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The Universe Made Me Do It? Testing "Free Will" With Distant Quasars

By **Andrew Friedman** on Wed, 19 Mar 2014

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Scientists usually assume we can freely choose what kinds of experiments to perform. After all, how could we ever hope to learn anything about the world without the free will to set up our laboratory tests in the first place? Still, there lurks a loophole in the heart of physics that might constrain this kind of freedom and allow some of the strangest features of quantum mechanics to be explained away by an underlying kind of conspiratorial coordination that pervades the entire cosmos.

Artist's conception of a quasar, a bright, young, galaxy powered by a voracious supermassive black hole. Courtesy ESO/M. Kornmesser

While a logical loophole in quantum theory may not be grounds for worrying you've unknowingly outsourced your apparent free will to the Matrix, this stuff actually keeps scientists and philosophers up at night. In fact, it motivated my colleagues —Jason Gallicchio at the University of Chicago and David Kaiser at MIT—and I to devise an experiment with the potential to close this so-called "free will" loophole once and for all, as much as the cosmos will permit. The trick, it turns out, is to use nearly the entire history of the universe.

The story of the "free will loophole" starts with the problem of quantum entanglement. Entanglement is a sort of link between particles that correlates their properties even at vast distances; it defies the logic of classical physics yet is fundamental to quantum mechanics. Here's one textbook way to create a pair of entangled photons. Start by sending a single photon through a special crystal that splits it into a pair of photons. Due to conservation of energy and momentum, the two new photons can have mutually perpendicular polarization directions, so one must be "horizontal" and the other "vertical." But which is which? Quantum mechanics can't tell us. In fact, according to standard quantum theory, the particles are in a superposition of both states, horizontal and vertical polarization, until the moment that one of them is measured. In that instant, both that photon and its entangled counterpart settle on a fixed polarization.

Imagine that the first photon's polarization is measured to be "horizontal." The other photon is now certain to have "vertical" polarization. But if the photons were too far apart to communicate with each other during the measurement, how did the second photon "know?" In other words, the choice of what to measure on one side of the experiment seems to instantaneously influence the outcome for later measurements on the other side, which could in principle be in another galaxy, far, far away. It is precisely this "non-local" feature of entanglement that Einstein dismissively described as "spooky action at a distance."

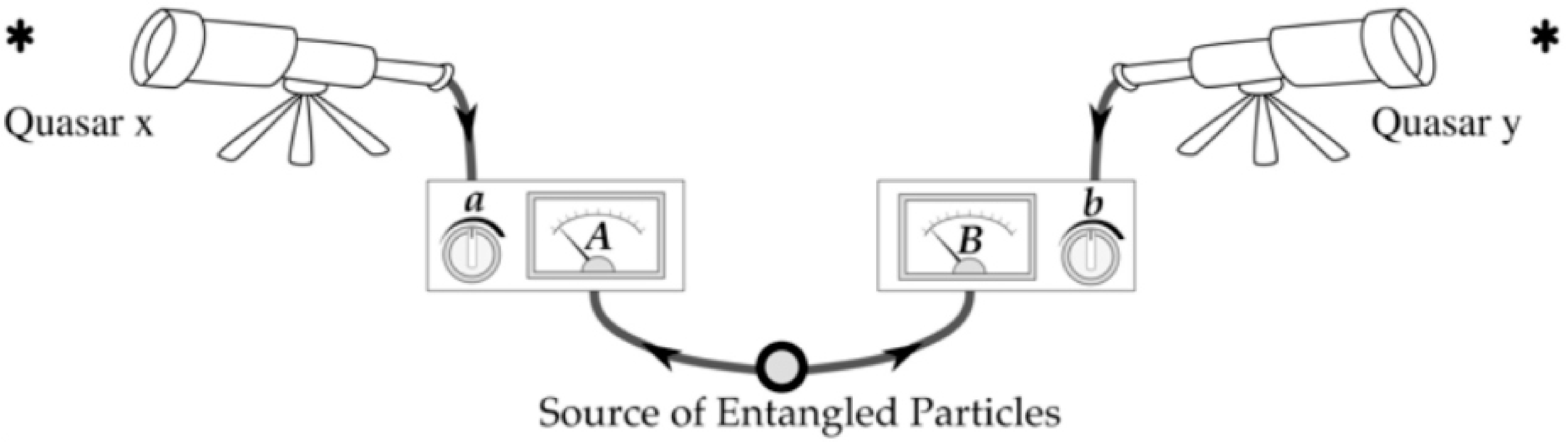
In a standard experimental setup, polarization-entangled photon pairs are sent to distant detectors that measure whether each photon passes through a polarizing filter. According to quantum theory, the orientation angle of the filter on each side—say 45 or 135 degrees—tells us the probability that a horizontally or vertically polarized photon will make it through. Over many runs, each side registers what look like random outcomes for photons passing or being absorbed, but when the results are eventually compared, correlations pop up between the sequences of measurements that seem impossible to explain based on any local, common cause that affected both entangled photons.

