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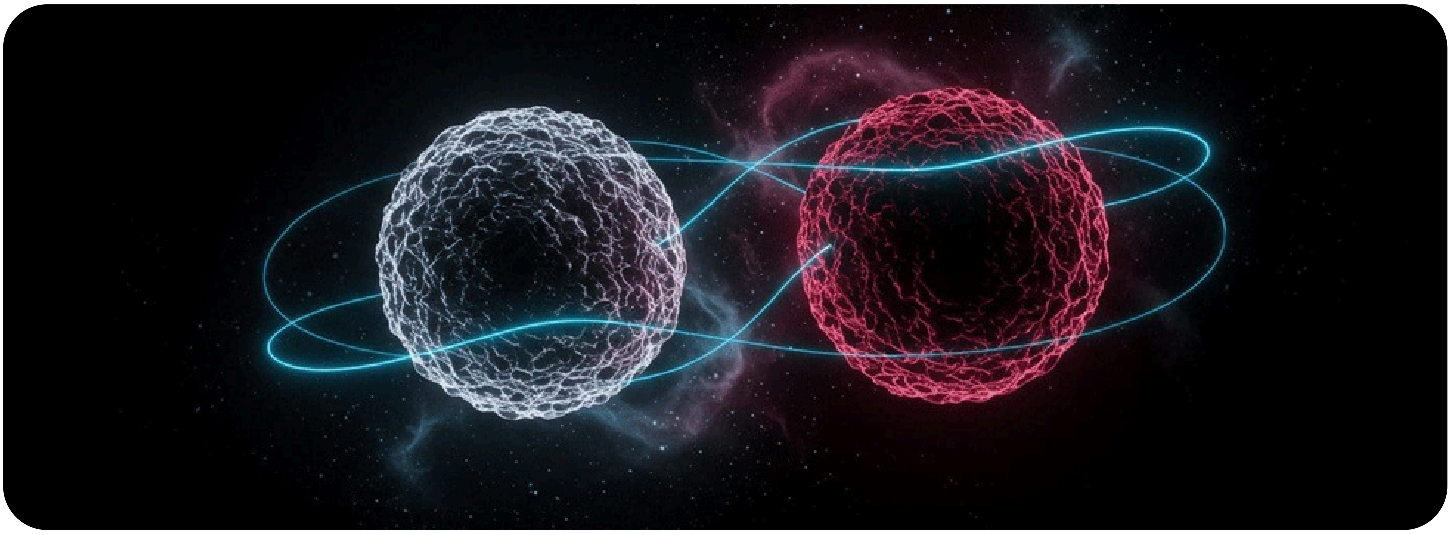
WRONG FOR THE RIGHT REASONS: How Einstein’s Doubts Led to the Greatest Discovery in Quantum Physics.



One of the greatest principles of physics is that nothing can travel faster than light. Called the principle of locality, it states that the order of cause and effect cannot be reversed. Essentially, locality means that physical phenomena are caused by things in their immediate vicinity. In a local world, in order for an event happening “here” to affect something “there,” a message must pass through the space between them. Since this message cannot travel faster than light, there will necessarily be some lag time involved. And this is precisely what makes the universe tick because all observers at all possible speeds and locations will be able to agree on the chronology of events. However, quantum mechanics contradicts this fundamental law, suggesting that elementary particles can affect each other instantaneously regardless of the huge distances between them on the cosmic scale. As crazy an idea as this seemed to be even to such luminaries of science as Einstein, it needed a genius proof along with a breakthrough experiment, the Bell experiment.

THE IDEA THAT CHANGED EVERYTHING

This whole debate began from the very beginning of our understanding of gravity. While Newton postulated that the gravitational forces traveled instantaneously no matter how far the distance, Einstein explained that it was mathematically impossible to have such instantaneous actions, since it would create paradoxes about which event came first. The solution that he found involved completely revolutionizing physics by way of general relativity.

However, the new theory of quantum mechanics threatened this local view of the universe. At the 1927 Solvay Conference, Einstein presented a thought experiment involving a single electron fired through a narrow slit toward a circular screen. Quantum mechanics says the electron travels as a wave function, spreading out through space. When the electron is detected at a single point, its wave function must instantly collapse to zero everywhere else, no matter the distance. Einstein argued that this "entirely peculiar mechanism" violated the postulate of relativity. Niels Bohr, a leading quantum physicist, countered with the Copenhagen interpretation. Bohr argued that physics isn't meant to describe what a particle is actually doing when we aren't looking; it merely provides the mathematical probabilities of our measurements. He famously claimed that the wave function tells you everything physics can or should tell you.

