What does quantum theory really tell us about the nature of reality?

For 100 years, quantum theory has painted the subatomic world as strange beyond words. But bold new interpretations and experiments may help us to finally grasp its true meaning

The problem with quantum mechanics, or at least the reason even physicists don't understand it, isn't that it paints an unfamiliar picture of reality. It isn't difficult to accept that the world of fundamental particles, of which we have no direct experience, is radically different to the world we perceive.

The problem is instead that it doesn't portray the hinterlands between these two worlds, offering no clear outline of how one emerges from the other. As a result, a century after it was committed to canvas, we still don't know what this scientific masterpiece means for our understanding of reality.

This article is part of a special series celebrating the 100th anniversary of the birth of quantum theory. Read more here.

We aren't short of ideas. Which of them you prefer is largely a matter of taste, or at least philosophical consideration, because they don't tend to submit to experimental testing. As physicist N. David Mermin has joked: "New interpretations appear every year. None ever disappear."

In the past decade, however, something has begun to shift. One new twist on quantum theory is the first to make explicit observational predictions, raising hopes of empirical progress. Another, meanwhile, has gathered momentum because it can seemingly solve several perplexing quantum mysteries in one fell swoop – even if it implies that there is no such thing as objective reality after all.

More promising still, physicists have even begun to feel out new ways to test the validity of such assumptions. As they turn mind-boggling thought experiments into real-world tests, we might finally be able to make progress on the question of what quantum theory is trying to tell us. “We can now narrow down the possibilities,” says Eric Cavalcanti, a quantum physicist at Griffith University in Queensland, Australia.

Quantum theory

The development of quantum mechanics in the mid-1920s upended long-held intuitions about how the universe works (see “Carlo Rovelli on what we get wrong about the origins of quantum theory”). Ever since Isaac Newton formulated his laws of motion and gravitation in the 17th century, physicists had built theories in a particular way: you have a physical system and equations that tell you how it will change over time.

But classical mechanics cannot describe the behaviour of subatomic particles like electrons and photons. Experiments show that these particles perform bizarre feats – sometimes behaving like waves, say – and appear to exist in a “superposition” of many possible states at once. Only when you measure them do they take on definite properties.

What is going on before a measurement? Quantum theory simply doesn't say

The Schrödinger equation captures this vagueness, incorporating a mathematical concept known as the wave function to encode all possible observable outcomes. That allows us to calculate the probability that our particle will manifest in a particular place upon measurement, at which point the wave function is said to "collapse". But it can't tell us for certain the outcome of a single measurement. In other words, all we have, until we look, are probabilities.

What is going on before a measurement? Quantum theory doesn't say. Nor does it specify what counts as a measurement. It doesn't even tell us whether the wave function, often referred to as the "quantum state", really represents physical reality. For such an exalted theory, that is a lot of unknowns. But, ultimately, they all boil down to one profound question: how does the predictable world we see, which is itself ultimately made of atoms and particles, emerge from this ethereal quantum netherworld? Physicists call this the measurement problem, and it remains the central mystery of quantum mechanics.

Rethinking reality: Is the entire universe a single quantum object?

The Copenhagen interpretation

The textbook answer is the Copenhagen interpretation, named after the Danish city where it took shape. It holds that we can say nothing about a particle's state before it is measured. The maths works, so "shut up and calculate", in another of Mermin's' memorable phrases. But Copenhagen was controversial from the start, with Albert Einstein famously railing against the apparently probabilistic nature of the quantum world with his insistence that God does not play dice with the universe.

Many physicists still feel Copenhagen is a cop-out. "It's not a serious answer to the question of what is there, in reality," says Roderich Tumulka, a theoretical physicist at the University of Tübingen in Germany. "We want statements about the true nature of reality." It also seems to leave open the seemingly absurd idea that it is us humans, the conscious beings making the observations, who collapse the wave function.

Tumulka is among those who prefer interpretations that treat the wave function as physically real – something that represents the world as it exists whether we are looking or not. The most famous is the many-worlds interpretation, the idea that all possible outcomes contained in the wave function are realised upon measurement in many separate universes branching off from ours.

But there is also objective collapse, a suite of models proposing that quantum mechanics is incomplete and that something else has to be tacked onto the Schrödinger equation to explain wave function collapse. “The [key] difference with the standard interpretation is that the collapse of the wave function is not something that occurs by magic at the end of the measurement process,” says Angelo Bassi, a theorist at the University of Trieste in Italy. “It’s just part of the dynamics.”

Collapse models have garnered more attention than most in recent years, partly because they offer a plausible explanation of how classical reality emerges without reference to human observers. We don’t see large objects like picture frames and paint brushes in a superposition, it says, because the collapse process works in such a way that the more interacting particles there are, the more readily collapse occurs.

