© NewScientist

- Feature

14 November 2018

Einstein was wrong: Why ‘normal’ physics can’t explain reality

The most ambitious experiments yet show that the quantum weirdness Einstein famously hated rules the roost – not just here, but across the entire universe

Daniel Bear

By **Anil Ananthaswamy**

IT WAS Dominik Rauch’s birthday, and he was 2300 metres up a mountain in the Canary Islands when a freak winter storm nearly wrecked his PhD. It could have been worse. A few hundred metres away, his colleagues only just managed to scramble out as the wind picked up their aluminium-framed office container and slammed it against the dome of a nearby telescope, just above a steep drop.

“Nobody was hurt,” says Rauch. “We were pretty happy.” But the crystal they planned to use to prise out reality's secrets was broken beyond repair.

Their experiment atop the Roque de los Muchachos on the Spanish island of La Palma was just the latest and most ambitious of many that have probed quantum mechanics, the inscrutable theory that describes nature's most basic workings. With six telescopes, oodles of delicate optical equipment and the light emitted by galaxies billions of years ago, they aimed to test an assertion championed by Einstein: that the weirdness of quantum mechanics is just a cover for some deeper, hidden reality.

And test it not just for here and now, but for almost all time, and across virtually the entire observable universe. If any experiment could break quantum theory, this one could.

When quantum mechanics was formulated almost a century ago, it overturned two particularly cherished assumptions about the world's workings. First was realism. Unlike classical physics, which says the world exists independently of observers and observations, quantum theory strongly implies that reality does not exist, or at least cannot be meaningfully described, until it is observed.

The second problem was "non-locality". This stemmed from the phenomenon of entanglement – what Einstein termed "spooky action at a distance" – in which events in one region of space-time can seemingly instantaneously affect events elsewhere, even light years away. This goes against Einstein's relativity, in which no influence can travel faster than the speed of light.

For Einstein, the anti-realism and non-locality of quantum mechanics meant the theory wasn't complete. There had to be some concealed underlying physics that gave better explanations.

The arguments rumbled on even after Einstein died in 1955. In 1964, Northern Irish theorist John Bell finally gave experimentalists a way to pit Einstein's local realism against quantum mechanics and see which better explained things. To start, you produce pairs of quantum particles, such as photons, in such a way that from the viewpoint of quantum mechanics they are entangled. You then separate every photon from its companion in space, and independently measure a specific quantum property of each.

Most such tests look at polarisation, measured in one of two directions. In classical physics, you would expect there to be no correlation between outcomes of measurements on photons of a pair, beyond what you would get by random chance. In Bell's test, any theory that preserves both reality and locality would permit only a certain maximum amount of correlation. Quantum mechanics, meanwhile, being non-local, would allow the correlations to exceed this bound.

In the 1970s, the experiments were finally done – and the answer seemed clear. Bell's bound was busted. Quantum mechanics ruled.

But these early experiments still couldn't fully discount the possibility that a local-realistic theory was pulling the strings. For example, if the two people running the experiments – call them Alice and Bob – aren't far enough apart, a hidden influence travelling at anything up to light speed could cause Alice's measurement to influence Bob's, or vice versa.

losing the loopholes

Alongside this "locality loophole", there's also the fair sampling loophole: if the detectors that Alice and Bob use are, as is likely, inefficient and detect only a small fraction of the photons, something in their sample might skew the results towards a non-existent correlation. Then there's the freedom-of-choice loophole: a watertight implementation of Bell's test requires that Alice and Bob are absolutely free to choose their measurement settings independently of each other.

By 2015, a slew of experiments claimed to have plugged these loopholes, by separating Alice and Bob in space, using high-efficiency detectors, and employing separate, ultra-fast random number generators with which Alice and Bob determined the experimental settings. The results remained the same.

But in 2011, Michael Hall at the Australian National University in Canberra had already floated the idea that using random number generators might not be enough to close the freedom-of-choice loophole. If the random number generators and the photon source had interacted via a hidden mechanism any time in the past, that could have influenced the choice of measurement settings and maybe even the properties of the photons, creating the observed correlations. Hall's work eventually forced the experimentalists to think again. "I wanted to say to people: stop saying quantum mechanics is non-local as a matter of fact," he says.

But how could you exclude this possibility in an experiment? "There was a feeling at the time that the freedom-of-choice loophole was simply unaddressable," says Morgan Mitchell at the Institute of Photonic Sciences in Barcelona, Spain.

Mitchell and his colleagues came up with an innovative answer: they outsourced the choice of detector settings to people playing video games. In the "Big Bell Test", each gamer was required to rapidly generate a sequence of 0s and 1s, while a machine-learning algorithm tried to predict what they would do next. The more unpredictable their sequences were, the higher the gamers scored on the game. On 30 November 2016, about 100,000 players produced nearly 100 million random digits, which were piped to 13 experiments on five continents performing different variants of Bell's test.

As the Big Bell Test team revealed earlier this year, all the experiments, fed with the random digits over 12 hours, broke Bell's bound. "If we assume that humans have free will, then we have closed the freedom-of-choice loophole," says Mitchell.

