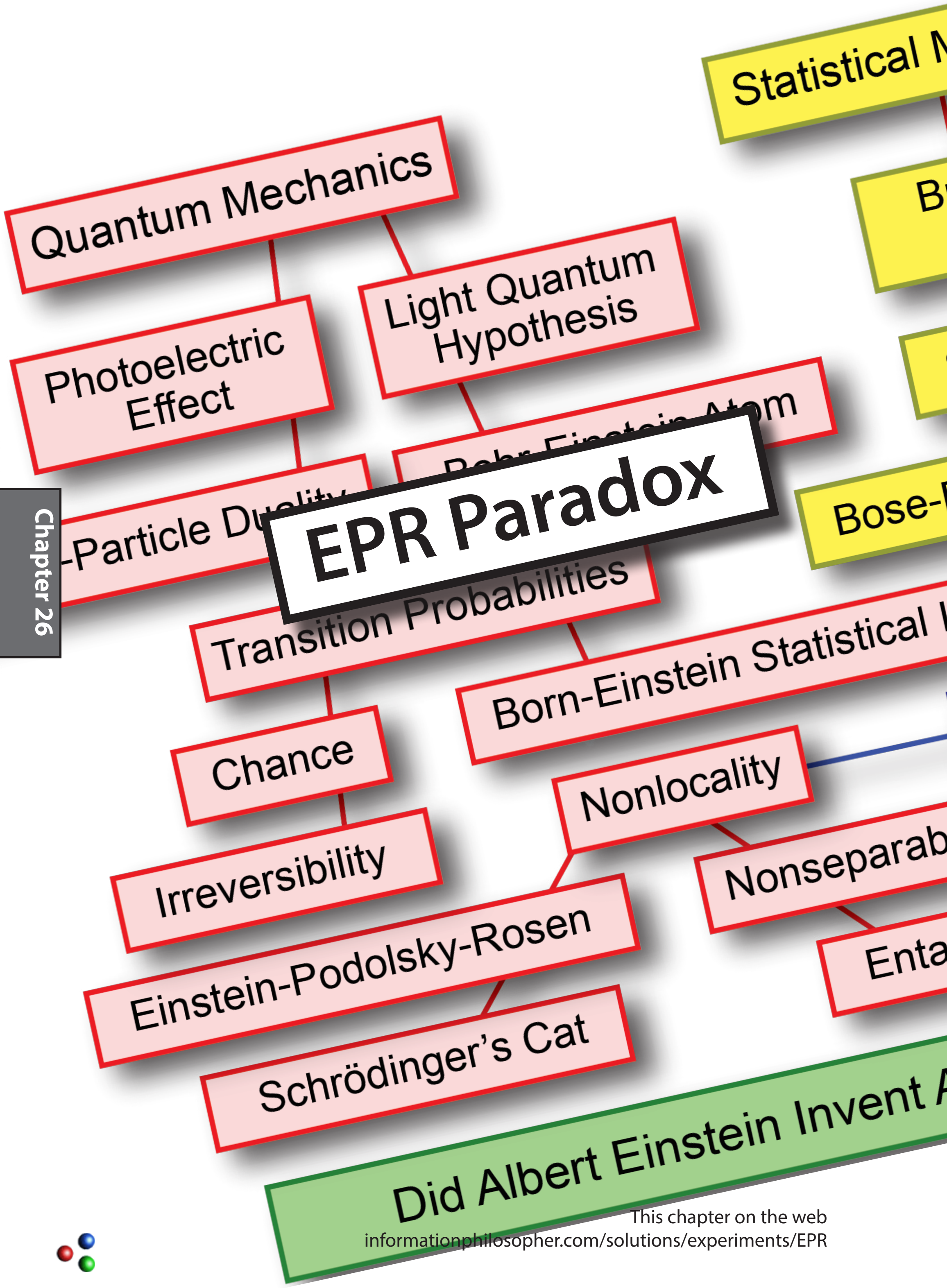
EPR Paradox



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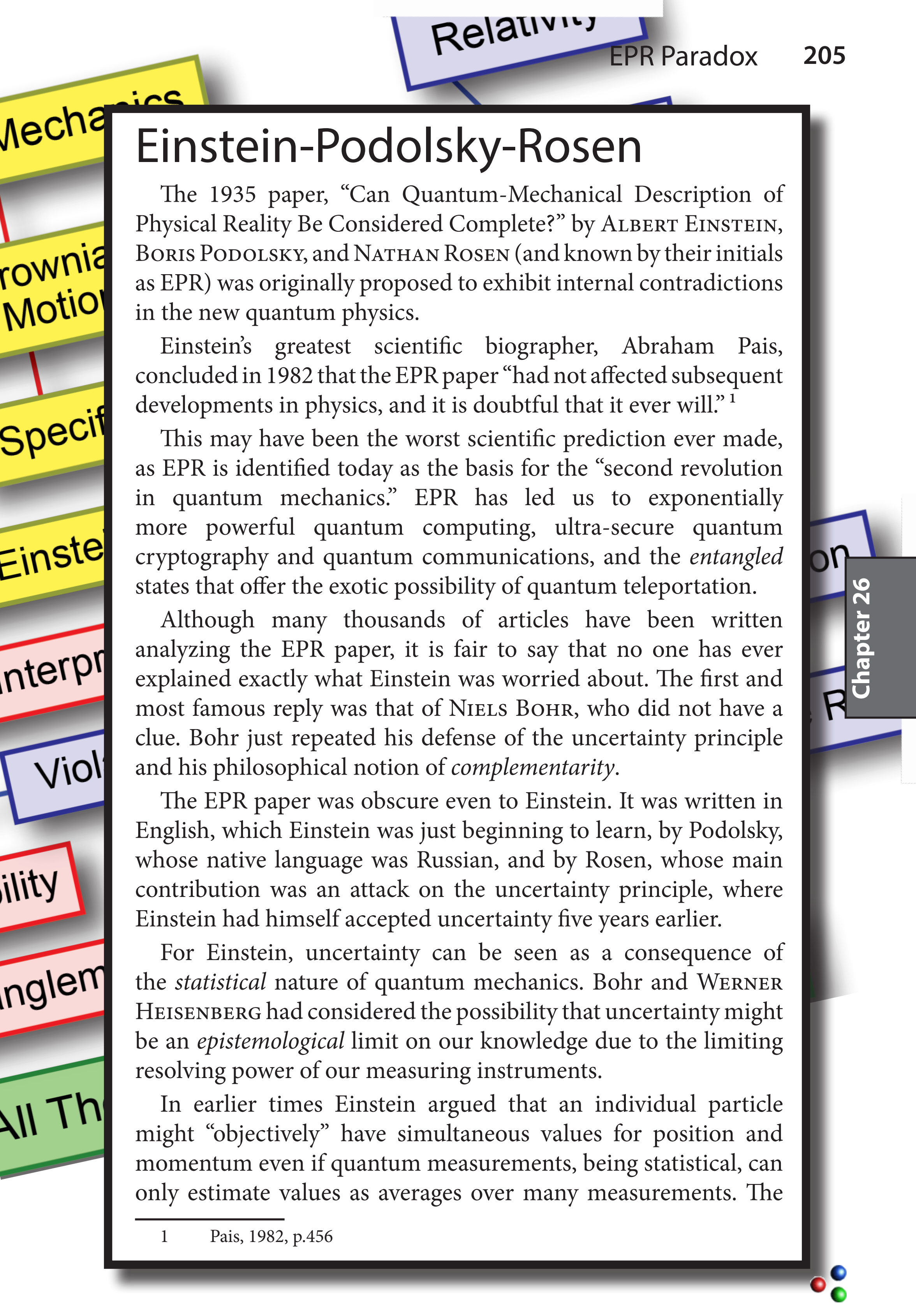

Einstein-Podolsky-Rosen

The 1935 paper, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" by Albert Einstein, Boris Podolsky, and Nathan Rosen (and known by their initials as EPR) was originally proposed to exhibit internal contradictions in the new quantum physics.

