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Reality check: Closing the quantum loopholes

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Can the universe really be as weird as quantum theory suggests? Ingenious experiments are coming close to settling the issue

WHEN Rupert Ursin stood in the darkness at the highest point of La Palma in the Canary Islands he found it scary. "Really scary," he says. It was less the blackness stretching out towards the Atlantic Ocean some 15 kilometres away. It was more the sheer technical challenge ahead- and perhaps just a little because of the ghosts he was attempting to lay to rest.

Ursin and his colleagues from the Institute for Quantum Optics and Quantum Information in Vienna, Austria, were there that night to see if they could beam single photons of light to the 1-metre aperture of a telescope on the island of Tenerife, 144 kilometres away. Even on a fine day, when Teide, Tenerife's volcanic peak, is clearly visible from La Palma, that would be a feat of mind-boggling precision. Attempting it in the dark seemed ludicrous. "At night you don't know where the other island is," says Ursin. "You are lost; you have no clue what to do."

In daylight, though, zillions of photons zinging around would have made their experiment impossible. And so, on moonless nights, the researchers would switch off the lights in their lab and slip outside to a night sky lit only by the Milky Way.

For what? To attempt to settle one of the longest-running debates in modern physics. To dispose of yet another ambiguity in our basic understanding of how nature ticks. To answer one of the most fundamental questions of all: is quantum reality real?

It was back in the mid-1920s that two big beasts of modern physics, Niels Bohr and Albert Einstein, first locked horns on this question (see "Quantum duellists"). By then it had become clear that classical physics could not explain a litany of small-scale phenomena, such as how light interacts with matter, or why orbiting electrons don't spiral inwards and crash into the atomic nucleus.

The new theory of quantum mechanics could, but it was a bitter pill to swallow. Gone were the old certainties and straight-down-the-line relations between cause and effect of the clockwork, Newtonian universe. In their place was a fuzzy world populated by particles that were simultaneously waves, that influenced each other seemingly without reason, and which could apparently exist in many states at once until the watchful eye of an observer disturbed them.

For Bohr, if we could not get our heads round that, then the problem lay in our heads, not with quantum mechanics. Distasteful as it might be to our classically attuned brains, the theory was a complete, fundamental description of how the world worked.

Einstein disagreed. He thought the weirdness of quantum mechanics meant the theory was missing something. He became convinced that a deeper layer of reality lurked beneath its surface, governed by as-yet undiscovered "hidden variables" that worked according to rules familiar from classical physics (see "Einstein's hidden world").

Bohr and Einstein's debate continued- firmly, decorously and with no definitive answer- for decades. It wasn't until 1964, after both men had died, that the first hint of a resolution appeared. It came courtesy of John Bell, a 36-year-old researcher at CERN, the European laboratory for particle physics near Geneva, Switzerland. His insight was that Bohr and Einstein's almost philosophical argument could be reformulated mathematically.

Bell began by considering particles that are correlated, in the sense that measuring the properties of one tells you the properties of the other. The existence of such correlations is not in itself surprising: if laws such as the conservation of energy or momentum hold, we expect that properties such as the speed or position of particles emitted from the same source at the same time will be related. But Bell derived a mathematical expression, called an inequality, to describe the maximum amount of correlation possible if two conditions dear to our classical intuitions, but seemingly violated by quantum mechanics, held: realism and localism. Realism embodies the idea that any measurable property of an object exists at all times, and its value doesn't depend on someone observing it. Localism assumes that these properties are only affected by nearby things, and cannot be influenced by anything remote.

Here, then, was a test for physicists to get their teeth into. All that was needed was an experiment to measure how intertwined two particles from the same source were. If their correlations busted Bell's inequality by a significant amount, then realism, localism or both had failed, and the weirdness of quantum mechanics really did exist: the particles were in some mysterious way "entangled". If Bell's inequality was satisfied, however, then something real, local and classical-like was pulling the strings: Einstein's hidden variables, for example.

Fittingly, the reality was somewhat more complex. It proved hard to implement the ideal conditions needed to test Bell's inequality, and all the experiments were proving inconclusive.

