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Physics

# Can we solve quantum theory's biggest problem by redefining reality?

With its particles in two places at once, quantum theory strains our common sense notions of how the universe should work. But one group of physicists says we can get reality back if we just redefine its foundations

By Karmela Padavic-Callaghan

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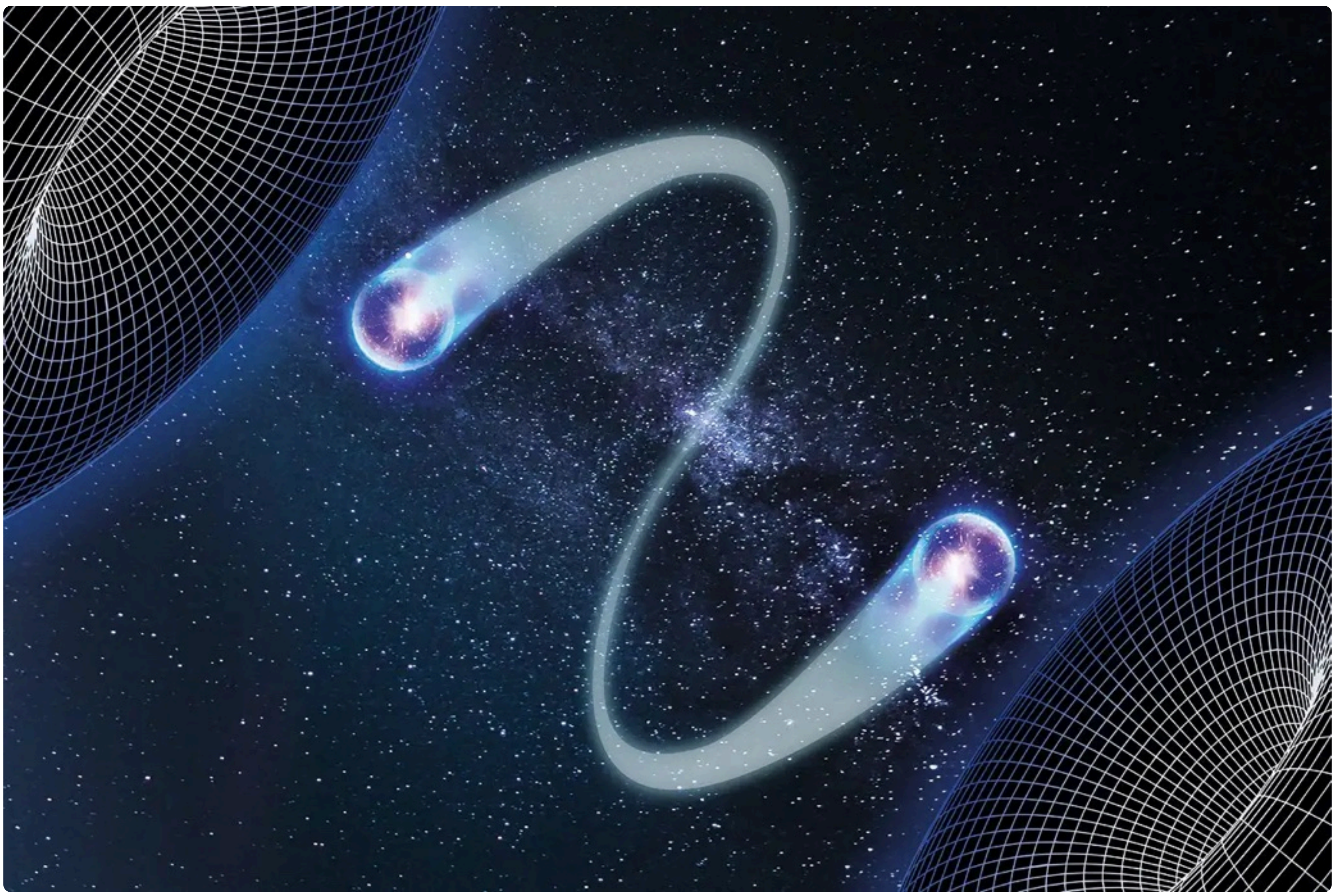
Ryan Wills; adboestock/Getty images

As one of the original architects of quantum theory, perhaps our most successful scientific idea, you would think that Niels Bohr would have been interested in the nature of reality. The subjects of his studies were atoms, electrons, photons – the things we think of as the fundamental ingredients of the universe.

