Why quantum mechanics defies physics

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Credit: University of Nottingham

The full, weird story of the quantum world is much too large for a single article, but the period from 1905, when Einstein first published his solution to the photoelectric puzzle, to the 1960s, when a complete, well-tested, rigorous, and insanely complicated quantum theory of the subatomic world finally emerged, is quite the story.

This quantum theory would come to provide, in its own way, its own complete and total revision of our understanding of light. In the quantum picture of the subatomic world, what we call the electromagnetic force is really the product of countless microscopic interactions, the work of indivisible photons, that interact in mysterious ways. As in, literally mysterious. The quantum framework provides no picture as to how subatomic interactions actually proceed. Rather, it merely gives us a mathematical toolset for calculating predictions. And so while we can only answer the question of how photons actually work with a beleaguered shrug, we are at least equipped with some predictive power, which helps assuage the pain of quantum incomprehensibility.

Doing the business of physics—that is, using mathematical models to make predictions to validate against experiment—is rather hard in quantum mechanics. And that's because of the simple fact that quantum rules are not normal rules, and that in the subatomic realm all bets are off.

Interactions and processes at the subatomic level are not ruled by the predictability and reliability of macroscopic processes. In the macroscopic world, everything makes sense (largely because we've evolved to make sense of the world we live in). I can toss a ball enough times to a child that their brain can quickly pick up on the reliable pattern: the ball leaves my hand, the ball follows an arcing path, the ball moves forward and eventually falls to the ground. Sure, there are variations based on speed and angle and wind, but the basic gist of a tossed ball is the same, every single time.

Not so in the quantum world, where perfect prediction is impossible and reliable statements are lacking. At subatomic scales, probabilities rule the day—it's impossible to say exactly what any given particle will do at any given moment. And this absence of predictability and reliability at first troubled and then disgusted Einstein, who would eventually leave the quantum world behind with nothing more than a regretful shake of his head at the misguided work of his colleagues. And so he continued his labors, attempting to find a unified approach to joining the two known forces of nature, electromagnetism and gravity, with an emphatically not quantum framework.

When two new forces were first proposed in the 1930s to explain the deep workings of atomic nuclei—the strong and weak nuclear forces, respectively—this did not deter Einstein. Once electromagnetism and gravity were successfully united, it would not take much additional effort to work in new forces of nature. Meanwhile, his quantum-leaning contemporaries took to the new forces with gusto, eventually folding them into the quantum worldview and framework.

By the end of Einstein's life, quantum mechanics could describe three forces of nature, while gravity stood alone, his general theory of relativity a monument to his intellect and creativity.

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