Einstein's greatest scientific biographer, Abraham Pais, concluded in 1982 that the EPR paper "had not affected subsequent developments in physics, and it is doubtful that it ever will."[1]

This may have been the worst scientific prediction ever made, as EPR is identified today as the basis for the "second revolution in quantum mechanics." EPR has led us to exponentially more powerful quantum computing, ultra-secure quantum cryptography and quantum communications, and the *entangled* states that offer the exotic possibility of quantum teleportation.

Although many thousands of articles have been written analyzing the EPR paper, it is fair to say that no one has ever explained exactly what Einstein was worried about. The first and most famous reply was that of Niels Bohr, who did not have a clue. Bohr just repeated his defense of the uncertainty principle and his philosophical notion of *complementarity*.

The EPR paper was obscure even to Einstein. It was written in English, which Einstein was just beginning to learn, by Podolsky, whose native language was Russian, and by Rosen, whose main contribution was an attack on the uncertainty principle, where Einstein had himself accepted uncertainty five years earlier.

For Einstein, uncertainty can be seen as a consequence of the *statistical* nature of quantum mechanics. Bohr and Werner Heisenberg had considered the possibility that uncertainty might be an *epistemological* limit on our knowledge due to the limiting resolving power of our measuring instruments.

In earlier times Einstein argued that an individual particle might "objectively" have simultaneous values for position and momentum even if quantum measurements, being statistical, can only estimate values as averages over many measurements. The

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[1] Pais, 1982, p.456

statistical deviations Δp and Δx around the mean values give us the uncertainty principle $\Delta p \Delta x = h/2\pi$.

In the EPR paper, Einstein argued that its statistical character makes quantum mechanics an *incomplete* theory relative to "*objectively real*" classical mechanics, where the outcome of a measurement is *independent* of the observer.

The EPR authors hoped to show that quantum theory could not describe certain "*elements of reality*" and thus was either *incomplete* or, as they may have hoped, demonstrably incorrect.

> the following requirement for a complete theory seems to be a necessary one: every element of the physical reality must have a counterpart in the physical theory. We shall call this the condition of completeness.
>
> We shall be satisfied with the following criterion, which we regard as reasonable. *If, without in any way disturbing a system, we can predict with certainty {i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.*[2]

Using Heisenberg's uncertainty principle, the EPR authors wrote, "when the momentum of a particle is known, its coordinate has no physical reality." But if both momentum and position had simultaneous reality—and thus definite values—"these values would enter into the complete description, according to the condition of completeness."[3]

Niels Bohr and his Copenhageners took this "incompleteness" as just one more of Einstein's attacks on quantum mechanics, especially its uncertainty principle.

Einstein shortly later gave an "objectively real" example of incompleteness that even a third grader can understand. Imagine you have two boxes, in one of which there is a ball. The other is empty. An *incomplete* statistical theory like quantum mechanics says, "the probability is one-half that the ball is in the first box." An example of a *complete* theory is "the ball *is* in the first box."[4]

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[2] Einstein, Podolsky, Rosen, 1935, p.777

[3] *ibid.* p.778

[4] June 19, 1935 letter to Schrödinger. See also Fine, 1996, p.36 and p.69.

Here Einstein is criticizing the Copenhagen Interpretation's use of PAUL DIRAC's principle of superposition, which we saw in chapter 19 is easily misinterpreted. Dirac suggests that we might *speak as if* a single particle is partly in each of the two states, that the ball above is "distributed" over Einstein's two boxes.