But for Bohr, reality was actually none of his business. “It is wrong to think that the task of physics is to find out how nature is,” he said in an often-repeated quote from the early days of quantum theory. “Physics concerns what we can say about nature.”

Though this distinction may sound pedantic, it can’t be dismissed when it comes to quantum physics. The picture this theory paints of the subatomic world is perplexing: particles can seemingly exist in two places at once, time stands still and there is no such thing as empty space. Can that really be what reality is like? 🔗 /round-up/reality/



**Quantum time travel: The experiment to 'send a particle into the past'**

Time loops have long been the stuff of science fiction. Now, using the rules of quantum mechanics, we have a way to effectively transport a particle back in time – here’s how

🔗 /article/mg26234932-900-quantum-time-travel-the-experiment-to-send-a-particle-into-the-past/

Some physicists shrug off the question. Like Bohr, they aren't talking about reality at all, only our pale perception of it. But many find this viewpoint deeply unsatisfying and want to believe in a world composed of sensible objects that exist independently of what we know about them. They are, in other words, realists. One of them is Robert Spekkens 🔗 https://perimeterinstitute.ca/people/robert-spekkens at the Perimeter Institute in Canada, who has a plan to free reality from the century-long quantum mess it has been in. He argues that reality is real after all – as long as we are prepared to modify what "real" means.

Since its birth roughly a century ago, thanks to Bohr and others, quantum mechanics has been incredibly successful. Understanding its rules and the particles that must follow them led us to develop technologies ranging from semiconductor chips, which make our computers and phones work, to 🔗 /article/2398994-fastest-ever-semiconductor-could-massively-speed-up-computer-chips/ quantum computers 🔗 /article-topic/quantum-computing/, which promise to be their more powerful successors. But from the start, it was mind-bendingly difficult to accept some of its implications.

Suppose you have two closed, opaque boxes, one holding a marble and one containing a quantum particle, like an electron. If you open the box with the marble and measure its position, you can rest assured that not much was different before you took a peek. In contrast, because the electron must follow quantum rules, there is no simple way to connect its out-of-sight past to the moment of measurement. Physicists instead must describe the particle's past using the wave function, a mathematical formula that only offers the probability of finding the electron in one place or another. Before you lift the lid, the best you can do is imagine the electron as a cloud of possibilities.

The challenge of interpreting what this really means is known as the measurement problem – and it is a gauntlet thrown down at the feet of realism. If an electron is real, why doesn't it behave like a marble? "People should be thinking about this if they're interested in the nature of reality," says philosopher of science James Ladyman 🔗 https://www.bristol.ac.uk/people/person/James-Ladyman-b61a10de-17f6-4cc9-afbb-fbc27e1f30fb/ at the University of Bristol, UK.

## Why entanglement is so strange

Reality's credentials look even more dubious if you consider a pair of particles. These can be quantum entangled, which means their characteristics correlate even when separated by distances so vast that no signal could conceivably travel between them. This flies in the face of a principle called locality, which says that for things to influence each other, they must be physically close. The fact that entanglement was "non-local" greatly bothered Albert Einstein, who called it "spooky action at a distance".

So what are we to make of this decidedly unreal picture of reality? 🔗 /article/mg24532670-700-what-is-reality-why-we-still-dont-understand-the-worlds-true-nature/ You could side with Bohr and say there's no real problem. Forget reality itself, all we can know is what we know about reality. Many of Bohr's contemporaries, including Einstein, were incensed by this idea, as were generations of scientists that followed. Like Spekkens, they were and are realists. For them, if quantum phenomena seem weird, then we must be missing a piece of the puzzle.

"Realism is, loosely speaking, the belief that the world exists independent of us and that there is a truth about how things 'really' are," says Sabine Hossenfelder 🔗 https://sabinehossenfelder.com/ at the Ludwig Maximilian University of Munich in Germany. "It is a philosophical position, not a scientific one, though I suspect that most scientists are realists."