That, however, is the kind of assumption that keeps philosophers awake at night.

And there was a way of avoiding it. Every event in space-time, such as Alice and Bob making a measurement, has a “past light cone”: a volume of space-time from which a hidden influence moving at the speed of light or slower, can have travelled to affect it. So what you needed to do was ensure the random events used to choose the measurement settings were from as far back in the past as possible, excluding such meddlings.

That’s where Andrew Friedman, Jason Gallicchio and David Kaiser had a brainwave. “We tried to outsource the random number generator to the universe itself, make the universe work for us,” says Kaiser, of the Massachussetts Institute of Technology.

The idea was simple, but radical. Alice and Bob could use telescopes to receive photons from distant astronomical objects, and exploit each photon’s colour to generate random digits for the measurement settings. For example, photons redder than some threshold wavelength could trigger a polarisation measurement in one direction, while bluer photons could trigger a measurement in the other. By using cosmological photons to determine the measurement settings, and demonstrating that the Bell bound was still broken, you could show that no hidden influence could have affected the detector settings in all the time the light was travelling towards Earth.

“The team outsourced the random number generation to the universe itself”

To do this, Kaiser and his colleagues teamed up with Rauch’s supervisor, Anton Zeilinger of the Institute for Quantum Optics and Quantum Information in Vienna, Austria. Their first experiment placed the source of entangled photons on the rooftop of the institute on Boltzmanngasse in the city, and Alice and Bob in two buildings with a clear line of sight to the source: Bob on the fifth floor of the University of Natural Resources and Life Sciences roughly north, about 1150 metres away, and Alice on the ninth floor of the Austrian National Bank some 550 metres in a southerly direction. “They print money in the basement there,” says team member Thomas Scheidl.

Each night, once darkness set in, the team used small telescopes to observe stars in opposite directions in the sky. The photons collected by these telescopes were piped through optical fibres to special mirrors that sent them one way if the photon’s wavelength was less than 700 nanometres, and another way otherwise, randomly generating 0s and 1s used to determine the measurement settings.

Like all others before it, the Vienna rooftop experiment broke Bell’s bound, showing that any hidden influence could not be at work now, or in the past 600 years or so, the time the starlight had taken to reach Earth.

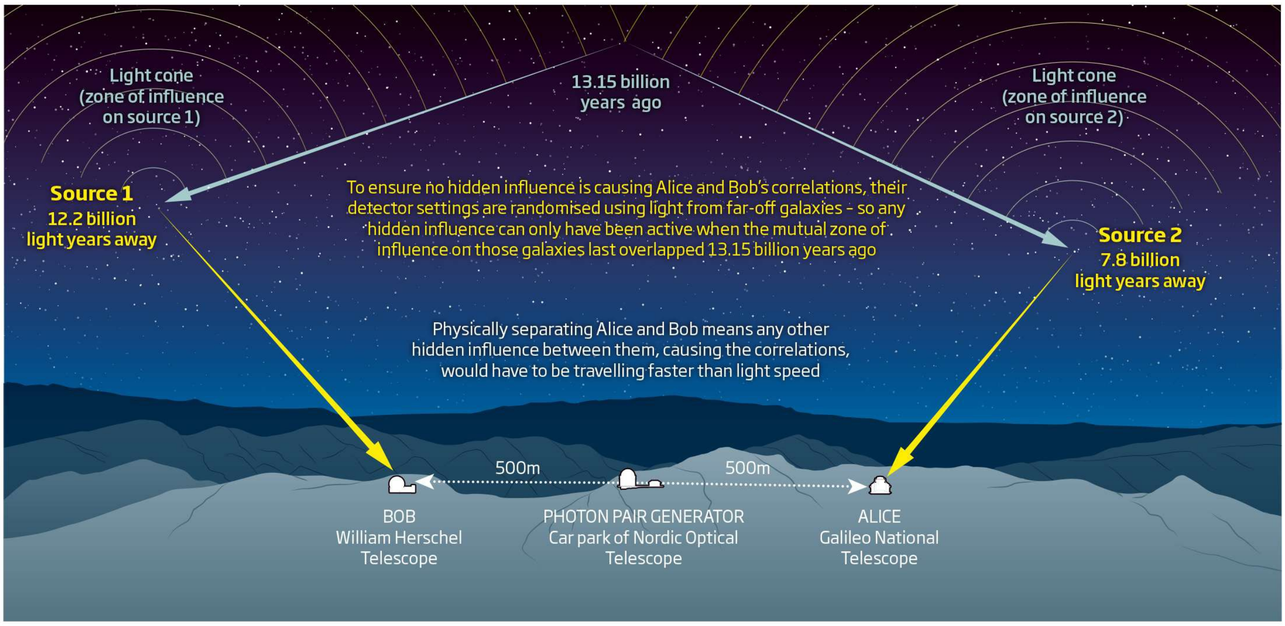
The William Hershel Telescope on La Palma was part of the most ambitious test of quantum reality yet
David Parker/Science Photo Library

But the original proposal by Kaiser and his colleagues was more ambitious. It envisaged using light from very luminous galactic sources known as quasars, billions of light years away. “Quasars are the objects furthest away from us that are still visible with optical telescopes,” says Scheidl. They were going to need a bigger telescope. It was time to climb a mountain.