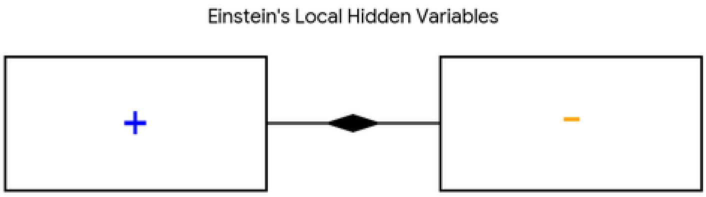
Einstein famously dismissed this as a "tranquilizing philosophy".

THE EPR PARADOX AND HIDDEN VARIABLES

The EPR paper was written by Einstein and his fellow researchers, Boris Podolsky and Nathan Rosen, in 1935, in which they claimed that quantum mechanics lacks completeness. Entanglement can be seen in the form of a highly energetic photon giving off two particles, namely, a particle and its antiparticle (an electron and a positron, respectively).

In order for the total spin to remain conserved, no matter what the electron does, the positron will have to perform the opposite action. As soon as one measures the spin of the electron and finds it spinning upwards (positive Z), the wave function of the remote positron instantaneously becomes downwards (negative Z). A simple way to do this without the need for anything moving faster than light is by using the local hidden variable theory, as mentioned in the EPR paper.

Local Hidden Variables Theory: In the local interpretation, the particles do not choose their state at the time of observation; rather, they make this decision while they are still bound to each other. Picture two envelopes with predetermined instructions within them. These are referred to as hidden variables, which are the characteristics possessed by the particles that will determine the results of any subsequent measurement done on the particles. Since the instructions are contained in the envelopes, they need not communicate through instant messages.

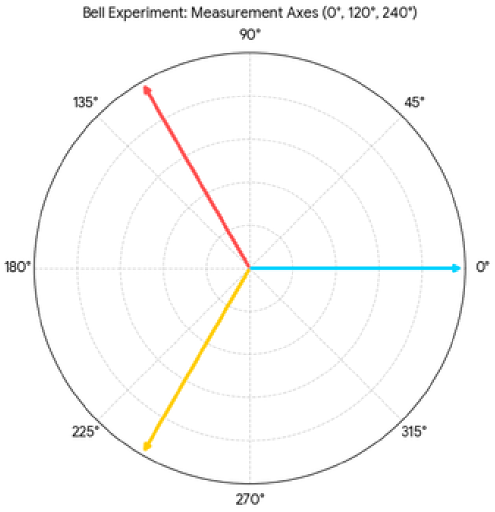


According to the Quantum View, the envelopes contain both answers simultaneously, in a state of superposition. Once one is opened, the other instantaneously collapses into the opposite position, regardless of space. As per the Hidden Variables Theory, the particles had decided how to spin in unison beforehand, and the information was encoded within the envelopes before separation. The positron would know what to do without any instantaneous communication. Physicists ignored this dispute for years since both views predicted identical results for the same measurements.

BELL'S THEOREM AND THE TWIST

This dispute remained a philosophical one until the year 1964, when John Bell, a physicist, found out that there was a way to prove whether one or the other theory was correct. Bell's innovation in the EPR paradox involved selecting three possible measurement axes: 0°, 120°, and 240°, instead of just one.

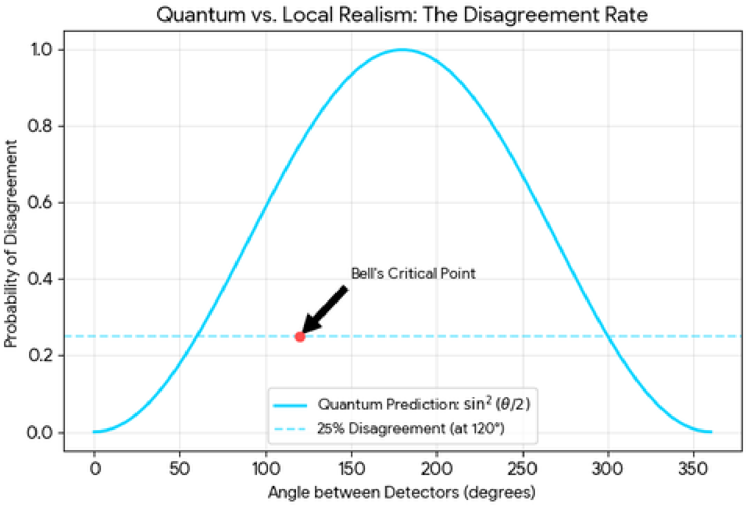
Bell calculated the "disagreement probability," which is the probability that the electron's answer will be different from the positron's.