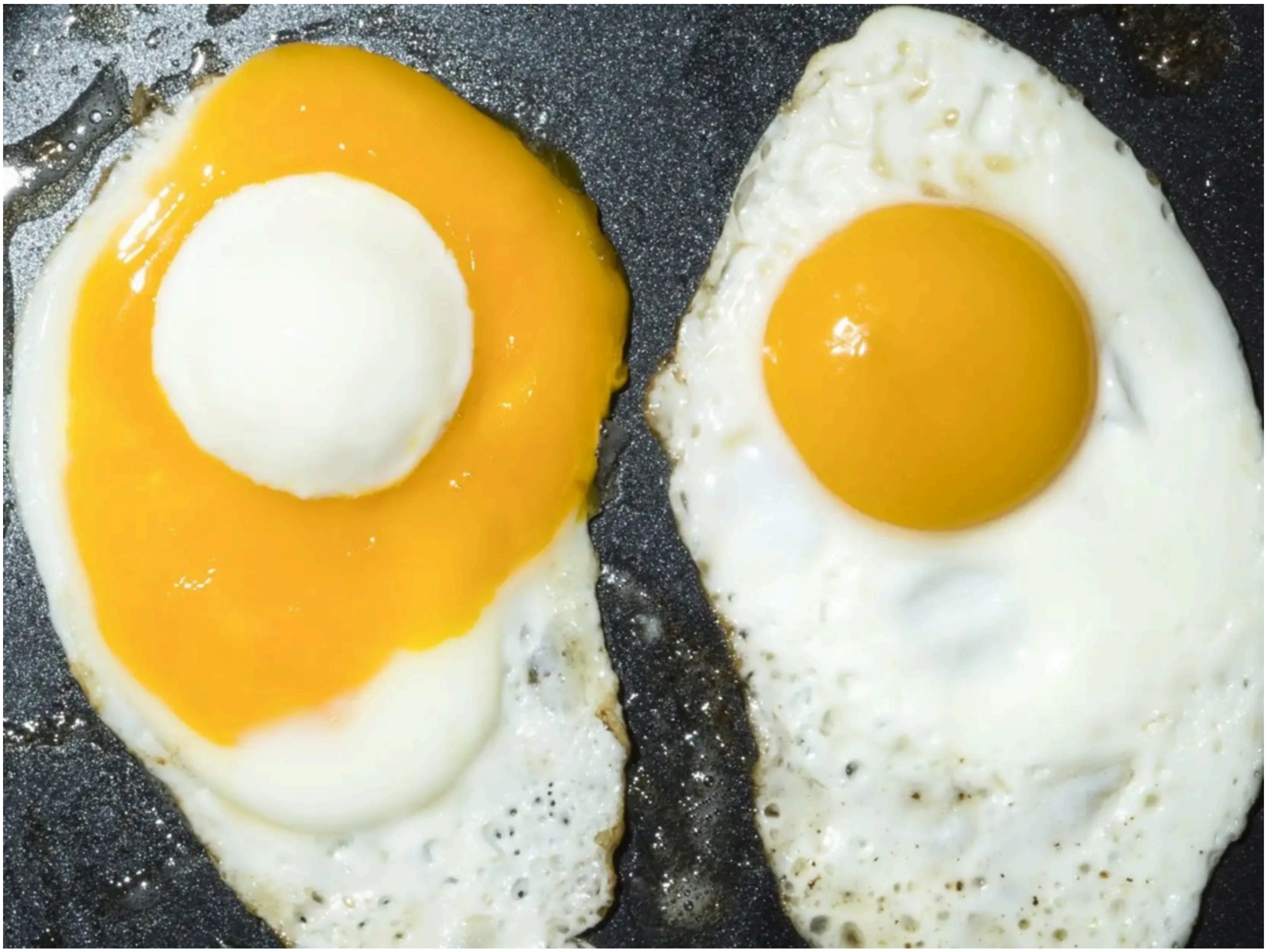
As realism is more of a philosophical stance than anything else, physicists often instead discuss the more concrete and experimentally testable notion of "local realism" – a combination of localism and realism, where Einstein's "spookiness" is explicitly forbidden.

## Reclaiming realism

There have been abundant efforts to create a tweaked version of quantum mechanics that adheres to local realism. Yet none has been successful enough to truly tip the scale. "The fact we have not yet achieved broad consensus on how to interpret the formulas of quantum theory means that none of the proposals on the table have got it right," says Spekkens.

This isn't purely a philosophical debate for Spekkens, it is practical too. One of the headline goals in modern physics is to combine quantum theory with Einstein's general relativity, and so find a unified theory 🔗 /article/mg26134773-000-why-physicists-are-rethinking-the-route-to-a-theory-of-everything/ that explains all the fundamental forces of nature in one go. But despite decades of effort, there's a sense that progress has stalled. Spekkens blames this on our lack of understanding of quantum theory as it stands. "The way you think about the formulas of quantum mechanics will impact very significantly how you approach that project," he says. "Not having the right interpretation is going to impede you."

