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PHYSICS FORUM

The interpretation of quantum mechanics: from disagreement to consensus?

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Quantum theory is a phenomenally successful cornerstone of physics. But a recent poll among quantum physicists shows that there is still little agreement on what the theory tells us about physical reality. Yet precious bits of consensus are emerging.

As always, Albert Einstein was ahead of his time. Quantum theory was still in its infancy, its formalism a mere sketch, and its implications only beginning to be realized. Yet Einstein, in 1917, already spotted what would trouble him throughout his lifetime. He concluded that the nascent theory, which he had helped initiate, seemed to leave "time and direction of elementary processes," such as the spontaneous emission of radiation from a molecule, "to chance" [1]. Einstein's conclusion was visionary. It was also incredibly bold, for it suggested a radical departure from the powerful, centuries-old deterministic and causal worldview of classical physics.

But Einstein also immediately expressed his discomfort with the idea of fundamental chance. In fact, his worries were just the seed of what would turn into one of the longest and most heated debates in the history of physics. What does quantum theory mean, and what does it tell us about the nature of reality? Some of the brightest minds in physics locked horns over these issues. Besides Einstein, there were Niels Bohr, Erwin Schrödinger, Werner Heisenberg, Pascual Jordan, Carl Friedrich von Weizsäcker, Wolfgang Pauli, and Richard Feynman, just to name a few.

Ask anyone today working on foundational questions in quantum theory and you are likely to hear that there is still no consensus on many of these questions—all the while, of course, everybody seems to be in perfect agreement on how to apply the quantum formalism when it comes to making experimental predictions. Remarkably, there has never been any serious attempt to find out what the current opinions of the community really are and how they may be correlated. We jumped on the opportunity and polled 33 participants at a 2011 conference on "Quantum Physics and the Nature of Reality" (Fig. 1) [2]. (We hasten to add that our poll is to be understood as merely a snapshot and certainly cannot claim to be representative.) As soon as we had collected the questionnaires, the respondents eagerly asked to hear the results. Evidently, we had not been the only curious party.

What did we find? The fundamental questions, it seems, still elicit radically different responses. Take the quantum state—represented by the wavefunction—as an illustration. The wavefunction is the

Figure 1 Participants at conference on Quantum Physics and the Nature of Reality (Picture: Charles Bennett).

central mathematical symbol of quantum mechanics. It allows us to make incredibly accurate predictions, be it in atomic, molecular, or solid-state physics. But how are we to interpret it? Is it itself a physical property, or does it merely represent our knowledge? Our poll revealed a tie between these two positions. And not only that: a third of respondents preferred a mix of both viewpoints—perhaps a sign that a more nuanced view, or even a synthesis of views, may be on the horizon. Only 3% of those polled thought that quantum states never refer to a single system but only to ensembles of systems. Perhaps this departure from the ensemble view—a view that, we suspect, remains more popular in the physics community at large—has to do with the fact that experiments with single quantum systems have become routine in today's quantum-information laboratories.

Sharp disagreement was in evidence on another deep question. Abraham Pais, Einstein's biographer, recalled that "during one walk Einstein suddenly stopped, turned to me and asked whether I really believed that the moon exists only when I look at it" [3]. Putting the issue differently, are the physical properties of objects well defined before we actually measure them? Half of the respondents in our poll believed that they sometimes were, while the other half said that they never were. These two positions correspond to radically different ways of understanding the function of measurement: either as simply ascertaining—at least sometimes—of what is already there, or as an act of genuine creation.

The role of measurement is also at the heart of another perennial favorite of foundational discussions, the measurement problem. The measurement problem highlights a curious fact about quantum theory: while the act of measurement assumes a fundamental role, it is not described—not without interpretive contortions, anyway—by the dynamical law of quantum theory, the Schrödinger equation. For decades, the measurement problem was seen by many as the main stumbling block for quantum theory, sparking a storm of rivaling attempts to deal with this perceived issue. Today, the waters seem to have calmed and attention shifted elsewhere, as only less than a fourth of respondents consider the measurement problem "a severe difficulty threatening quantum mechanics."

