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QBism AND LOCALITY IN QUANTUM MECHANICS FREE

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LETTERS TO THE EDITOR

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QBISM AND LOCALITY IN QUANTUM MECHANICS

Felix Bloch recounted that after Erwin Schrödinger introduced his wave function ψ, a verse circulated among his fellow students:

> Erwin with his psi can do
>
> Calculations quite a few.
>
> But one thing has not been seen:
>
> Just what does ψ really mean?[1]

According to Fuchs *et al.*,[2] the question regarding the meaning of ψ, which was raised shortly after the formulation of quantum mechanics, has remained unsolved. Originally, Schrödinger had proposed that $|\psi(x,t)|^2$ represented the charge density of the electron at time t in an interval between x and $x+dx$, but he soon realized that this interpretation ran into difficulties even for a free electron, because his equation for ψ implied that ψ would spread as a function of time.[3] But experimentally, it was well known that the electron remains localized like a point particle. Shortly afterwards, Max Born introduced the interpretation that $|\psi(x,t)|^2$ is the *probability* density for an electron to be found at time t in this interval.[4,5] In his own words, "the motion of particles follows the laws of probability, but the probability itself spreads in harmony with causal laws," and in a footnote he clarified his statement with the remark that "the knowledge of a state at all points in one moment, determines the state at all times."[5] By probability, it is important to emphasize here that Born meant the *frequency* of different outcomes predicted by $|\psi|^2$, after a given experiment is repeated multiple times under identical initial conditions. These conditions, and the various possible final outcomes are experimentally established by measurement devices that can permanently record such events by a macroscopic and time irreversible process. Virtually, all experiments in quantum mechanics have these features, whether the measuring apparatus consists of an ancient Geiger counter or a modern detector. The observer's main role is to design and build the devices required for a given experiment, to calculate the frequency or probability for all possible outcomes according to quantum mechanics, encapsulated in ψ, and to publish the results. Up to date, experiments in the micro-world have always confirmed Born's frequency interpretation of $|\psi|^2$.

By taking a *subjective* or Bayesian view of probabiltiy, the QBist interpretation of quantum mechanics, described in the article by Fuchs *et al.*, effectively denies that the outcome of experiments are described by permanent records, independently of the views of any particular observer or so-called "agent." Although Fuchs *et al.* agree that quantum states determine probabilities through the Born rule, they assert without any justification that, "since probabilities are the personal judgements of an agent, it follows that a quantum state assignment is also a personal judgment of the agent assigning that state" (p. 749). But for any experiment these agents calculate the same values for ψ, and therefore they all obtain the same probability $|\psi|^2$ to observe the possible outcomes of their experiment. In their article, Fuchs *et al.* do not provide a single experiment that falsifies this conventional view of quantum mechanics, proposing, instead, their QBism interpretation of quantum mechanics without providing a single experiment that validates it.

For an example, consider the eponymous double-slit experiment discussed in all elementary textbooks on quantum mechanics. At sufficiently low intensity, a light beam containing only a few photons impinging on the slit with a photographic screen behind it records the individual impacts of these photons. At first, these photons appear randomly scattered on this screen but after a large number of them are recorded, a pattern forms corresponding to the well known interference pattern that forms on the screen when a high intensity light beam is transmitted through the slits. It has been demonstrated in numerous experiments that this interference pattern corresponds precisely to the frequency or probability distribution evaluated according to $|\psi|^2$ that individual photons land on a given spot on the screen.

Regarding the question addressed by Fuchs *et al.* on whether quantum mechanics is nonlocal, consider the correlation between the spin states of two electrons with total spin angular momentum zero. This is the main spin component in the ground state of the helium atom, and there has never been any issue about locality concerning this correlation, because the two electrons are confined spatially to the domain of the atom. Now suppose that these two electrons are ionized simultaneously without affecting their total spin state, and the two electron move apart. Then quantum mechanics predicts that in the absence of any new interaction or entanglement with other particles (e.g., the environment) these correlations remain the same, even after these electrons are separated by a large distance. What would be "spooky," using Einstein's terminology, is that the initial two-electron spin correlation would change under these conditions. Hence, contrary to the claim of Fuch's *et al.* (p. 751), quantum mechanics does assign correlations to space-like separated events. Unlike in classical mechanics, however, the observed spin state of an electron depends also on the measuring device, which can be altered during the time that these electrons travel to reach these devices in a correlation experiment, leading, from the viewpoint of *reality* in classical physics, to an *apparent* non-locality. Correlated events can be recorded by detectors at space-like separations, and afterwards sent to a single "agent", as it is readily done in practice. Hence, the question of locality is not resolved by fiat as claimed by Fuchs *et al.* in their QBist interpretation of quantum mechanics.