He isn't the first to try to rescue realism. Starting decades ago, scientists have been pursuing the same ends through so-called hidden-variable theories. Here, physicists assert that there must be some hidden variable – a factor that, by definition, we can't know or measure – that would explain the transition a particle makes when we observe it snap from nebulous wavefunction to definite position. In the 1960s, however, physicist John Stewart Bell came up with a mathematical test of a whole swathe of local hidden-variable theories – a subset that also requires that the world be local – and its results weren't promising.



**Some see the foundations of quantum theory as all mixed up**
American Glitch/Orejarena & Stein. Courtesy of the artists and Palo Gallery, NY

Bell considered taking two entangled particles, making a series of measurements on each separately, then analysing the distribution of those measurements. He wanted to determine how that distribution would differ in a world that followed a local hidden-variable theory – a realist world where no odd, far-reaching correlations happen – and a world governed by quantum theory where entanglement is as counterintuitive as it seems. His test, now known as Bell's inequality, does exactly that. If you plug in your experimental data and find the correlations between the entangled particles exceed a certain value, local hidden variables are ruled out. Unfortunately for realists, all experiments to date fall into this category.

Using our most advanced devices and cutting-edge techniques to probe the nature of our world has put hidden-variable theories on shaky ground. These ideas, which were once promising a return to normalcy, had to be spookily non-local after all to fit with experimental observations.

Realism, then, is ripe for reinvention and Spekkens is giving it a shot. His strategy starts with a hidden-variable theory, but when issues with non-locality emerge, he doesn't want to compromise his realist values. Instead of allowing for non-locality or making some other exception, as other theorists have chosen to do, he would rather rebuild the foundations of the concept. "The approach I favour is to say, no, let's stick to our guns, on the idea that the wave function is really describing incomplete information," he says. "But let's change the framework relative to which we try to imagine reality."

But how does one reinvent the framework of reality? Spekkens points to one troublesome feature of quantum theory: it contains two different kinds of information. Or, in the words of physicist Edwin Jaynes, it is "a peculiar mixture describing in part realities of Nature, in part incomplete human information about Nature – all scrambled up' into an omelette". The key to resurrecting realism is to unscramble this omelette, says Spekkens.

**Stephen Hawking's final theorem turns time and causality inside out**

In his final years, Stephen Hawking tackled the question of why the universe appears fine-tuned for life. His collaborator Thomas Hertog explains the radical solution they came up with

🔗 /article/mg25734310-200-stephen-hawkings-final-theorem-turns-time-and-causality-inside-out/

He sees the ingredients of quantum theory falling into two categories. First there is causality, or how physical systems – particles and fields, say – relate to and affect each other, like a particle moving because another collided with it. Second is inference, or what we believe about physical systems and how we update our beliefs when we obtain new information, such as by making measurements of particles' mass. Quantum theory scrambles causality and inference into an eggy mess.

Physicists' ideas about how our world works are diverse; they might describe particles, strings or information. But generally they use numbers and equations to tackle causality, and a framework called Bayesian probability to describe what we infer about reality. Usually, these tend to get blended together in line upon line of equations.

In contrast, Spekkens and his colleagues devised an approach where causality and inference are kept strictly separate. To drive the point home, in addition to traditional equations, they are employing diagrams like those usually used to describe electrical circuits – wires in the diagrams represent systems like sets of particles, and gates acting on those wires represent physical processes. Whether a wire is vertical or horizontal indicates whether it conveys a causal effect or an inference. Spekkens set all this out 🔗 https://arxiv.org/abs/2009.03297 in a 2020 paper, written with his Perimeter Institute colleague David Schmid 🔗 https://perimeterinstitute.ca/people/david-schmid and John Selby 🔗 https://old-en.ug.edu.pl/node/111706 at the University of Gdansk, Poland.

Their framework is an attempt to resurrect reality, but it invites a very different kind of thinking about it. Whereas we typically regard particles, fields and objects as reality's key constituents, the new framework puts the focus not on objects, but on the relationships between them. For Bob Coecke 🔗 https://www.quantinuum.com/qai/bobcoecke at the Colorado-based quantum computing company Quantinuum, who pioneered the diagrammatic language the team is using, the approach is a philosophical cousin of the relational interpretation of quantum theory 🔗 /article/mg24933250-500-quantum-weirdness-isnt-weird-if-we-accept-objects-dont-exist/, proposed by the physicist Carlo Rovelli. This says that we can't separate a description of an object from the other objects it interacts with. In other words, we can't consider reality to be made of real objects, only real relations.

