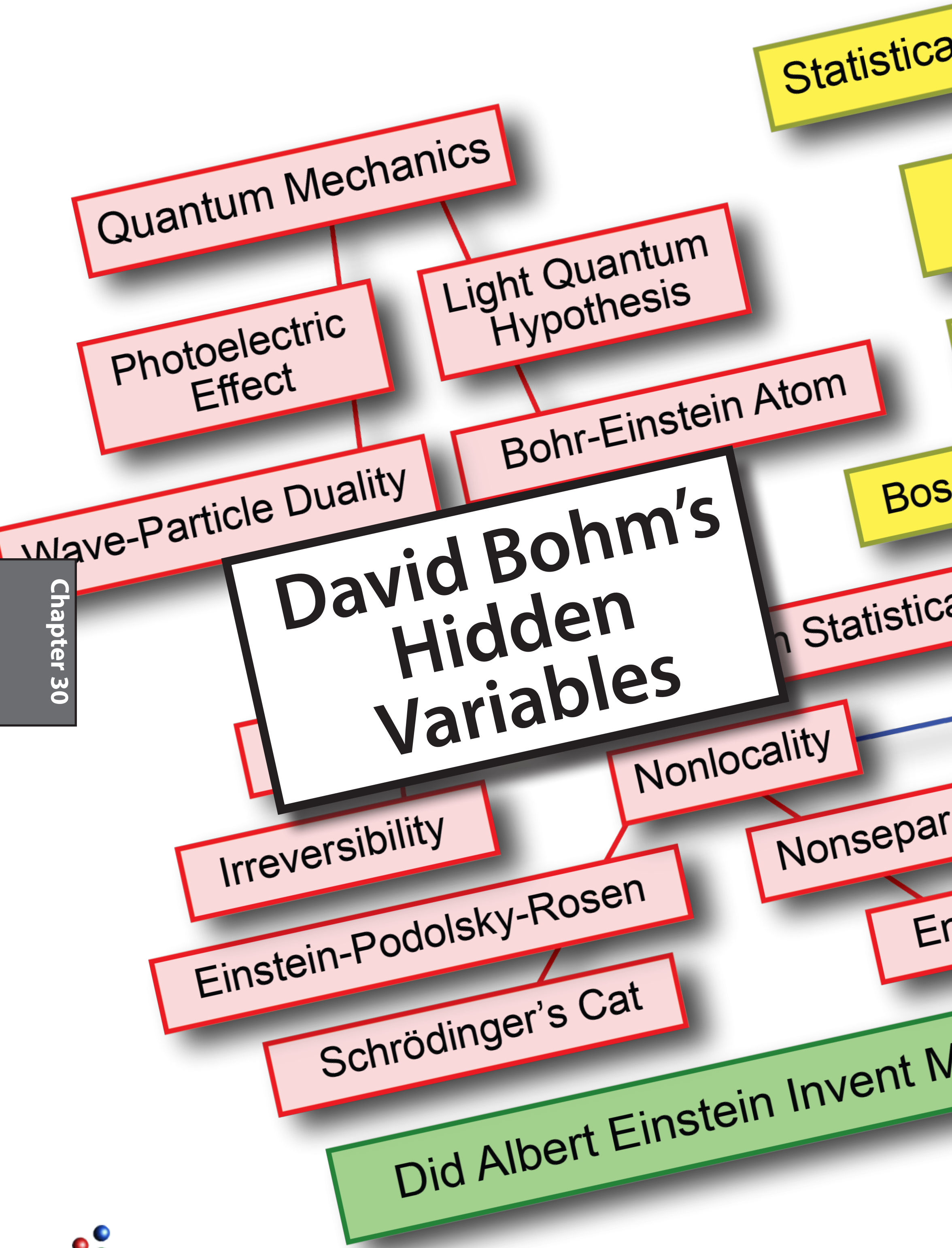
Chapter 30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David Bohm's Hidden Variables

David Bohm is perhaps best known for new experimental methods to test Einstein's suggestion of "additional variables" that would explain the EPR paradox by providing the information needed at the distant "entangled" particle, so it can coordinate its properties perfectly with the "local" particle. Bohm proposed the information would be transmitted by a new vector or "quantum" potential that travels faster than the speed of light.