Although we know this phenomenon cannot be used to send signals faster than the speed of light, we still don't know how to tell a consistent, local, causal story about what entanglement really means. Over the years, physicists have used this argument to claim that quantum mechanics is not capturing the whole story: There must be some other factor, some local "hidden variables," linking the states of the two particles. But fifty years ago, physicist John Bell formulated a mathematical theorem that seemed to rule out all local hidden variable theories on logical grounds. Entangled particle experiments have repeatedly confirmed the violation of the mathematical inequalities in Bell's theorem, exactly as quantum theory predicts. The usual interpretation of Bell's theorem is thus that quantum mechanics—and the spooky world that we live in—is fundamentally non-local. But this has left many folks uneasy, including Bell himself.

So physicists began examining the assumptions built in to Bell's proof. Along the way, they have identified a handful of logical loopholes that could allow alternative, non-quantum, explanations of entangled particle experiments — in essence, pulling the sheet off the spooky quantum ghost.

Previous experiments have already closed many of these loopholes. However, a particularly subtle loophole remains open: whether the settings of the detectors that measure the entangled particles could be correlated with any “hidden” information in their shared causal pasts. If events before the experiment could in principle have influenced both detector-setting choices, this could lead to a correlation whereby the settings were not, in fact, chosen “freely” and independently of the hidden variables, as is usually assumed. In fact, recent theoretical work has shown that this “free will” loophole is the most fragile of the major loopholes, in the sense that only a small correlation between the detector settings and any local hidden variables would be more than enough to mimic the predictions of quantum mechanics. If such hidden correlations were present, one interpretation is that the experimenters might not actually have complete “free will” to choose the experimental settings. While this “free will” loophole admittedly seems somewhat crazy, fully meriting the application of the word “conspiracy,” it remains an open logical possibility.

Amazing recent experiments by Anton Zeilinger and collaborators have begun to narrow this loophole, by using quantum random number generators to set the detectors and ruling out conspiratorial correlations during the experiment. But these experiments only rule out conspiracies set up less than a millisecond or so before the test began. Our group sought to improve on that by finding a way to rule out conspiracies over almost the entire history of the universe, all the way back to the Big Bang 14 billion years ago.



Schematic of our proposed “Cosmic Bell” experiment. A source sends entangled particles to two distant detectors. While the particles are in flight, light from distant quasars x and y is used to randomly choose the detector settings a and b on each side, which then measure experimental outcomes A and B. Many runs would be compared to confirm that the results always violate the Bell inequalities and are independent of the choices of which quasars to observe. Source: Gallicchio, Friedman, & Kaiser 2014

We can do this with the help some of the oldest light in the cosmos. Rather than letting the experimenters or even Earth-bound random number generators choose the crucial laboratory parameters, our idea is to let the *universe itself* decide how to set up our experiment. First, a source sends entangled particles to two distant detectors in the usual way. While the particles are in flight, we use light from two distant cosmic sources to randomly choose the settings (e.g. polarizing filter angles) for each of the two detectors, which then measure experimental outcomes A and B, as in the illustration above. This requires real-time observations of distant astronomical objects like quasars or patches of the cosmic microwave background that would allow us to turn the sky itself into a special kind of random number generator, based, for example, on the random arrival times of the cosmic photons.