- **Quantum Mechanics Calculation**: Assuming that wave collapse happens instantaneously and is non-local, quantum mechanics dictates that the probability that the two answers will be different is precisely 25%.
- **Local Hidden Variables Calculation**: Assuming that there are local hidden variables within the envelopes that enable the particles to imitate quantum mechanics, simple logic proves that the disagreement will occur at least 33.3% (1/3) of the time.

Disagreement Rate Calculation: There are three questions posed to the particles, each related to the angles of 0°, 120°, and 240°. In order to respect locality, both particles should agree on their answers to all three questions prior to separation.

- **Strategy: Identical Response to All Angles**: If the electron gives the response of "Minus" to all three questions and the positron responds with "Plus," they will always disagree when the questions are asked of them at different angles. This result is far from the predicted quantum outcome of 25%.
- **Strategy: Alternative Responses:** If the electron gives the response of "Minus" to two angles and "Plus" to the third (say, M, M, P), then the positron must give the opposite responses (P, P, M).
- **Probability Outcome:** If the experimenters choose two different axes at random, a simple count of the combinations shows they will pick an axis where the answers match a portion of the time. Bell's proof showed that for any such local strategy, the disagreement rate must be at least 1/3.



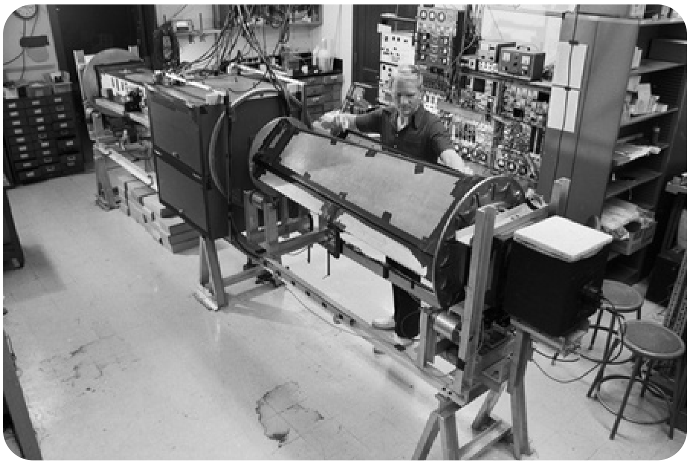
Because **25%** is a different number than **33.3%**, Bell's Theorem proved that local hidden variables and non-local quantum mechanics make mathematically different predictions. All that was left was to perform the experiment.

THE EXPERIMENT IN ACTION

The difficult part was to implement this process in the lab. At the Institut d'Optique, Alain Aspect and his colleagues conducted an important version of Bell's test. Instead of using electrons, they used two crystals to create entangled photons, directing them through two separate paths in their testing apparatus. The polarization angle of each path was adjustable, using half-wave plates and polarizers, exactly as predicted by Bell.

In order to measure the rate, scientists first adjust the axes to check whether the particles will be at odds whenever they are in the same position, forming a baseline measurement for the total number of entangled particles. Then they rotate one axis, dividing the number of pairs that are at odds by second by the baseline number. The calculation of the number of pairs that are at odds gives a rate of 25% disagreement exactly. The local hidden variable theory is proven false using mathematics.

While Bell himself believes that quantum mechanics is right, he recognizes that it is in "serious tension" with relativity on the matter of locality.



John Clauser with the quantum mechanics experiment he and Stuart Freedman built to test Bell's theorem in the 1970s. (Photo credit: Steve Gerber, courtesy of Berkeley Lab)

WHAT THIS MEANS FOR REALITY

The Bell experiment reveals that locality, taken as a foundational idea, fails within our universe. Towards the latter part of his life, even Bell stated, "I think you're stuck with the non-locality. I don't know any conception of locality that works in quantum mechanics."

Although Einstein's fears concerning hidden variables were unjustified, his worries were valid nonetheless. Instantaneous effects at a distance do occur in the quantum world. But quantum mechanics manages to avoid the problem of time travel thanks to one fundamental restriction. This restriction is that of randomness since the outcomes of measurements are random; any form of controlled communication via quantum mechanics is impossible.

The only loopholes to keep locality intact are:

- **The Many Worlds Interpretation:** According to this theory, the wave functions don't collapse; all possibilities are true at the same time, and the observer splits in different universes. There is no superluminal communication because both possibilities occur.
- **Pilot Wave Theory**: A non-local theory of hidden variables that even Bell supported.

Whether we live in an odd universe with quantum entanglement or one that branches off infinitely into various universes, the Bell test is a remarkable accomplishment in history. It made humans realize that our universe is more bizarre than we have thought before.

> "I felt that Einstein's intellectual superiority over Bohr, in this case, was enormous—a great difference between the man who knew exactly what was required and the obscurantist."
>
> **—John Bell, Physicist**

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