Does the quantum wave function represent reality?

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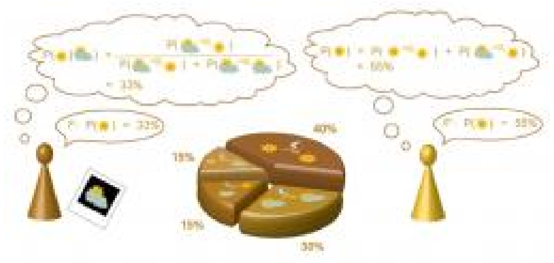

Two meteorologists predicting the chance of sunshine in a weather forecast. The meteorologist on the left has access to additional data (today's weather, which is partly cloudy), and consequently the two make different forecasts. Unlike a weather forecast, the quantum mechanical wave function gives a complete description of a quantum system's future behavior, and nature itself is inherently probabilistic at small scales. Image credit: Colbeck and Renner. ©2012 APS

(Phys.org) -- At the heart of quantum mechanics lies the wave function, a probability function used by physicists to understand the nanoscale world. Using the wave function, physicists can calculate a system's future behavior, but only with a certain probability. This inherently probabilistic nature of quantum theory differs from the certainty with which scientists can describe the classical world, leading to a nearly century-long debate on how to interpret the wave function: does it representative objective reality or merely the subjective knowledge of an observer? In a new paper, physicists Roger Colbeck of the Perimeter Institute in Waterloo, Ontario, and Renato Renner who is based at ETH

Zurich, Switzerland, have presented an argument strongly in favor of the objective reality of the wave function, which could lead to a better understanding of the fundamental meaning of quantum mechanics.

As Colbeck and Renner explain in their paper published in Physical Review Letters, there are two prominent interpretations of the wave function dating back to its origins in the 1920s. In one view, the wave function corresponds to an element of reality that objectively exists whether or not an observer is measuring it. In an alternative view, the wave function does not represent reality but instead represents an observer's subjective state of knowledge about some underlying reality. In 1927, Niels Bohr and others advocated this alternative view in the Copenhagen interpretation, in which the wave function is merely a mathematical probability that immediately assumes only one value when an observer measures the system, resulting in the wave function collapsing. Still others disagree with both views: in the '30s, Einstein, Podolsky, and Rosen argued that the wave function does not provide a complete physical description of reality and suggested that the entire theory of quantum mechanics is incomplete.

In their paper, Colbeck and Renner illustrate the difference between the two main views of the wave function's probabilistic nature with a simple example:

“Consider a meteorologist who gives a prediction about tomorrow’s weather (for example, that it will be sunny with probability 33% and cloudy with probability 67%),” they write. “We may assume that classical mechanics accurately describes the relevant processes, so that the weather depends deterministically on the initial conditions. The fact that the prediction is probabilistic then solely reflects a lack of knowledge on the part of the meteorologist on these conditions. In particular, the forecast is not an element of reality associated with the atmosphere but rather reflects the subjective knowledge of the forecaster; a second meteorologist with different knowledge may issue an alternative forecast. Moving to quantum mechanics, one may ask whether the wave function that we assign to a quantum system should be seen as a subjective object (analogous to the weather forecast) representing the knowledge an experimenter has about the system or whether the wave function is an element of reality of the system (analogous to the weather being sunny)."

Colbeck and Renner argue that, unlike a weather forecast, the wave function of a quantum system fully describes reality itself, not simply a physicist's lack of knowledge of reality. In their paper, they logically show that a quantum system's wave function is in one-to-one correspondence with its "elements of reality," i.e., the variables describing the system's behavior. The claim's only assumptions are that measurement settings can be freely chosen and that quantum theory gives the correct statistical predictions, both of which are usually implicit in physics research, as well as experimentally falsifiable.

"This [idea that the wave function represents reality] means that the wave function includes all information that is in principle available about the system, i.e., nothing is missing," Renner told *Phys.org*. "Nevertheless, even if we knew the wave function of a system (and therefore reality), its future behavior cannot be predicted with certainty. This means that there is inherent randomness in nature."

The scientists' claim relies on two seemingly opposite statements: First, any information contained in the system's complete list of elements of reality (the list is complete if it contains all possible predictions about the outcome of an experiment performed on the system) is already contained in the system's wave function. That is, the wave function includes all the elements of reality. The physicists formulated this statement in a paper last year. The second statement, which the physicists present here, is that a system's list of elements of reality includes its wave function. Taken together, the two statements imply that a system's wave function is in one-to-one correlation with its elements of reality. By showing that the wave function fully describes reality, the argument also implies that quantum mechanics is a complete theory.

“Take again the analogy to a meteorologist's work,” Renner said. “In this analogy, the data and models used by the meteorologist take the place of the wave function, and reality corresponds to the current weather. If there was a one-to-one correspondence between the meteorologist's data and the weather, we would be in a very favorable situation: the forecast would then be as accurate as it can possibly be, in the sense that there does not exist any information that has not been accounted for.

“Similarly, our result that there is a one-to-one correspondence between the wave function and the elements of reality means that, if we know a system's wave function then we are exactly in such a favorable situation: any information that there exists in nature and which could be relevant for predicting the behavior of a quantum mechanical system is represented one-to-one by the wave function. In this sense, the wave function is an optimal description of reality.”

This argument is not the only one made recently in favor of the wave function's complete representation of reality. In November 2011, a team of physicists from the UK (Matthew F. Pusey, Jonathan Barrett, and Terry Rudolph) argued that the subjective interpretation of the wave function contradicts plausible assumptions in quantum mechanics, such as that multiple systems can be prepared in a way so that their elements of reality are uncorrelated. While this approach is completely different from that of the current paper, the support from both papers may help point to an answer to one of the most long-standing debates in physics. In the future, Colbeck and Renner plan to work on making the assumptions less stringent than they already are.

“Our result is based on the assumption that an experimenter can, in principle, 'freely' choose which measurements he would like to carry out,” Renner said. “Hence, if one is ready to accept this assumption, our answer can be considered final. However, it is certainly legitimate to question this 'free choice' assumption (as well as the way 'free choice' is defined). We are currently working on a proof that the assumption can be replaced by a weaker one (which one might term 'partial freedom of choice').”

More information: Roger Colbeck and Renato Renner. “Is a System's Wave Function in One-to-One Correspondence with Its Elements of Reality?” *PRL* 108, 150402 (2012). DOI: 10.1103/PhysRevLett.108.150402