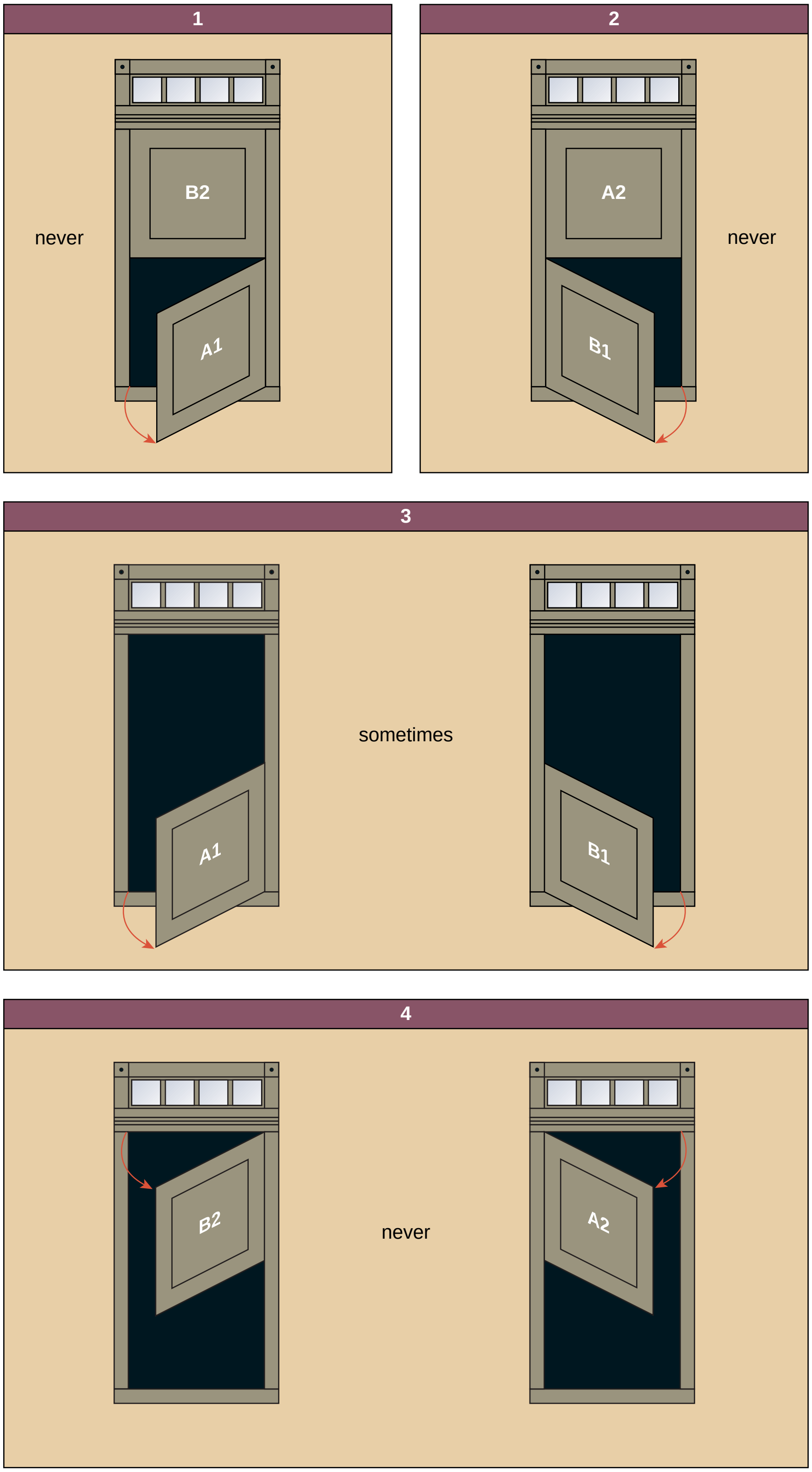

Figure 7. Rochester experiment adds a twist to the Hardy-Jordan Dutch doors. The polarizers were set to pass one of six polarizations: A1, A2, $\underline{\text{A2}}$, B1, B2 or $\underline{\text{B2}}$, where $\underline{\text{A2}}$ and $\underline{\text{B2}}$ are perpendicular to directions A2 and B2, respectively. This leads to a couple of changes in the propositions. Open bottom doors and closed top doors will never exist together *(1* and *2)*. The remaining propositions *(3* and *4)* remain the same. In the experiment, the configurations *1* and *2* did appear a few times, indicating that the Dutch-door "latches" did not work perfectly. Allowing for the imperfect latches, one would expect configuration 4 to occur almost as often as configuration *3* on the basis of local realism. However, configuration *4* occurred much more rarely than this.

crystal splits a beam of high-energy light into two beams of lower-energy light. Each high-energy *pump* photon that undergoes downconversion produces two lower-energy photons—historically dubbed the *signal* and the *idler*—that leave the crystal in different directions but have identical, fixed polarizations.

In an experiment designed to test the Hardy-Jordan propositions and the accompanying Dutch-door paradox, my colleagues, Justin Torgerson and Carlos Monken, and I aimed a 351-nanometer argon-ion laser at a parametric-downconversion crystal composed of lithium iodate. The signal and idler beams emerged with wavelengths of 702 nanometers and polarizations denoted as *x*. The idler beam passed through a half-wave plate, which rotated that beam's polarization by 90 degrees, thereby converting its polarization from *x* to *y*. Mirrors directed the idler beam's *y* photon and the signal beam's *x* photon to a partially reflecting beamsplitter, where a photon would be either reflected or transmitted. The optical path lengths to the beamsplitter were equal to within 10 micrometers, so both photons arrived at the beamsplitter within 35 femtoseconds of one another.