Then, in the early 1970s, a young French student named Alain Aspect came on the scene. He had just finished his mandatory military service as a teacher in Cameroon and was casting around for a PhD topic. Chancing upon Bell's paper and the history of the debate between Bohr and Einstein, he was entranced. "It was the most exciting thing for an experimentalist to test who was right," says Aspect, now at the Institute of Optics in Palaiseau, France.

So Aspect visited Bell to seek his blessing. Bell warned Aspect that many regarded investigating the roots of quantum reality as "crackpot physics", and asked him whether he had a secure job. "I did. It was small, but it was permanent," says Aspect. "They could not fire me." That security allowed Aspect to embark on a seven-year search to find out who was right: Bohr or Einstein.

Aspect's experiments broadly followed a pattern established in previous tests of Bell's inequality. Atoms were first stimulated to emit pairs of photons that were correlated in their polarisation states. These polarisations were then measured at two separate detectors, which are by convention maintained by two characters called Alice and Bob (see diagram).

That depended on measuring large numbers of photon pairs to get statistically significant results. By the time Aspect, together with his students Philippe Grangier and Jean Dalibard, was ready to perform his definitive tests, advances in laser technology were making that an easier task. "By 1980, I had by far the best source of entangled photons in the world," says Aspect. Whereas it had previously taken hours or even days to get the number of photons required, he could now get them in just 1 minute.

It was still painstaking work. But by 1982 the researchers had the most convincing retort yet in the quantum reality debate. There was no doubting the results. Bohr was right; Bell's inequality was violated (*Physical Review Letters*, vol 49, p 91). The world is just as weird as quantum theory says it is. "It was thrilling," says Aspect.

Niggling doubts

End of story? Not a bit of it. Experiments are rarely entirely conclusive, and- influenced no doubt by Einstein's reputation- niggling doubts remained that perhaps nature had fooled the experimenters into thinking quantum theory was the true answer. Even if the measured correlations exceeded Bell's maximum, there were enough loopholes in the experiments to leave wiggle room for something other than quantum mechanics to be the cause.

"The question of whether nature is local, realistic or quantum-mechanical is so deep and so important that we should try to do these experiments as cleanly and as loophole-free as possible," says Johannes Kofler, a theorist with the Vienna team. "It's really all about ruling out conspiracy theories of nature against us."

Aspect's experiments had already done sterling work in trying to close one loophole that Bell had identified - the locality loophole. Unless the detectors used by Alice and Bob are far enough apart to prevent communication between them at light speed or below, some influence might propagate through a hidden layer of reality, telling Alice's detector the outcome of Bob's measurement before she performs her own, say, and maybe even fiddling with her detector's settings to change the outcome. "If you allow such a communication, it would be easy to violate Bell's inequality in local realism," says Kofler.

The highly efficient source of entangled photons and superior optics used by Aspect had enabled his team to separate Alice and Bob by about 6 metres. That gave them just enough time to change the settings of the detectors after the photons had left the source, hopefully stymieing any attempt of a hidden communication channel to ambush the experiment (*Physical Review Letters*, vol 49, p 1804).

That was cunning, but not quite cunning enough. The team had only nanoseconds to change the detectors' settings, which was not enough time to change them randomly. Instead, they had to use a predictable, periodic pattern. If some hidden channel did exist, then over time the detectors used by Alice and Bob might figure out each other's settings and again trip up the experiment.

To nip that sort of thing in the bud, in 1998 Gregor Weihs, Anton Zeilinger and their colleagues strung Alice and Bob 400 metres apart over their university campus in Innsbruck, Austria, using optical fibres to connect the detectors to a photon source placed between the two. That gave them about 1.3 microseconds' grace after the photons were fired to switch the detector settings randomly. To close the locality loophole even tighter, atomic clocks ensured that Alice and Bob's measurements were made within 5 nanoseconds of each other - quick enough to prevent a hidden message being transferred. The test showed clear violations of Bell's inequality (*Physical Review Letters*, vol 81, p 5039). Quantum mechanics reigned supreme.

