Researchers Limit Experimental Free Will to Fake Quantum Entanglement

Study exploring fundamental nature of reality could inform future quantum encryption protocols

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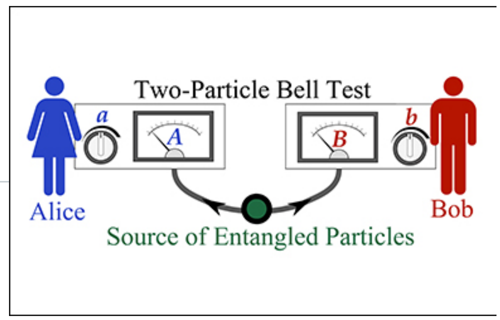
For entangled particles, "spooky" correlations recognized by Einstein persist no matter how far apart the particles are in space and time. Entanglement is thus amo the most fascinating features of quantum-mechanical systems, challenging common sense notions about how strongly the behavior of objects separated across vast distances can remain correlated through time. By following Einstein's assumptions about realism (each particle has a set of definite properties prior to measurement) and locality (information cannot travel faster than light), physicist John Bell set an upper limit to such correlations in "local realist" theories during th 1960s. Called "Bell's theorem," it distinguishes between quantum theory, which allows more correlation than the limit from Bell's inequality, and the more intuitive local realist theories.

Two experimenters, Alice and Bob (or alternatively, two randomizing devices), each choose (a,b) how to measure their half of a pair of entangled particles. If these choices were not really "free" choices, but instead were subtly correlated with hidden information in the past of the experiment, it would be possible for an alternative theory, distinct from quantum mechanics, to still explain the "spooky" correlations between measurement outcomes (A,B) seen in real entanglement experiments, such as the "cosmic Bell" tests where Friedman and colleagues addressed the freedom-of-choice loophole by randomly choosing measurement settings using ancient light from stars and quasars. Image by Andrew S. Friedman and Jason Gallicchio.



But, according to Andrew Friedman, a research scientist at the UC San Diego Center for Astrophysics and Space Sciences, Bell's original theorem also assumed that experimenters are completely free to select which measurements to perform on each of two entangled particles. If measurement selections were not independent of relevant "hidden variables" missing from quantum theory that might affect the objects' behavior, then the "freedom-of-choice" or "free will" loophole would open up.

To further explore the loophole, Friedman and his co-authors Alan Guth and David Kaiser, MIT; Michael J. W. Hall, Griffith University/Australian National University, a Jason Gallicchio, Harvey Mudd College, derived a new set of modified Bell inequalities that apply to cases in which either or both experimenters have only limited freedom to select measurements. They constructed local realist models that mimicked the predictions of quantum theory by yielding correlations exceeding Bell's original inequality. Their findings are shared in an article titled, "Relaxed Bell Inequalities with Arbitrary Measurement Dependence for Each Observer," published recently in "Physical Review A."

"Our theoretical results can help quantify how easy it would be to break certain quantum encryption schemes by exploiting the freedom-of-choice loophole," noted Friedman. "By messing with measurement choices in specific ways, future hackers could, in principle, fake genuine quantum entanglement with considerably less effort than exploiting some of the other more well known loopholes."

While the practical applications of entanglement are of key interest to many national and corporate players, Friedman acknowledged that he is even more intereste in how these heady, theoretical exercises might lend insight into the fundamental nature of reality.

"From entanglement tests that violate Bell's inequality, we know that at least one of Bell's assumptions can't be true in nature, but we don't know which one," he sai "Our new results show that it is at least logically possible for our world to still obey realism and locality, just as Einstein hoped, at the price of giving up a modest amount of experimental freedom."

Friedman explained that, regardless of hackers, if the world itself actually exploits the freedom-of-choice loophole, we will likely need a new theory that combines quantum mechanics and gravity to fully understand what this truly means about how our choices are constrained in subtle ways by the laws of nature.

"Perhaps when gravity is included, we will realize that it simply isn't possible for objects to be completely independent of one another, or for choices to be complete free of relevant events in the past."

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