Dirac's "manner of speaking" gives the false impression that the single ball can actually be in the two boxes at the same time. This is seriously misleading. Dirac expressed the concern that some would be misled - don't "give too much meaning to it," he said.

Two Places or Paths at the Same Time?

Einstein's Boxes were his criticism of the most outlandish claim of the "orthodox" Copenhagen Interpretation, that particles can be in two places at the same time and move simultaneously along different paths. The square of the wave function Ψ^2 gives us the probability of finding a particle in different places. Specifically, this means that when we do many identical experiments, we find the statistics of many different places and paths agrees perfectly with the probabilities. But in each individual experiment, we always find the whole particle in a single place!

Einstein's Boxes example also criticizes the idea that particles do not even exist until they are measured by some observer. Einstein said, sarcastically, "Before I open them, the ball is not in *one* of the two boxes. Being in a definite box only comes about when I lift the covers."[5] Einstein used his conservation principles to argue that a particle can not go in and out of existence, split into two, or jump around arbitrarily violating conservation of momentum.

A third tenet of the Copenhagen Interpretation that Einstein criticized is that the properties of a particle are not determined in advance of measurement. Properties are sometimes random or indeterministic, and in some sense determined by the observer, where for Einstein real objects have properties *independent of the observer*. Where his first two criticisms above were accurate, and flaws in the standard interpretation of quantum mechanics, this criticism was in part one of Einstein's mistakes.

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[5] Fine, 1996, p.69.

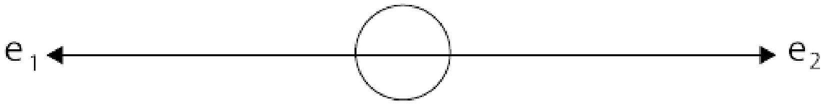
Einstein's fourth and most revolutionary criticism leads directly to entanglement and the "second revolution" in quantum mechanics. This is what he described as *nonlocality* and *nonseparability*.

Einstein's fundamental concern in the EPR paper was not *incompleteness*, which caught Bohr's attention.. It was *nonlocality*, which had been on Einstein's mind for many years, but Bohr never understood what Einstein was talking about, as we saw in chapter 23. Nonlocality challenged Einstein's special relativity and his claims about the *impossibility of simultaneity*.

Two years before EPR, and just before Einstein left Europe forever in 1933, he attended a lecture on quantum electrodynamics by LEON ROSENFELD.[6] Keep in mind that Rosenfeld was perhaps the most dogged defender of the Copenhagen Interpretation. After the talk, Einstein asked Rosenfeld, "What do you think of this situation?"

> Suppose two particles are set in motion towards each other with the same, very large, momentum, and they interact with each other for a very short time when they pass at known positions. Consider now an observer who gets hold of one of the particles, far away from the region of interaction, and measures its momentum: then, from the conditions of the experiment, he will obviously be able to deduce the momentum of the other particle. If, however, he chooses to measure the position of the first particle, he will be able tell where the other particle is.

We can diagram a simple case of Einstein's question as follows.



Two particles moving with equal and opposite momentum leave the circle of interaction (later "entanglement") in the center. Given the position of one particle, the position of the second particle must be exactly the same distance on the other side of the center.

Measuring one particle tells you something about the other particle, now assumed to be at a large spacelike separation. Does that knowledge require information to travel faster than light? No.

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[6] Lahti and Mittelstaedt, 1985, p.136

Einstein asked Rosenfeld, “How can the final state of the second particle be influenced by a measurement performed on the first after all interaction has ceased between them?” This was the germ of the EPR paradox, and ultimately the problem of two-particle entanglement.

Why does Einstein question Rosenfeld and describe this as an “influence,” suggesting an “action-at-a-distance?”

It might be paradoxical in the context of Rosenfeld’s Copenhagen Interpretation, since the second particle is not itself measured and yet we know something about its properties, which Copenhagen says we cannot know without an explicit measurement..