And yet it still wasn't a final answer. As the locality loophole closed, attention shifted to other loopholes. One was the fair-sampling, or detection, loophole. The photon detectors used in all the experiments were inefficient and sampled only a small fraction of the photons sent out by the source. What if only a small subset of photons were sufficiently correlated to violate Bell's inequality, and the detectors just happened to be sampling those? Implausible, perhaps, but not impossible.

This loophole was first closed in 2001 by a group led by David Wineland at the National Institute of Standards and Technology in Boulder, Colorado. Instead of photons, the researchers entangled a pair of beryllium ions, each of which could exist in a quantum-mechanical superposition of two energy states. Depending on which state an ion was in, it scattered either very many or very few photons. By probing the ions with a laser and measuring the variation in photon counts, the ions' states could be determined with almost 100 per cent efficiency (*Nature*, vol 409, p 791).

Again, the correlations found between the beryllium ions' states were far greater than could be explained by anything other than quantum mechanics. But this, too, came with a caveat: at the point of measurement, the ions were only 3 micrometres apart. Although the detection loophole was closed, the locality loophole remained open.

Freedom to choose

Besides, there was another subtle loophole to be considered. Tests of Bell's inequality generally assume that researchers have the freedom to choose their detectors' settings. But do they? What if the source of particles has some way of influencing the settings on the detectors used by Alice and Bob, again through some hidden layer of reality? By exploiting this "freedom of choice" loophole the source could emit photons that mimicked the entanglement of quantum mechanics.

That brings us to the Canary Islands. The aim of shooting photons from La Palma to Tenerife- an experiment combining the expertise of Ursin, Kofler, Zeilinger and others- was to close the freedom of choice loophole while also keeping the locality loophole tightly shut. While one entangled photon was beamed over the Atlantic to Bob in 479 microseconds, the other was pinged 6 kilometres down an optical fibre to Alice, reaching her in 29.6 microseconds. Random number generators triggered the detector settings for Alice and Bob once the photons were in transit (see diagram).

To ensure freedom of choice for Alice, her random number generator was kept 1.2 kilometres away from the photon source, and the random number generation and emission of photon pairs were timed so one could not influence the other. On Tenerife, the random number generator chose the setting for Bob's detector before the photon arrived from La Palma, ensuring that the source couldn't influence Bob's choice- assuming no influence travels faster than a photon.

The result? Yet again, the experiment violated Bell's inequality spectacularly (*Proceedings of the National Academy of Sciences*, vol 107, p 19708).

With that, all three major loopholes- locality, fair-sampling and freedom of choice- have seemingly been closed. Has the debate between Einstein and Bohr finally been settled, in Bohr's favour?

Perhaps. While some are keeping things interesting by discovering ever more nuanced loopholes (see "Collapse of reality"), nitpickers note that as yet no one experiment has closed all three major loopholes simultaneously. Paul Kwiat and Nobel laureate Anthony Leggett, both at the University of Illinois at Urbana-Champaign, are heading a team attempting just that. Using a potent light source, blisteringly fast random number generators and high-efficiency detectors, they hope to create a loophole-free test.

Leggett doesn't expect any surprises. "It would really be a very weird sort of conspiracy of nature if everything had worked when you closed two of the three loopholes in one experiment, and then when you closed three simultaneously, things went awry," he says.

More provocative is the question of whether we are actually at liberty to close the freedom of choice loophole. What if we live in a completely deterministic world, where even the outcome of a quantum random number generator is preordained? That would make us mere pawns in a greater game. "If the universe runs deterministically, there is nothing you can do as an experimentalist," says Kofler.

But for the vast majority of physicists that is not the prime concern, says Leggett. The point is that a local-realistic hidden variable theory, as preferred by Einstein, is not a viable description of nature. While quantum mechanics may not be the last word, it is certainly the best description of reality we have right now.

So, was Einstein wrong? That is missing the point, says Zeilinger. "Yes, Einstein was wrong about reality," he says. "And I'd give a lot to hear his comments on the situation." But by forcing us to examine the basis of quantum mechanics so closely, Zeilinger says, Einstein's concerns have delivered us a theory that, however weird, is better rooted in reality than any that preceded it.