By selecting sufficiently distant cosmic sources, we can be sure that they have never been in causal contact with each other, and that there hasn't been enough time in the history of the universe for third party hidden variables to have communicated with both quasars. Unlike our entangled laboratory particles, by design, the quasar photons are as un-entangled with each other as possible and their arrival times should also be as uncorrelated with each other as the universe will allow. While no experiment can rule out the most extreme cosmic conspiracies such as "superdeterminism" (although see here), we still argue that our "Cosmic Bell" setup would close the free will loophole more decisively than any experimental test thus far.

While our concept began as a thought experiment (and we soon discovered that others had arrived at the same basic idea independently) our work shows that such a test turns out to be surprisingly feasible in the real world. And thanks to the welcome enthusiasm of our experimentalist collaborators, it is likely to happen soon.

So what should we expect to see? The safe bet is on seeing the straightforward quantum predictions, further narrowing the free will loophole, and increasing our confidence in quantum theory. But in all fairness, no one has ever done a test like this, so who knows what we will find? After all, that's why we do the experiments! For example, we could see something not predicted by quantum mechanics, like a lack of Bell violation when using distant quasars, a dependence on which quasars we observed, or even a link to rival models of cosmic inflation or other theories of the very early universe. Seeing anything not predicted by quantum mechanics would necessarily be probing new physics, for example, a future theory of quantum gravity. From my perspective, any of these outcomes would be a win. Still, if there ever were a test where we would be least surprised to see something spookier than quantum mechanics—which might even let a Cosmic Bell experiment be turned around to test cosmology itself—it would be exactly when leveraging the entire history of universe to test fundamental physics.

Either way, while we don't think our experiment would impinge in any way on our everyday conception of free will, I certainly consider myself extremely lucky to be able to freely choose to think about such fun and exciting things for a living.

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Author's picks for further reading

arXiv: Testing Bell's Inequality with Cosmic Photons: Closing the Setting Independence Loophole
This paper, published in Physical Review Letters, describes the Cosmic Bell experiment.

arXiv: The shared causal pasts and futures of cosmological events
A previous paper, published in Physical Review D, calculates the theoretical cosmology conditions needed to choose pairs of cosmic sources with no shared causal pasts since the early universe.

arXiv: Violation of local realism with freedom of choice
This seminal paper, published in Proceedings of the National Academy of Sciences, USA, describes the Zeilinger group's state of the art experimental test of Bell's inequality where entangled photons were sent through open air a world record 144km between two observatories in the Canary Islands.

Dance of the Photons: From Einstein to Quantum Teleportation
Physicist Anton Zeilinger's 2010 popular science book describing he and his colleague's impressive experimental work performing fundamental tests of quantum mechanics.

Nature News: Cosmic light could close quantum-weirdness loophole
Zeeya Merali explains the "cosmic Bell" test for Nature News.

Quantum Non-Locality and Relativity: Metaphysical Intimations of Modern Physics
Philosopher of Science Tim Maudlin's comprehensive guide to the physics and philosophy of Bell's theorem, quantum non-locality, and its potential conflicts with relativity, first published in 1994.

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Andrew Friedman

Andrew Friedman is a recent National Science Foundation Science, Technology & Society postdoctoral fellow at the Massachusetts Institute of Technology and currently a Visiting Research Scientist at the MIT Center for Theoretical Physics. Before MIT, he received a Ph.D. in Astronomy and Astrophysics from Harvard University and a B.A. in Physics and Astrophysics from the University of California, Berkeley. He is currently working on several theoretical and observational cosmology projects, including devising fun experiments that leverage cosmology to help test fundamental physics. His research background is primarily in observational astronomy and cosmology, specifically cosmological studies of Gamma-Ray Bursts and infrared observations of Type Ia Supernovae which can be used to measure the expansion history of the universe, cosmic acceleration, and dark energy. He is very interested in projects at the intersection between astrophysics, cosmology, and the philosophy of science, and is excited to continue bringing some of these fascinating scientific questions to the public through science writing, art, animation, and other media.

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