

The End of the Quantum Road?

Caslav Brukner ponders whether we've already found the ultimate theory of nature, without realizing it.

by BOB SWARUP

fq(x)
News

FQXi Awardee: Caslav Brukner

December 19, 2008

The philosopher Thomas Kuhn once described science as "a series of peaceful interludes punctuated by intellectually violent revolutions." To Kuhn, scientific progress was never a gradual accumulation of knowledge, but an endlessly repeating battle between established theories, such as Newtonian gravity, and younger upstarts, such as Einstein's general relativity.

Kuhn's influence has been profound—and it's left some wondering whether physicists will ever find the much sought after *Theory of Everything*, or whether every theory we create will inevitably be overthrown by a deeper more fundamental theory. Now, Caslav Brukner at the University of Vienna in Austria is asking precisely this question about quantum mechanics. The theory stands as our most accurate description of nature and is fundamental to our understanding of chemistry, the development of modern technology, and our insight into the origins of our universe. Given its enormous success, have we already found our ultimate theory, without realizing?

Theories-in-Waiting

The germ of Brukner's obsession with quantum theory goes back to his childhood. Born in Novi Sad, Serbia, in 1967, the young Brukner was always more interested in asking "why?" rather than "how?". He recalls being more excited about pondering the nature of time and what makes a watch tick, rather than taking it apart and putting it back together again. When his brother gave him a copy of *What's Going On in the Atomic Nucleus?* by Vladimir Paar for his thirteenth birthday, there was no turning back.

"Over the years, I have learned that quantum physics is weird and eludes every attempt to be understood within a classic-

al picture," says Brukner. "It is this weirdness that keeps my curiosity alive—like that of a child—and searching for answers to nature's puzzles."

Brukner is now searching for those answers with the help of a \$69,600 grant from the Foundational Questions Institute. At the heart of his research is the question of whether quantum physics provides the ultimate description of reality or whether there are other more fundamental theories lying in wait.

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Although quantum physics is extremely successful, some are troubled by its inherent randomness, which prevents us from predicting the behavior of quantum objects with certainty. According to standard interpretations, quantum objects do not have well-defined properties, until those properties are measured by an observer. Prior to observation, the particle exists in a *superposition* of many mutually exclusive states.

Some physicists find this quantum weirdness hard to stomach and hope to retrieve a classical concept of realism in which properties of the world about us exist regardless of whether or not we observe them. Einstein famously believed

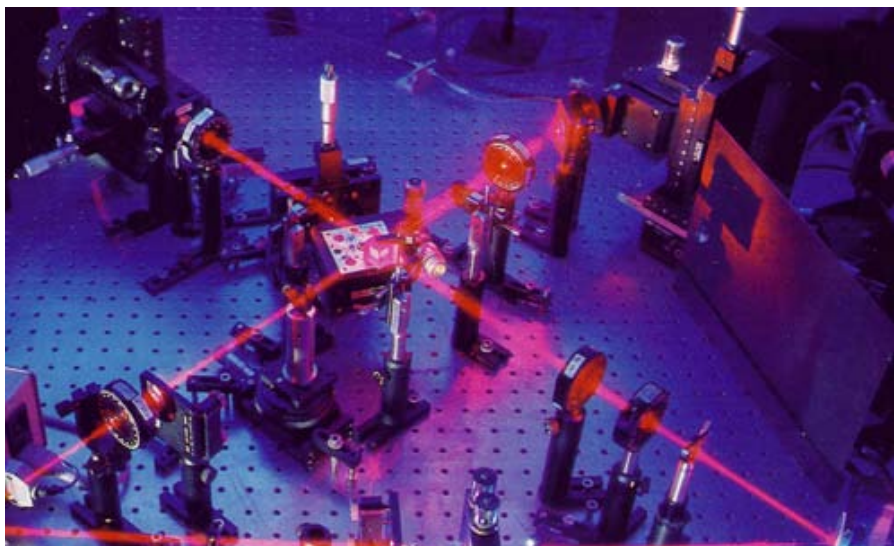
that particles contain extra properties, or "hidden variables," that serve as blueprints, determining the particles' behavior completely. If we knew what these hidden variables were, we could predict the fate of particles with certainty. But, asks Brukner, just how plausible is this concept of realism?