The so-called quantum state of the light at the beamsplitter could lead to four possible outcomes: both photons transmitted, both photons reflected, the *x* photon reflected and the *y* photon transmitted, or the *y* photon reflected and the *x* photon transmitted. In the first two cases, a photon would leave each side of the beamsplitter. In the third and fourth cases, both photons would emerge from either the right or left side of the beamsplitter.

After the beamsplitter, the photon paths to the right and left included polarization rotators, which could be adjusted to change the polarization of the light by any desired angle. Next, a polarizer in the path transmitted only photons with a particular polarization, and photons that passed through landed on a photodetector—a silicon "avalanche" photodiode that emitted discrete electronic pulses when triggered by the energy of a single photon. A pulse could be emitted anytime within a so-called *jitter* time of 5 nanoseconds after the arrival of a photon. The quantum efficiency of each detector was roughly 50 percent, which means that only half of the arriving photons actually triggered a pulse.

Of the four possible outcomes at the beamsplitter, our experiment concentrated on the first two, where each detector could receive a photon. We used a coincidence counter to record the events in which photons were detected simultaneously at the two photodetectors. The jitter time of the detectors meant that any pair of signals that arrived within a 10-nanosecond *coincidence window* would be considered as simultaneous.

Rochester Results

In the course of our experiment, we recorded the number of coincidence counts in a fixed period of time when the rotators and polarizers were set to pass photons of specially chosen polarizations to the detectors. We calculated those polarizations—A1, A2, $\underline{\text{A2}}$ (perpendicular to A2), B1, B2 and $\underline{\text{B2}}$ (perpendicular to B2)—to correspond with Hardy's propositions and to make the following statements true: *1.* P(A1, $\underline{\text{B2}}$) = 0; *2.* P($\underline{\text{A2}}$, B1) = 0; *3.* P(A1, B1) > 0; and *4.* P(A2, B2) = 0. In these equations, P(A, B) is the joint probability that a photon is detected at each photodetector, with one polarization rotator set to pass photons of polarization A, and the other rotator set to pass those with polarization B. In these calculations we assumed that the polarizers were ideal, transmitting all photons possessing a certain polarization and blocking those with the perpendicular polarization. The photodetectors were also assumed to be ideal, producing a signal for every photon that hit them.

Our four equations include the same constraints as the Hardy-Jordan propositions, albeit in a somewhat different form. Our first equation, P(A1, $\underline{\text{B2}}$) = 0, states that there can be no simultaneous photodetections when the rotators are set to pass photons of polarization A1 and $\underline{\text{B2}}$, because an A1-polarized photon would be accompanied by a blocked B2-polarized photon—as in the first Hardy-Jordan proposition. Similarly, our second equation, P($\underline{\text{A2}}$, B1) = 0, says that a B1-polarized photon would be accompanied by a blocked A2-polarized photon—as in the second Hardy-Jordan proposition. Our third and fourth equations, P(A1, B1) > 0 and P(A2, B2) = 0, respectively, are the direct mathematical equivalents of the third and fourth Hardy-Jordan propositions; our third equation establishes the possibility for the detectors to sometimes find photons polarized along A1 and B1, and our fourth equation says that there can never be a pair of A2- and B2-polarized photons. In addition, our equations contain the Dutch-door paradox, because all four of our equations cannot be true simultaneously.

Did our apparatus demonstrate the Dutch-door paradox? Our experiments produced the following results for our probability equations:

$$\begin{aligned} P(A1, \underline{B2}) &= 0.0034 \pm 0.0004 \\ P(\underline{A2}, B1) &= 0.0040 \pm 0.0004 \\ P(A1, B1) &= 0.0990 \pm 0.0020 \\ P(A2, B2) &= 0.0070 \pm 0.0005 \end{aligned}$$

As predicted, the third probability is greater than zero. Ideally, the first, second and fourth equations would equal zero, within some margin of error, but they are all slightly greater than zero for experimental reasons. Therefore, the Dutch doors in our experiment were imperfect; the latches connecting the tops and bottoms together occasionally broke. The first two equations tell us that, in less than 0.5 percent of the trials, the top door on each side was closed while the bottom one was open, indicating that the latch had failed. Therefore, one or the other of the latches might fail in as many as 1 percent of the trials. However, the third equation shows that the bottom two doors were found open in about 10 percent of the trials, which means that we would expect the top two doors to be open in about 9 percent of the trials according to local realism. Yet, the tops were actually both found open in less than 1 percent of the trials, a rate that is lower than the local realistic one by 45 standard deviations.

Despite this, our work does not provide irrefutable evidence for the existence of the Hardy-Jordan Dutch doors, or a world that violates local realism, because our experiment contains loopholes. For instance, our detectors were not perfectly efficient, and Adan Cabello of the Universidad Complutense in Madrid and Emilio Santos of the Universidad de Cantabria in Santander, also in Spain, have developed a theory that could explain our experimental results by incorporating a nonrandom detector failure, but not violating local realism. Their model might be likened to the following: Suppose that the Dutch doors are located at the far end of a crowded ballroom, so that our line of sight is sometimes blocked by various couples. If the couples perform a dance that requires them to be in the way whenever the top two doors are open, this would explain why we are never able to see that configuration. In contrast, our assumption was that the couples blocked our view at random times, independent of what the doors were doing, so that no such bias could be introduced. This kind of "fair sampling" assumption has been a necessary loophole in every experimental test of local realism to date.

The dream of a loophole-free experimental violation of local realism remains alive for many physicists, and progress continues toward that goal in many research groups around the world. In the meantime, the debate over the completeness of quantum mechanics, which began with Einstein and Bohr, remains one of the most interesting facets of modern physics.

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