Just as in Vienna, the experiment required three sites, with Alice and Bob both hooked up to telescopes, a source of entangled photons in the middle, and a clear line of sight between the three. The Roque de los Muchachos on La Palma, a mountaintop pockmarked with telescopes, had the perfect configuration. Alice could use photons from the Italian-run Galileo National Telescope, and Bob photons from the William Herschel Telescope, jointly funded by the Netherlands, Spain and the UK. Meanwhile, the car park for the Scandinavian-run Nordic Optical Telescope, situated almost exactly halfway between, roughly 500 metres from each, would house a container office with the optics to produce photons and beam them towards Alice and Bob (see “graphic).

Sorry, Einstein

In experiments atop the Roque de los Muchachos on La Palma in the Canary Islands, researchers have measured weird quantum correlations between pairs of generated photons – excluding the possibility the correlations could be explained by conventional physics. Quantum characters Alice and Bob show how they did it



It took a while to persuade the astronomers to give quantum physicists time on the two telescopes, but eventually three days of observing time were scheduled in January – with news that a team in China was doing a similar experiment setting the European competitive juices flowing.

It was during final preparations, on 13 December last year, that disaster struck. Zeilinger, Scheidl and others were in Vienna when they heard the news of the overturned container. "You will eventually have your PhD and you will at least have a story to tell," Rauch recalls Zeilinger telling him. "I could not quite share his optimism at that point."

Even as construction workers were securing the container, the wind blew it away again. This time, it almost fell over the edge. "I thought everything that wasn't broken before was broken now," says Rauch. Over the next few days, the team fixed most of the experimental apparatus, and re-established the links between the photon source and Alice and Bob. But the light crystal that generated the photon pairs was beyond repair. Rauch ordered a new one and flew home for Christmas.

Almost miraculously, the team managed to get the experiment up and running again to hit the allotted observing time. But the first night was lost to another storm: it was hailing and the telescope dome couldn't be opened. Bad weather ruined the second of the allotted nights too. On the third night, things cleared up. With the moon below the horizon, and the sky dark except for the stars, the two large telescopes began tracking quasars.

But a problem with Alice's equipment meant she couldn't collect enough photons from her quasar – and before the team could fix it, telescope time was up. The next day, they went begging for more. The Galileo telescope was available, but at the other end it took the largesse of one Herschel astronomer, who gave up 2 hours of his allotted time to the quantum physicists. “We bought him some beer and wine,” says Scheidl.

That night in mid-January, the two telescopes locked into quasars in opposite patches of the sky to trigger the measurement settings for Alice and Bob. One had emitted its light 7.8 billion years ago and the other 12.2 billion years ago. The researchers were able to collect and analyse data for nearly 18,000 pairs of photons. Bell’s bound was yet again broken, and strongly so.

“If Einstein’s universe exists, it has been pushed into a tiny corner of the cosmos”

Because the quasar sources are in different directions in the sky, their past light cones only overlap 13.15 billion light years in the past. That rules out any local-realistic mechanism pulling the strings from all but 4 per cent of the space-time it might have existed in – “virtually the entire past light cone of the experiment extending all the way to the big bang”, says Kaiser.

The final word? Not quite. Even though the experiment closed the locality loophole and pushed the freedom-of-choice loophole to an extreme, “we were not even trying to close the fair sampling loophole”, says Kaiser. The need to transmit the photons from the source to Alice and Bob through the air meant too many were lost to ensure watertight detection efficiency.

Meanwhile, the competing team in China, led by a former student of Zeilinger’s, Jian-Wei Pan at the University of Science and Technology of China, made a stab at shutting all three loopholes. Losses of photons were minimised by using optical fibres to transmit them from the source to Alice and Bob, all situated on the outskirts of Shanghai. To generate the random numbers, the team used light from stars only 11 light years away, but still, “our experiment conclusively rules out local hidden variable models taking place 11 years before the experiment”, says Pan.

Both teams are now thinking how to push things further, for example by using photons from the cosmic microwave background, the radiation left over from the big bang. “It’d be a delicious technical challenge, a really beautiful, really hard experiment,” says Kaiser. “There is no earlier source of light in the cosmos that one could try to use.”

Niggles aside, however, the conclusion already seems clear. It comes as little surprise to most physicists, but it’s as well to check: Einstein’s local-realistic universe, if it exists, has been pushed into a tiny corner of the cosmos. Elsewhere, there seems little room for doubt that quantum mechanics, or something based on it, is the correct description of nature. The theory’s mysteries may remain as unfathomable as ever, but for Kaiser that is cause for celebration. “I think ordinary quantum theory looks as good as it ever has – which is to say, it looks terrific.”

This article appeared in print under the headline "Reality's last stand"

Anil Ananthaswamy is a consultant for *New Scientist*

Magazine issue 3204, published 17 November 2018