The second particle must have knowable properties. When we measure the first particle, we learn its momentum. By conservation laws, we know the second particle’s equal and opposite momentum, and this means that we can know its position. How does Rosenfeld explain this? We do not know his answer.

Nonlocality in 1905 and 1927 involved only one particle and the mysterious influence of the probability wave. But in the EPR paper Einstein has shown nonlocal effects between *two* separated particles.

Einstein’s basic concern was that particles now very far apart may still share some common information, so that looking at one tells us something about the other. And it tells us instantly, faster than the speed of light.

He later called nonlocality “*spukhaft Fernwirkung*” or “*spooky action-at-a-distance*.”[7] But calculating and predicting the position and momentum of a distant particle based on conservation principles is better described as “*knowledge-at-a-distance*.”

There is no “action,” in the sense of one particle changing the properties of the other.

But Einstein’s idea of a measurement in one place “influencing” measurements far away challenged what he thought of as “local reality.” These “influences” *appear* to be nonlocal.

What is it Einstein saw? What was Einstein worried about? We have been arguing that it challenged the *impossibility of simultaneity* implied by his theory of special relativity.

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[7] Born, 1971, p.155

Note that Einstein knew nothing of the simultaneous spin or polarization measurements by Alice and Bob that constitute modern entanglement experiments. But Einstein's insight into the guiding field of the probability wave function can be applied to both entanglement and the two-slit experiment, in which case it might solve two mysteries with one explanation.

It will show Einstein was wrong about the "impossibility" of simultaneity, but like many of his mistakes, gives us a deep truth.

Is Quantum Mechanics Complete or Incomplete?

NIELS BOHR had strong reasons, mostly philosophical, for defending completeness. For one thing, his idea of complementarity claimed to have found the two complementary sides of all dualisms that combine to explain the wholeness of the universe.

But also, Bohr was a great admirer of the *Principia Mathematica* of BERTRAND RUSSELL and ALFRED NORTH WHITEHEAD, which claimed to be a "complete" system of propositional logic. This claim was challenged by GOTTLOB FREGE's linguistic puzzles about sense and reference[8] and by Russell's own famous "paradox." But even more devastating was KURT GÖDEL's 1931 theorems about inconsistency and incompleteness in mathematics.

Gödel visited the Institute for Advanced Study in 1933 and developed a lifelong friendship with Einstein. In 1934 Gödel gave a lecture series on undecidable propositions. Einstein, and probably Podolsky and Rosen, attended. Incompleteness, in the form of limits on knowledge, was in the air.

Heisenberg's uncertainty principle can be understood as an epistemological limit, where Einstein's goal was an ontological understanding of the objectively real. Any measurement apparatus uses an electromagnetic interaction to locate a material particle, so it is limited by the finite wavelength of the light used to "see" the particle. In his 1927 Como lecture, Bohr embarrassed Heisenberg by deriving his uncertainty principle on the basis of light waves alone, which limit the so-called "resolving power" of any instrument.

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[8] Doyle, 2016b, p.241

Einstein may well have continued to believe that a real particle actually has precise properties like position and momentum, but that quantum measurements are simply unable to determine them. Heisenberg also called his principle *indeterminacy*.

What Einstein wanted to "complete" quantum mechanics was more information about the paths and properties of individual systems between measurements. The Copenhagen Interpretation dogmatically insisted that nothing can be known about quantum particles and their paths until they are measured.

That its position cannot be known can not justify the claim that a particle can therefore be anywhere, or have no position. For example, that it can be in multiple places at the same time, as the principle of superposition of probabilities mistakenly suggests. This was explained by Paul Dirac as just a "manner of speaking."

As we saw in chapter 19, Einstein perfectly understood Dirac's superposition principle as our inability to say whether a particular photon will pass a polarizer or not, although we can predict the *statistics* of photons passing through with high accuracy.

Einstein might have seen this randomness as connected to his 1916 discovery of ontological chance, and so might not have liked it.