Quantum Overload

Brukner began to examine the features of quantum mechanics when he moved to Austria to pursue a Ph.D. at the Vienna University of Technology with Anton Zeilinger. Together, they realized that many weird quantum features could be explained by thinking about the *information* contained in a quantum system, just as computer scientists look at how



CASLAV BRUKNER
University of Vienna



QUANTUM CROSSROADS

Should we now accept that quantum mechanics is the final theory? Or keep looking for a deeper reality?

(Image: IQOQI, University of Vienna)

information is encoded, stored, and transferred in bits. According to their approach to quantum mechanics, the most elementary quantum system, the *qubit*, carries one bit of information.

Information theory, says Brukner, is the key to showing how plausible (or indeed implausible) it is that a deeper classical reality underlies quantum mechanics. It reveals that even within the simplest quantum system—an electron spin—classical realism is extremely resource demanding. That's because it would take infinitely many hidden variables to encode all the instructions needed to explain the results of all possible measurements of the electron's spin.

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Brukner argues that the total information that can be carried by an electron spin is finite. That means, by necessity, the system's answers to some questions will contain an element of randomness. Thus, Brukner and Zeilinger realized that the observed quantum behavior could be explained by nothing more mysterious than a lack of storage space for sufficient information.

Not So Spooky

Information theory can also be easily extended to naturally explain quantum entanglement—or “spooky action at a distance,” as it was dubbed by Einstein. Entangled particles are inextricably intertwined, so that measuring one of them immediately changes the state of the other. This strange phenomenon has been confirmed many times in the lab, in quantum optics experiments (pictured above).

Brukner and Zeilinger have analyzed how information can be stored in an entangled system. For example, it would take two bits of information to jointly encode entanglement into two particle spins, so that they are parallel to each other. Once those two bits have been exhausted, there is no more storage space to encode extra spin information into either of the two entangled particles individually, says Brukner. As a result of this lack of extra encoded information, measuring the spin of one of the pair must yield a random value, while the spin of its partner will be immediately fixed, regardless of distance.

Final Theory?

Brukner's work suggests that weird quantum properties such as superposition and randomness are here to stay—any theory that tries to get rid of them will fail to overcome this information limit. So, does that mean that quantum theory is the final

theory? Should we now stop hunting for anything deeper? Not necessarily.

“One of the most exciting questions for physicists is what is our next theory,” says Brukner. “The entire history of science has taught us accepted scientific theories are superseded by new ones, of which the old are special cases. It is therefore hard to believe that quantum theory is our final theory.”

Although most proposed alternatives to standard quantum mechanics have steadily fallen by the wayside, Brukner believes that this is because they all tried—mathematically and conceptually—to save some part of the pre-quantum concepts of classical physics. Brukner, however, wants to study alternatives that preserve the seemingly bizarre properties of quantum mechanics. “I want to investigate those theories, which, like quantum theory, are intrinsically probabilistic, allow superposition and entanglement, but may still differ [from quantum theory].”

Brukner is a very deep thinker, who believes in fundamental connections between physics and information.

- Vlatko Vedral

“Approaches to quantum theory where information is a basic concept and plays a crucial role are seemingly now in a revival period,” says Thomas Durt, a quantum physicist at Vrije University Brussels, in Belgium. Durt believes new approaches are good because they lead to new insights. However, he adds that physicists are often less receptive to attempts to reconstruct working physical theories to explain observed facts.

Vlatko Vedral, a quantum physicist at the University of Leeds, UK, likes Brukner's attempts to derive theories beyond quantum mechanics. “Brukner is a very deep thinker, who believes in fundamental connections between physics and information,” says Vedral. “Herein lies the hope to go beyond speculation and arrive at some experimentally testable predictions, which is the main goal of physics and underpins its wonderful power to comprehend the world.”