Survey the foundations

It is easy to dismiss research into the foundations of quantum mechanics as irrelevant to physicists in other areas. Adopting this attitude misses opportunities to appreciate the richness of quantum mechanics.

Quantum physics is weird. This is one of the most widely held perceptions of physics, running through almost all popular reporting of the topic. When studying physics, we learn the axioms of quantum mechanics and how to apply these rules to understand the world around us. Eventually, phenomena such as wave–particle duality and the existence of quantum superpositions between multiple states become familiar.

There are, of course, some loose ends about how these axioms correspond to what we actually experience. Quantum systems can be in a superposition of states but when measured by a classical observer these are apparently collapsed to a classical outcome. However, the dynamics of a wavefunction collapse has never been observed and involves an uncomfortable division between the classical observers and the quantum systems they are measuring. Attempts to resolve unsolved problems like this are addressed by the field of quantum foundations, seeking to understand the physical meaning of quantum theory.

Discussions of such issues are often dismissed as irrelevant philosophical matters because they do not have immediate consequences for how most physicists use quantum mechanics. With the continued improvement in experimental capabilities, we may eventually reach a stage where observations are able to provide a resolution[1]. But, as with searches beyond the standard model in particle physics, there is no guarantee that experiments will find anything new in the near term. For the day-to-day user of quantum physics there seems to be little reason to worry about quantum foundations.

This is a pity. Even taking the axioms of quantum mechanics for granted, their full implications can still be difficult to interpret. Many important results in quantum foundations serve to rigorously identify and analyse features of the theory that are not immediately obvious.

One classic example is the developments that followed the Einstein–Podolsky–Rosen paradox[2,3]. The alleged paradox arises by considering a quantum particle that is in a superposition of two states. By the rules of quantum mechanics, a measurement of which state the system is in produces a probabilistic outcome. But the particle can at the same time be entangled with another particle located elsewhere such that the outcome of measuring one particle determines the state of the other. This change is instantaneous and so seems to violate the physical law that no information can travel faster than the speed of light.

One route out of this paradox could be an undetected, so-called hidden variable associated with both particles that underlies the correlated behaviour. However, John Stewart Bell proved[4] that such an approach cannot explain the quantum mechanical outcomes. Any theory that uses hidden variables still requires non-local physics.

Bell's work eliminated a class of theories explaining quantum behaviour. It did so by rigorously establishing that entangled quantum particles are non-locally correlated in a way that cannot be reproduced classically. This is a remarkable feature of quantum mechanics that has been exhaustively tested, providing perhaps the clearest experimental demonstration so far that quantum technologies can accomplish things that classical devices cannot. The correlations established by Bell's theorem are even potentially useful. There has been significant progress in developing quantum cryptographic protocols that detect the presence of entanglement to ensure there is no malicious interference[5].

Most physicists would acknowledge the historical case of Bell's theorem as an exceptional result in terms of its breadth of impact. On the other hand, modern quantum foundations research has a reputation for esoteric thought experiments and difficult jargon. Yet, physics is full of abstract models such as the Ising model of magnetism that can appear distant from reality but clearly elucidates key physical ideas. Imagining that human observers themselves can be in superpositions clarifies what a complete theory of wavefunction collapse would imply[6], while generalized theories that modify quantum mechanics establish what features are essential to produce what is observed experimentally[7].

It is notable that quantum foundations is a field where superficially simple thought experiments can make a significant impact. This is a wonderful feature, which can help make new ideas accessible to a broader audience. However, that does not mean that it is easy to make progress. Any forum that invites contributions on the topic of quantum mechanics is likely to receive a number of submissions from enthusiasts with little to no expertise in studying foundational questions.

Although a fresh view can invigorate any field, much of this work also manifests a disregard for the progress that has been made since quantum mechanics was established. The quantum foundations literature is the product of decades of careful thought about the issues involved in understanding and interpreting the physical world. As with any topic, a failure to constructively engage with existing work runs the risk of repeating earlier mistakes and misunderstandings.

Of course we do not mean to suggest that everyone should drop their research and bring themselves up to date with the finer details of interpretations of quantum mechanics. However, quantum physics does play a significant role in many physicists' day-to-day research. Rapid public and private investment into quantum technologies might mean the maxim "no one understands quantum mechanics" is a little less true than it used to be, at least in a practical sense. But it is still intellectually satisfying to reflect on the more subtle and 'weird' nature of quantum foundations. ❒

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