> *One new interpretation can solve several quantum mysteries in one fell swoop*

What triggers this continuous collapsing isn’t entirely clear. Some models don’t say, others posit that it is just gravity. But Bassi says there may ultimately be no good answer – it may just be a property of nature. “That’s why I like collapse models, because they try to open the door to a new world which we don’t understand at the moment – something beyond quantum mechanics that we are not grasping.”

What really sets collapse models apart, however, is that they can be put to the test. Uniquely, they make explicit observational predictions that differ from what standard quantum mechanics predicts. The idea is that this constant process of spontaneous collapse should cause quantum objects such as particles to constantly jiggle around, which, in turn, means they emit excess energy that should be detectable, even if the signal is extremely faint.

Testing quantum interpretations

For the past decade, Bassi has been working with colleagues around the world on an ambitious experimental programme in search of such a signal. They have mostly been repurposing detectors designed to sense hints of dark matter or elusive particles called neutrinos, such as the ultra-sensitive instruments located deep underground beneath the Gran Sasso massif in Italy. And the results are trickling in. In 2020, for instance, a team including Bassi and Cătălina Curceanu, an experimentalist at Italy's National Institute of Nuclear Physics, was able to rule out the simplest form of one model in which gravity does the collapsing.

Similar experiments are ongoing, and with each new analysis we get fresh constraints on which, if any, of these models might work. But while the fact that we finally have a shot at ruling out objective collapse with experimentation is itself progress, actually doing so is a slow process. "So far, we saw no signal, but this is just the beginning," says Bassi.

Is everything predetermined? Why physicists are reviving a taboo idea

Superdeterminism makes sense of the quantum world by suggesting it is not as random as it seems, but critics say it undermines the whole premise of science. Does the idea deserve its terrible reputation?

If we were to detect a signal that everyone can agree supports objective collapse, it would surely be worthy of a Nobel prize. Whether that would immediately tell us anything about the meaning of quantum theory is another matter, according to Magdalena Zych at Stockholm University in

Sweden, because we would still have to figure out what it is in the environment that is doing the collapsing.

"It would solve the measurement problem in the sense of, if you believe that quantum theory is missing something, this is it," says Zych. "But it doesn't really reveal what quantum mechanics is telling us about reality, because you still have to impose some meaning yourself to some extent: you have to say what is the 'noise' in the environment [that collapses the wave function]."

More importantly, Zych says we would also be none the wiser about why the observable properties of quantum objects emerge in a probabilistic way, from the act of measurement itself. "That's really the deep mystery of all this, the fact that we have to speak about probabilities at all," she says. There is no self-evident reason why the behaviour of subatomic particles cannot be governed by deterministic laws. The fact that they aren't demands an explanation.

Quantum Bayesianism

For Zych, the take on quantum mechanics that tackles that challenge head on falls into a whole different category of interpretations. While the likes of Bassi and Tumulka insist that quantum states are real, some physicists take a starkly different view: that they don't represent independent reality at all.

Arguably the most striking example of this approach is QBism, originally known as Quantum Bayesianism because it is founded on a framework for interpreting probabilities first developed by 18th-century minister Thomas Bayes.

Conventionally, probabilities are viewed in “frequentist” terms: we count up the outcomes of many coin tosses to conclude that the odds of getting heads or tails are 50/50. Similarly, many measurements of a particle give you the relative probability of it having one state or another when measured. The Bayesian approach, by contrast, recasts probability as a subjective value that updates as you gain more information.

Running with this idea, the central argument of QBism is that quantum mechanics is similarly subjective. It supplies recommendations about what an observer should believe about what they will see on making a measurement, allowing them to update those beliefs as they take into account fresh experiences. “It’s a theory for agents to navigate the world,” says Ruediger Schack at Royal Holloway, University of London, who developed QBism with Chris Fuchs at the University of Massachusetts Boston.

Roger Penrose: "Consciousness must be beyond computable physics"

The mathematician shares his latest theories on quantum consciousness, the structure of the universe and how to communicate with civilisations from other cosmological aeons

The appeal of this interpretation is that it seems to address several quantum conundrums at once. It deals with the measurement problem by providing and even requiring a central role for subjective experience. The mysterious collapse of the wave function is simply the observer updating their beliefs on making a measurement, says

Schack.

QBism’s answer to the question of how classical reality emerges from the quantum fog, meanwhile, is that it is a result of our actions on the world, of our constant updating of our beliefs about it. The idea even makes light work of a notorious conundrum known as the Wigner’s friend paradox, a thought experiment proposed in the 1950s by physicist Eugene Wigner. Essentially, it demonstrates that two observers – Wigner and a friend observing him making measurements on a quantum system – can have two contradictory experiences of reality.