Motivation enough for dark nights atop La Palma, scanning a black horizon for a distant photon target. If the ghosts of Bohr and Einstein had been haunting those starlit vigils, then they would both have had cause for quiet satisfaction: Bohr that the researchers had once again confirmed his world view; Einstein for ensuring they had taken the road to the summit at all.

Einstein's hidden world

Einstein was unconvinced by quantum theory, and in 1935 he aired his concerns in a paper written with two young physicists, Boris Podolsky and Nathan Rosen, called "Can quantum-mechanical description of physical reality be considered complete?" (*Physical Review A*, vol 47, p 777).

In it, they formulated what came to be known as the EPR paradox. For a theory to be complete, the trio argued, it must describe every element of physical reality. If a moving object has a position and a momentum, for instance, the theory should include elements, or "variables", that tell you their values.

While this works fine when talking about cars, say, in the minuscule quantum world things are not that simple. According to the notorious uncertainty principle laid down by Werner Heisenberg in 1927 you can only extract an exact value for the position of a particle when the momentum is unknown, and vice versa. This, said Einstein, invited one of two conclusions: either position and momentum do not exist simultaneously, or quantum mechanics as a description of reality is incomplete.

It got worse. An explosion that sends two pieces of shrapnel shooting off in opposite directions is easily explained by classical physics. There is an easily verifiable connection between the fragments' speed, direction and mass, one that is fixed at the time of the explosion according to the law of conservation of momentum.

An analogous quantum-mechanical situation, on the other hand, is more problematic. Imagine a particle at rest decaying into two particles that shoot off in different directions. According to the kind of interpretation of quantum physics favoured by Niels Bohr and other pioneers of quantum theory, particle properties are not clearly defined until they are measured. But measuring the position or momentum of one particle immediately sets the other's position or momentum in another part of space, even though it was previously undefined. How can this change in status be communicated instantly through space?

Not, said Einstein, through some "spooky action at a distance", as implied by quantum mechanics. Instead he believed there must be an element of an underlying theory- a "hidden variable"- that set the results of both measurements in advance, much as conservation of momentum sets the outcome of measurements of the shrapnel fragments in the classical case. Quantum mechanics as formulated must be an incomplete description of reality, he concluded.

In his annus mirabilis of 1905, Einstein not only came up with his special theory of relativity and the mass-energy equivalence equation $E = mc^2$, but also became the first person to ascribe a physical reality to the quantum, a concept introduced by Max Planck five years earlier.

Einstein described the liberation of electrons from an illuminated metal's surface- the photoelectric effect- in terms of the action of tiny, discrete packets of light energy: photons. It was for this insight that he received the Nobel prize for physics in 1921.

In 1913, Bohr used the principle of quantisation to postulate that electrons in atoms can exist only in discrete energy states, and thus explained the spectrum of light emitted by a hydrogen atom. This work ensured he followed Einstein to the Nobel prize for physics in 1922.

Bohr went on to develop the principle of complementarity, the bedrock of the dominant "Copenhagen" interpretation of quantum theory. This states that the quantum world is both wave- and particle-like; it is the act of measurement that causes it to show one face or the other.

Collapse of reality

Even as the main loopholes in tests of quantum mechanics are closed (see main story), others open up. Take the "collapse locality" loophole, the brainchild of Adrian Kent at the University of Cambridge.

According to many interpretations of quantum theory, a pair of entangled photons exists in a superposition of quantum states until the point of measurement, at which point it collapses into a specific state. The experiments performed so far have assumed this collapse to be instantaneous. But it isn't. In interpretations that require events to be registered by human consciousness for states to collapse, it takes as much as 0.1 seconds.

That means one quantum state could potentially signal its collapse to another remote location before the second state's collapse could be registered. To close this loophole, real humans would have to record the events and be spaced more than 0.1 light-seconds apart- about 30,000 kilometres (*Physical Review A*, vol 72, p 012107).

"It seems far-fetched," says Nobel laureate Anthony Leggett of the University of Illinois at Urbana-Champaign. "But on the other hand if you had told me back in 1985 that by 2010 people were going to be doing this kind of experiment over 100 kilometres, I'd have said you must be joking."

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