**The Large Hadron Collider blips that could herald a new era of physics**

Hints of a new particle carrying a fifth force of nature have been multiplying at the LHC – and many physicists are convinced this could finally be the big one

/article/mg25333693-200-the-large-hadron-collider-blips-that-could-herald-a-new-era-of-physics/

So, have Spekkens and his colleagues really managed to reverse the whisk and make sense of the quantum omelette? Not everyone is convinced. Jonte Hance at Newcastle University, UK, says the notion of realism put forward in the new framework is "very non-standard" https://www.ncl.ac.uk/computing/staff/profile/jontehance.html. Hossenfelder has a similar worry. She thinks that the deep problems with making sense of quantum theory cannot be solved just by reinterpreting the maths. She also says that the framework contains a predefined notion of locality, which makes it inappropriate for studying non-local effects in an unbiased way. There may be value in unscrambling the omelette at this highly mathematical level, "but not the way they are doing it", says Hossenfelder.

Coecke, in contrast, says that using any other mathematical approach would make the unscrambling project impossible. And while Ana Sainz 🔗 https://www.absainz.com/ at the University of Gdansk says she isn't yet ready to go all in on realism, she nevertheless finds the new framework compelling and valuable. "This really describes the situation clearly," she says. "It's a tool for better understanding what's going on."

Since publishing their basic idea in 2020, Spekkens and his colleagues have taken on several staples of quantum theory, such as uncertainty relations, which set fundamental limits on how precisely properties of quantum objects can be measured. Across the board, they are trying to identify how much of each iconic quantum phenomenon must be attributed to something quantum that challenges our intuitive understanding of reality. Working with "toy theories" and analysing specific instances of quantum weirdness, they have been trying to unscramble the omelette, one metaphorical spoonful at a time.

**Are we turning a corner in our understanding of the quantum world?**
John MacLean/Millennium Image

Physicists tend to agree, though, that the decades-long lack of consensus about realism in quantum mechanics is unlikely to end thanks to heady debates and mathematical abstractions alone. Attempts to redefine reality would turn more heads if they produced testable predictions. “I’m a philosopher, so I’m keen on people playing with formal systems and theories, but don’t we want to make new predictions?” asks Ladyman.

## Realism and quantum computers

Coecke is certain that those predictions are coming. In recent years, the swelling interest and investment in quantum computing has boosted studies of the foundations of quantum theory, and the two are bound to keep feeding into each other, he says. Hance says the fact that quantum computers rely on phenomena like entanglement to work may mean that this isn’t just a debate between different philosophical camps, but it could have consequences for those who are trying to harness quantum states.

**The physicist betting that space-time isn't quantum after all**

Most experts think we have to tweak general relativity to fit with quantum theory. Physicist Jonathan Oppenheim isn't so sure, which is why he’s made a 5000:1 bet that gravity isn’t a quantum force

🔗 /article/mg25734301-000-the-physicist-betting-that-space-time-isnt-quantum-after-all/

Selby, Spekkens's collaborator, says there is a way to test the new framework that would make a big splash, if they could actually try it. It builds on a thought experiment devised by physicist Eugene Wigner in the 1960s, known as the Wigner's friend thought experiment 🔗 /article/mg24132220-100-schrodingers-kittens-new-thought-experiment-breaks-quantum-theory/. In this scenario, a friend of Wigner's is observing a quantum system, like a particle in a box, in a lab. At the same time, Wigner is standing outside the lab and observing both his friend and the particle. The two can never agree on what exactly is happening to the particle, so their realities are mismatched.

Recently, there have been several proposals for implementing some version of this Wigner's friend situation inside quantum computers, which puts it at the top of Selby's wish list. He wants to use the new framework to look for a reality that Wigner and his friend do share after all. "It's really early days, but we have a framework and a target to aim for," he says.

Spekkens shares this view. "I want to resist the notion that coming up with an interpretation of quantum theories is somehow not going to be useful, that it's not going to add anything except maybe a story to the formalism," he says. "I think it will advance modern physics."

If he is right, then physicists can claim that reality is their business after all.