For a QBist, there is no paradox because a measurement outcome is always personal to the person experiencing it. All of which means that QBism stands starkly athwart the idea that it is possible to achieve an objective view on the universe. But that is exactly the point, says Schack, and this is the great lesson of quantum mechanics: that reality is more than any third-person perspective can capture. “It’s a radically different way of looking at the world.”

> *What really set collapse models apart is that they can be put to the test*

Others find QBism hard to swallow. Bassi, for instance, insists that objective reality is too high a price to pay. “What physics is about is describing nature in an objective way,” he says. Another problem is that QBism doesn't appear to offer any observable predictions differing from standard quantum mechanics, and no realistic prospect of submitting to experimental tests. "Convincing people might be a case of pointing out the inadequacies of the alternatives," says Schack.

That arguably leaves us back where we started. If our best hope of an empirical solution to the measurement problem would leave open questions even if it were proved correct, and an alternative that can address those questions can't be tested, where do we go from here?

There might still be cause for optimism. In the past few years, some physicists have begun to demonstrate that the assumptions underpinning how we think about the meaning of quantum theory – typically considered more in the realm of metaphysics than science – might themselves submit to testing.

Experimental metaphysics

They call it experimental metaphysics. "It's an approach that tries to be clear about the landscape of metaphysical assumptions made by different interpretations," says Cavalcanti, who is one of its key proponents. Among those assumptions are the absoluteness of observed events, which is to say that the outcomes of a measurement are the same for all observers; freedom of choice, the notion that the outcome of any measurement isn't due to factors involved in the measurement; and locality, or the idea that a free choice cannot influence the observed outcome of an experiment at a distance or in the past. "Individually, these may not be testable, but when you group them together, they can be," says Cavalcanti. In this way, you can potentially at least disprove classes of quantum interpretation, he says.

Cavalcanti was part of the team behind the most powerful demonstration of this approach to date. In 2020, he and his colleagues used photons to perform an extended version of the Wigner's friend thought experiment that also involved entanglement, another quantum phenomenon that links particles across vast distances. In short, they found that if standard quantum mechanics is right – if we find no signals for objective collapse, for example – we must abandon one of these assumptions: locality, freedom of choice or the absoluteness of observed events.

Do we create space-time? A new perspective on the fabric of reality

For the first time, it is possible to see the quantum world from multiple points of view at once. This hints at something very strange – that reality only takes shape when we interact with each other

That placed the most stringent constraints yet on physical reality, says Cavalcanti. "If you want to keep the notion of freedom of choice, together with locality, then you need to reject the assumption of absoluteness of observed events," says Cavalcanti – just as QBism insists we must. So, although we aren't at a stage where we can say QBism or any other interpretation is the right way to think about the meaning of quantum mechanics, "we can now narrow down the possibilities," says Cavalcanti.

He now wants to go further. In their 2020 experiment, Cavalcanti and his colleagues used photon detectors in place of Wigner and photons themselves as a proxy for his friend. Yet photons are obviously a far cry from the human observers imagined by Wigner in the 50s, and most people would presumably say photons don't count as observers. It is extremely difficult to keep a molecule comprising a couple of thousand atoms in a superposition, owing to the fragility of quantum states, never mind anything approaching the complexity of a human. But Cavalcanti and his colleagues have suggested that we might one day do the same experiment with an advanced artificial intelligence algorithm running on a large quantum computer, performing a simulated experiment in a simulated lab (see "What exactly would a full-scale quantum computer be useful for?"). That, he says, could show us whether we really do have to relinquish our cherished notion of objectivity – even if we are a long way from being able to do such an experiment.

Quantum gravity

What, then, after all that, are the prospects for some sort of resolution on what quantum mechanics is really telling us about reality? In some ways, we are no further along than we were when the pioneers of quantum mechanics fell out over its meaning. “What we do know for sure is that a certain classical way of looking at the world fails, and we can demonstrate that with mathematical and experimental certainty as much as we can know anything in science,” says Cavalcanti.

For now, we have to each decide for ourselves which of the various interpretations of what quantum mechanics means is more appealing based on theoretical considerations – whether you are prepared to give up one assumption or another, and what price you are happy to pay in turn for keeping the assumptions you prize above all else.

Cavalcanti says we would ideally get some guidance from our attempts to figure out if quantum mechanics fits with Einstein’s general theory of relativity, which describes gravity as the result of mass warping space-time. If a particular interpretation helps us make progress on that front, he says, it would be a strong clue. “I think these foundational experiments are relevant here,” he says. “Because the question of whether or not events are absolute is important for the construction of a viable theory of quantum gravity.”

In the meantime, we have at least begun to clarify things by putting the problems quantum mechanics throws up in terms we can understand and devising experiments that can narrow down the plausible solutions. And all we can do is to strive for ever more sophisticated ways to do that, says Cavalcanti. “I think you can’t understand the world less by understanding more than one way to see it.”

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