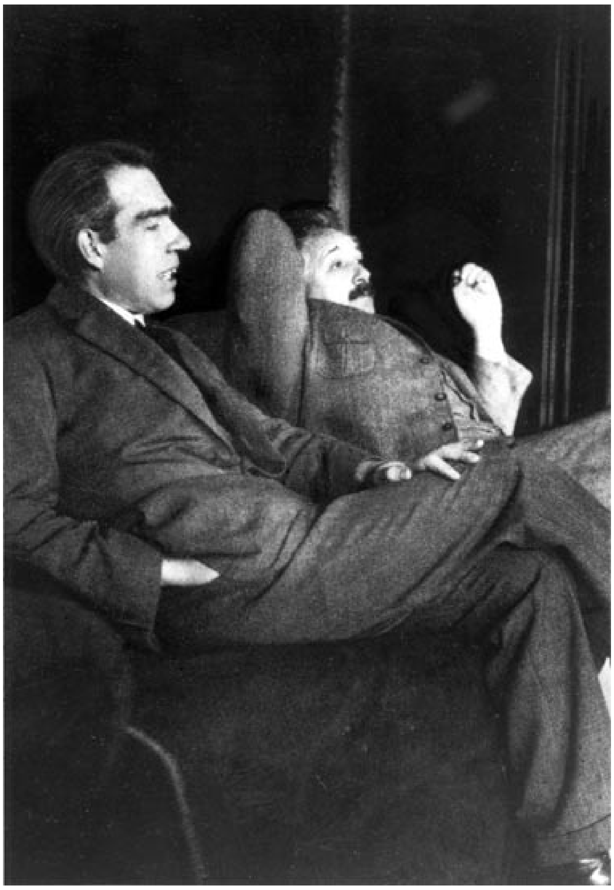

Figure 2 Niels Bohr (left) and Albert Einstein (right) in 1925. While Einstein wanted quantum mechanics to answer what nature is, Bohr insisted that the theory primarily refers to what can be said about nature and only indirectly to what it is. The community is still far from a consensus on this issue (Picture file in public domain).

Changing attitudes are also evident when it comes to the issue of chance Einstein had brought to light in 1917. Today, the question of the randomness of quantum events no longer seems to be all that contentious. Most of our respondents accepted randomness as irreducible or a fundamental concept in nature (or both). Less than one-tenth of respondents thought that quantum randomness was merely apparent rather than fundamental, and no one believed in a hidden determinism governing quantum events. We wish we could hear Einstein's opinion today.

Why have attitudes and priorities changed? It's hard to say, but we think there may be several driving forces. The rapid ascent of quantum information science has not only led to applications such as secure cryptography and the promise of lightning-fast quantum computers, but has also shed new light on foundational problems and handed us new tools for addressing them. Our poll shows that these tools are considered a welcome addition, with three-fourths seeing quantum information as a breath of fresh air for foundational investigations.

There is also optimism about the future technological development of quantum information, with more than 75% of respondents expecting a working and useful quantum computer to be realized within the next fifty years. Such optimism might be rooted in the astonishing experimental progress we have witnessed over the past decades, another driving force behind changing attitudes. We are now at stage where almost perfect experimental control of single quantum systems has been achieved. The 2012 Nobel Prize in physics was awarded for just such experiments. This has put at our fingertips the ability to actually carry out the thought experiments—or approximations thereof, at any rate—that the founders of quantum theory had dreamed up.

Take Schrödinger's cat. In 1935, Schrödinger wanted to illustrate what seemed to him an absurd prediction of the new theory: that the strange quantum superpositions of the atomic world can be amplified to everyday objects. Schrödinger's object of choice was a cat in a specifically prepared box. Quantum theory then suggested that the state of the cat should become transformed into a bizarre quantum superposition of being simultaneously alive and dead. But what Schrödinger had intended as a "burlesque" [4] thought experiment is now approaching experimental reality. Over the last decades, researchers have become increasingly skilled in breeding small versions of Schrödinger's cat. While they don't involve actual cats, they do already involve large biological molecules.

Our respondents, it seems, were inspired by such developments. A solid two-thirds majority declared that they don't expect any fundamental limit in this enterprise of observing larger and larger objects in superpositions of macroscopically distinct states. No limit, then, for quantum theory—something that Bohr had already suggested when he, in some of his early thought experiments, considered apparatuses that included macroscopic parts behaving in quantum-mechanical ways.

There are other new trends. Why do people seem to be much more at ease with relativity theory than with quantum theory? For one, both special and general relativity theory are grounded in a few simple physical principles. By contrast, quantum theory is lacking such a foundation and is instead based on a rather abstract mathematical body. Today, several researchers are out to change this situation, trying to derive quantum theory from a small set of physical or information-theoretic principles. They hope that in this way, we will understand why we have this peculiar theory to begin with. A majority in our poll regarded such "reconstructions" of quantum theory as giving useful insights, indicating once more that any new tool that promises fresh insights is embraced with an open mind.

To be sure, many (albeit not all) of the questions we asked in the poll are interpretive questions. This means that unless we should find out some day that quantum theory is in fact not always valid—in which case we would have to rethink the whole game—experiments arguably can't play the role of the arbiter. Some physicists will conclude from this that we need not bother with such questions, and relegate them to philosophy. We think this is too quick. Many ideas in physics didn't come out of thin air, but came about when someone started looking at a problem with a certain philosophical disposition. In this sense, we may think of the plurality of views in quantum mechanics as productive. Every interpretation highlights some aspect of quantum theory, is particularly suited for explaining particular phenomena, and may inspire new technologies—such as the quantum computer—or even new physics.

What, then, does the future hold? Half of the respondents in our poll believe that in fifty years from now, we will probably still be coming together for conferences on the fundamental questions of quantum theory. But what kinds of questions will be on the agenda? Will we still be worrying about the same problems as today? Or will these problems have been solved—or found to be less relevant—and our focus shifted to new questions once again? Who knows. But the location of the conference where we conducted the poll may tell a story. It was the place of a monastery, and a central position in the battle between Catholics and Protestants during the seventeenth century. Many of the questions that were hotly debated back then are no longer of interest to many people today, and other, new questions have since taken center stage in our society. Maybe some of the battles over the interpretation of quantum theory will meet a similar fate.

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