Dirac called this inability to predict a path "Nature's choice." It is randomness or chance beyond the control of an experimenter.

By contrast to Dirac, Heisenberg insisted on what he and Bohr called the "free choice" of the experimenter, for example whether to measure for the position or the momentum of a particle. Einstein might well have endorsed this freedom as supporting his belief in the "free creations of the human mind."

In the EPR paper, the authors mention that we can freely choose to measure the first particle's momentum or its position.

Copenhagen is correct that we cannot know the instantaneous details of a particle's path and properties without continuous measurements during its travel, but we can use conservation laws and symmetry to learn something about a path *after the fact* of a measurement.

Back to EPR, after the measurement on the first particle, conservation laws give us “knowledge-at-a-distance” about the second particle. With this knowledge, we can retrospectively construct the path of the second particle.

Because of its perceived “incompleteness,” Einstein mistakenly suggested that “additional variables” might be needed in quantum mechanics. In chapter 30, we will see that in 1952 David Bohm added a faster-than-light vector potential to make what Einstein thought were nonlocal events possible and to restore classical physical determinism to quantum mechanics.

Bohm also proposed an improved EPR experiment using *discrete* electron spins rather than *continuous* momentum values. Today the Bohm version has become the standard presentation of the EPR experiment, using either spin-1/2 material particles or spin-1 light particles (photons). The spatial components of spin values that are observed provide canonical examples of both Heisenberg’s “free choice of the experimenter” and Dirac’s “Nature’s choice,” neither of which was a part of Einstein’s original concerns.

If we freely choose to measure electron spin in the z-direction, our choice brings the z-direction components into existence. The x- and y-components are indeterminate. Heisenberg was right. The experimenter has a “free choice.”

But the particular value of the z-component is random, either +1/2 or -1/2. So Dirac was also right. This is “Nature’s choice.” Now this randomness is sometimes criticized as rendering all events *indeterministic* and the results of mere chance. It is said to threaten reason itself.

If events are really uncaused, some fear that scientific explanations would be impossible. In 1927, Heisenberg said that his quantum mechanics had introduced *acausality* into nature. He thought it might contribute to human freedom. But he did not seem to know that in 1916 Einstein discovered ontological chance when matter and radiation interact. Einstein’s ontological chance is physically and metaphysically much deeper than Heisenberg’s epistemological uncertainty.

EPR in the 21st Century.

The next six chapters describe how Einstein's radical ideas about nonlocality and nonseparability morph into the "second revolution" in quantum mechanics.

It is a story of twists and turns, which began with Einstein seeing "action-at-a-distance" between the continuous light wave spread out everywhere and the discrete light quantum detected at a particular spot on a screen (chapter 23).

In the EPR article, Einstein insisted this "action-at-a-distance" must be impossible once the particles separate far enough so they no longer can interact.

In later 1935, Erwin Schrödinger reacted to Einstein's separability principle by saying that the "entangled" particles could not be separated as long as they did not interact with other particles (see chapters 27 and 28).

In 1952 Bohm proposed a new test of nonseparability could be done using electron spins. Bohm argued for a return to deterministic physics, which he thought Einstein wanted.

Twelve years later, John Bell developed a theorem to distinguish between standard quantum mechanics, including Schrödinger's entanglement, and what Bell thought was Einstein's idea of a realistic physics and Bohm's determinism.

A few young physicists hoping for a new foundation for quantum mechanics set out to test Bell's theorem experimentally, motivated by the chance their work would invalidate quantum mechanics.

Instead, they found the predictions of quantum mechanics were confirmed, including Einstein's concern that widely separated events could simultaneously acquire new properties.

A pair of entangled particles is now the basis for what is called a "qubit," the elementary piece of data in quantum computing. These two particles are called an "EPR pair," after Einstein, or they are said to be in a "Bell state," after John Bell.

And so Einstein's insight and imagination, even when wrong, continue to this day to produce new science and technology.