Bohm wrote in 1952,

> The usual interpretation of the quantum theory is based on an assumption having very far-reaching implications, viz., that the physical state of an individual system is completely specified by a wave function that determines only the probabilities of actual results that can be obtained in a statistical ensemble of similar experiments. This assumption has been the object of severe criticisms, notably on the part of Einstein, who has always believed that, even at the quantum level, there must exist precisely definable elements or dynamical variables determining (as in classical physics) the actual behavior of each individual system, and not merely its probable behavior. Since these elements or variables are not now included in the quantum theory and have not yet been detected experimentally, Einstein has always regarded the present form of the quantum theory as incomplete, although he admits its internal consistency. [1]

Bohm's new supraluminal signaling would communicate extra variables he called "hidden" that would "complete" quantum mechanics, restoring the determinism of classical physics that Bohm mistakenly thought Einstein was looking for.

Five years later, Bohm and his Israeli student Yakir Aharonov reformulated the original EPR argument in terms of electron spin. They said experimental tests with continuous variables are much more difficult than tests with discrete quantities, such as the spin of electrons or polarization of photons. They wrote:

1 Bohm 1952, p.166

> We consider a molecule of total spin zero consisting of two atoms, each of spin one-half. The wave function of the system is therefore
> $\psi = (1/\sqrt{2}) [\psi+ (1) \psi- (2) - \psi- (1) \psi+ (2)]$
> where $\psi+ (1)$ refers to the wave function of the atomic state in which one particle (A) has spin $+\hbar/2$, etc. The two atoms are then separated by a method that does not influence the total spin. After they have separated enough so that they cease to interact, any desired component of the spin of the first particle (A) is measured. Then, because the total spin is still zero, it can immediately be concluded that the same component of the spin of the other particle (B) is opposite to that of A. [2]

Einstein may have encouraged his Princeton colleague Bohm to develop hidden variables to "complete" quantum mechanics and possibly restore determinism. Einstein had heartily approved of Bohm's textbook and was initially supportive of Bohm's new mechanics. Einstein thought Bohm was young enough and smart enough to produce the mathematical arguments that the older generation of "determinist" physicists like Erwin Schrödinger, Max Planck, and others had not been able to accomplish.

But when Bohm finished the work, based on Louis de Broglie's 1923 "pilot-wave" idea (which Einstein had supported), Einstein rejected it, as he always had rejected nonlocality in the form of instantaneous "action-at-a-distance." Bohm's work was simply inconsistent with Einstein 's theory of relativity. It still involved the "impossible" simultaneity of events in a spacelike separation.

No "Hidden Variables," but Hidden Constants?

There may be no hidden variables, local or nonlocal. But as we saw in the previous chapter, there are "hidden constants." Hidden in plain sight, they are the "constants of the motion," *conserved* quantities like energy, momentum, angular momentum, and spin, both electron and photon. Created indeterministically when the particles are *entangled*, they then move along with the *apparently* separating particles, conserving total spin zero.

In our application of Einstein's "objective reality," we assume the particles have continuous paths from the start of the experiment to the final measurement(s), although the limits of quantum measurement never allow us to "know" those paths.

2 Bohm and Aharonov, 1957, p. 1070

Conservation of momentum requires that positions where they finally do appear are equidistant from the origin, in order to conserve linear momentum. And every other conserved quantity, like angular momentum, electron or photon spin, as well as energy, also appear perfectly correlated at all *symmetric* positions.

But the particles appear to not have definite values of electron or photon spin *before* their first measurement by Alice or Bob. This state preparation created no new information about definite spin directions. It was not a "measurement" that leaves the particles in a definite state, as will Alice's measurement.

We call it a measurement of the zeroth kind.

Once particles are in a definite state of | + - > or | - + > it is the fundamental principle of conservation that governs the correlated outcome, not some hypothetical, faster than light, communication of information between the particles at the time of measurement.

Einstein's "objective reality" means that conservation laws hold at every position along the path, from the first measurement by Alice or Bob to their second measurement. Just because we cannot measure positions and paths does not mean that they don't exist.

The hidden constants of the motion include electron spins, which were suggested by Bohm as the best test for the hidden variables needed to support nonseparability and entanglement. The two particles conserve the same opposing spins up to the time of their measurement by Alice or Bob.

Unfortunately, hidden constants are not able to explain the "simultaneous" assignments of the spin components. Although Einstein never considered two opposing spins that conserve total spin zero, his thinking applies perfectly. And Alice's measurement direction corresponding exactly to Bob's is one more case of what Einstein saw first in 1905- his "impossible" simultaneity.