Fuchs *et al.* conclude that: "…quantum mechanics itself does not deal directly with the objective world; it deals with the experiences of that objective world that belong to whatever particular agent is making use of the quantum theory" (p. 750). But in his lengthy correspondence with Einstein, Born already had emphasized that in practice, classical mechanics also is a statistical theory, because the initial conditions and the final outcome are never know with absolute precision.[6] In particular, in systems obeying chaotic dynamics, sensitivity to initial conditions implies that the outcome can be completely random. The essential difference in quantum mechanics, however, is that the precision of initial conditions is limited by Heisenberg's uncertainty principle $\Delta p\Delta x \geq \hbar/2$. Hence, contrary to Fuchs *et al*, quantum theory deals with the objective world as directly as does classical mechanics.

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[1] F. Bloch, "Reminiscenses of Heisenberg and the early days of quantum mechanics," Phys. Today **29**(12), 23–27 (1976).

[2] C. A. Fuchs, N. D. Mermin, and R. Schack, "An Introduction to QBism with an application to the locality of quantum mechanics," Am. J. Phys. **82**(8), 749–754 (2014).

[3] K. Przibrtam, *Letters on Wave Mechanics* (Philosophical Library, NY, 1967), p. 59. In a letter to Lorentz on June 6, 1926, Schrodinger wrote: "Would you consider it a very weighty objection against the theory if it were to turn out that the electron is incapable of existing in a completely field-free space?"

[4] M. Born, "Zur Quantenmechanik der Stossvorgänge," Z. Phys. **37**, 863–865 (1926).

[5] M. Born, "Quantummechanik der Stossvorgänge," Z. Phys. **38**, 803–827 (1926).

[6] M. Born, "The statistical interpretation of quantum mechanics," Nobel Lecture, December 11, 1954, from *Nobel Lectures, Physics, 1942-1962* (Elsevier Publishing Company, Amsterdam, 1964), pp. 256–267.

REPLY TO NAUENBERG

Although the meaning of the quantum state ("ψ") seems evident to Michael Nauenberg, among the physicists and philosophers interested in quantum foundations, there continues to be broad and irreconcilable disagreement even after 90 years. Can these 90 years of widespread confusion have something to do with almost all physicists taking for granted the frequentist interpretation of probability? It seems a possibility worth considering.

The subjective view of probability, dating back to Laplace, and eloquently advocated by de Finetti, Savage, Jeffrey, and many others, is introduced on our first page. QBism explores what such an understanding of probability implies for the interpretation of quantum mechanics. Our assertion ("without any justification") further along the page, beginning "since probabilities are the personal judgments of an agent…," refers back to the *premise* of subjective probability, whose implications we are about to examine.

An immediate consequence is that the quantum state an agent assigns to a system depends on what the agent believes about that system. This is not unique to QBism. That different agents can assign different states is the point of Wigner's famous parable about his friend. The probabilities determined by the Born rule are contingent on the state assignment, whether one understands those probabilities from a subjectivist or frequentist perspective. Any experiment that validates or invalidates the standard link between the Born rule and the state assignment for a frequentist does so for a subjectivist too.

QBism is not about the validity of quantum mechanics, but about how to understand the basic concepts that appear in the theory: states, probabilities, measurements, and outcomes. Is the state of a system an objective fact about that system (as Nauenberg seems to believe) or is it a judgment made by a particular agent on the basis of her prior experience of that system (the QBist view)? Is the outcome of a measurement a permanent record of an experiment made "by a macroscopic and time irreversible process," or is it the personal experience induced in an agent by the response of her external world to any action she takes upon it?

Frequencies are indeed ubiquitous in physics. But the subjective theory of probability distinguishes between frequencies and probabilities. Frequencies are data; probabilities are personal degrees of belief. Frequencies can be assigned probabilities. And probabilities can be refined in the light of subsequently measured frequencies. A famous theorem of de Finetti relates the two.

Nauenberg misses a central point of QBism in his criticism of our discussion of nonlocality. Events are deductions an agent makes to account for her experience. The correlations each agent extracts from quantum mechanics are not between disembodied "events," but between the experiences (outcomes of her actions on the world) from which she constructs such events.

Nauenberg concludes that "Contrary to Fuchs *et al.*, quantum theory deals with the objective world as directly as does classical mechanics." Setting aside our doubts about his "essential difference" between classical and quantum mechanics, we only remark that the QBist understanding of science applies to classical as well as quantum physics. Unlike QBism, CBism is not needed to resolve a scandalous incoherence at the foundations of the subject, although it does succeed in clearing up at least one long-standing puzzle.[1]

QBism is a genuinely novel way of thinking about the function of science. It raises subtle questions about the nature of science, the nature of human experience, and the relation of scientists to each other and to the world they are attempting to understand. We welcome criticism, but urge critics to pay some attention to what we are saying.

Christopher A. Fuchs
N. David Mermin
Rüdiger Schack

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[1] N. David Mermin, "QBism puts the scientist back into science," Nature **507**, 421–423 (2014).