Bohmian Mechanics

Bohm is also well known for his "Bohmian Mechanics," a formulation of non-relativistic quantum mechanics that emphasizes the motion of particles and promises to restore causality to physics. It is a deterministic theory, one of several "interpretations" that are today's most popular alternatives to the Copenhagen Interpretation.

By emphasizing the motion of particles, Bohmian mechanics de-emphasizes the wave function Ψ, limiting its role to *guiding* the motion of the particles, in comparison to competing interpretations that deny the existence of particles altogether.

Bohmian mechanics includes a mechanism whereby physical effects can move faster than light, providing an explanation for Einstein's *nonlocality*. But as we saw in the last chapter, Einstein's "objective reality " provides a simpler solution that removes any conflict between relativity and quantum mechanics.

It's a surprise Einstein did not agree with Bohm, because Bohmian mechanics describes particles as moving along continuous paths, just as we visualize for Einstein's "objective reality." In the famous two-slit experiment, Bohm's particles always move through just one slit, even as the guiding wave function moves through both slits when both are open.

> we must use the same wave function as is used in the usual interpretation... We do not in practice, however, control the initial location of the particle, so that although it goes through a definite slit, we cannot predict which slit this will be. [3]

The Bohmian mechanics solution involves three simple steps:

First, close slit 1 and open slit 2. The particle goes through slit 2.
It arrives at x on the plate with probability $|\psi_2(x)|^2$,
where ψ_2 is the wave function which passed through slit 2.
Second, close slit 2 and open 1. The particle goes through slit 1.
It arrives at x on the plate with probability $|\psi_1(x)|^2$,
where ψ_1 is the wave function which passed through slit 1.
Third, open both slits. The particle goes through slit 1 or slit 2.
It arrives at x with probability $|\psi_1(x)+\psi_2(x)|^2$.
Now observe that in general, $|\psi_1(x)+\psi_2(x)|^2$ =
$|\psi_1(x)+\psi_2(x)|^2 = |\psi_1(x)|^2+|\psi_2(x)|^2 + 2R\psi^*_1(x)\,\psi_2(x)$.
The last term comes from the *interference* of the wave packets ψ_1 and ψ_2 which passed through slit 1 and slit 2.
The probabilities of finding particles when both slits are open are different from the sum of slit 1 open and slit 2 open separately.
The wave function determines the probabilities of finding particles, just as Einstein first proposed. [4]

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3 Bohm 1952, p.174
4 Dürr and Teufel, 2009, p.9

This reduces Richard Feynman's "one" mystery. We need not worry as he did about how a particle can go through both slits. But there remains the deeper mystery, how an abstract probabilities function (mere information) can influence the motions of the particles to produce the interference patterns. A wave in one place influencing the particle in another is "impossible" simultaneity.

Bohm's explanation of the two-slit experiment is completely compatible with Einstein's "objective reality." It does not solve the "deep mystery" of how the wave function "guides" the particles.

Irreversibility

In his excellent 1951 textbook, *Quantum Theory*, Bohm described the necessity for irreversibility in any measurement. Bohm followed John von Neumann's measurement theory in which recorded data is *irreversible*. A measurement has only been made when new information has come into the world and adequate entropy has been carried away to ensure the stability of the new information, long enough for it to be observed by a "conscious" observer.

> From the previous work it follows that a measurement process is irreversible in the sense that, after it has occurred, re-establishment of definite phase relations between the eigenfunctions of the measured variable is overwhelmingly unlikely. This irreversibility greatly resembles that which appears in thermodynamic processes, where a decrease of entropy is also an overwhelmingly unlikely possibility...
>
> Because the irreversible behavior of the measuring apparatus is essential for the destruction of definite phase relations and because, in turn, the destruction of definite phase relations is essential for the consistency of the quantum theory as a whole, it follows that thermodynamic irreversibility enters into the quantum theory in an integral way. [5]

But Bohmians today have a different view on irreversibility. As Dürr and Teuful describe it in their book, *Bohmian Mechanics*,

> The second law of thermodynamics captures irreversibility, and at the same time points towards the problem of irreversibility, which is to justify the special atypical initial conditions on which, according to Boltzmann, the second law is based... What is the physics behind the selection? We do not know. That ignorance of ours deserves to be called an open problem: the problem of irreversibility. [6]

5 Bohm, 1951, p.168

6 Dürr and Teufel, 2009, p.90. See our chapter 12.