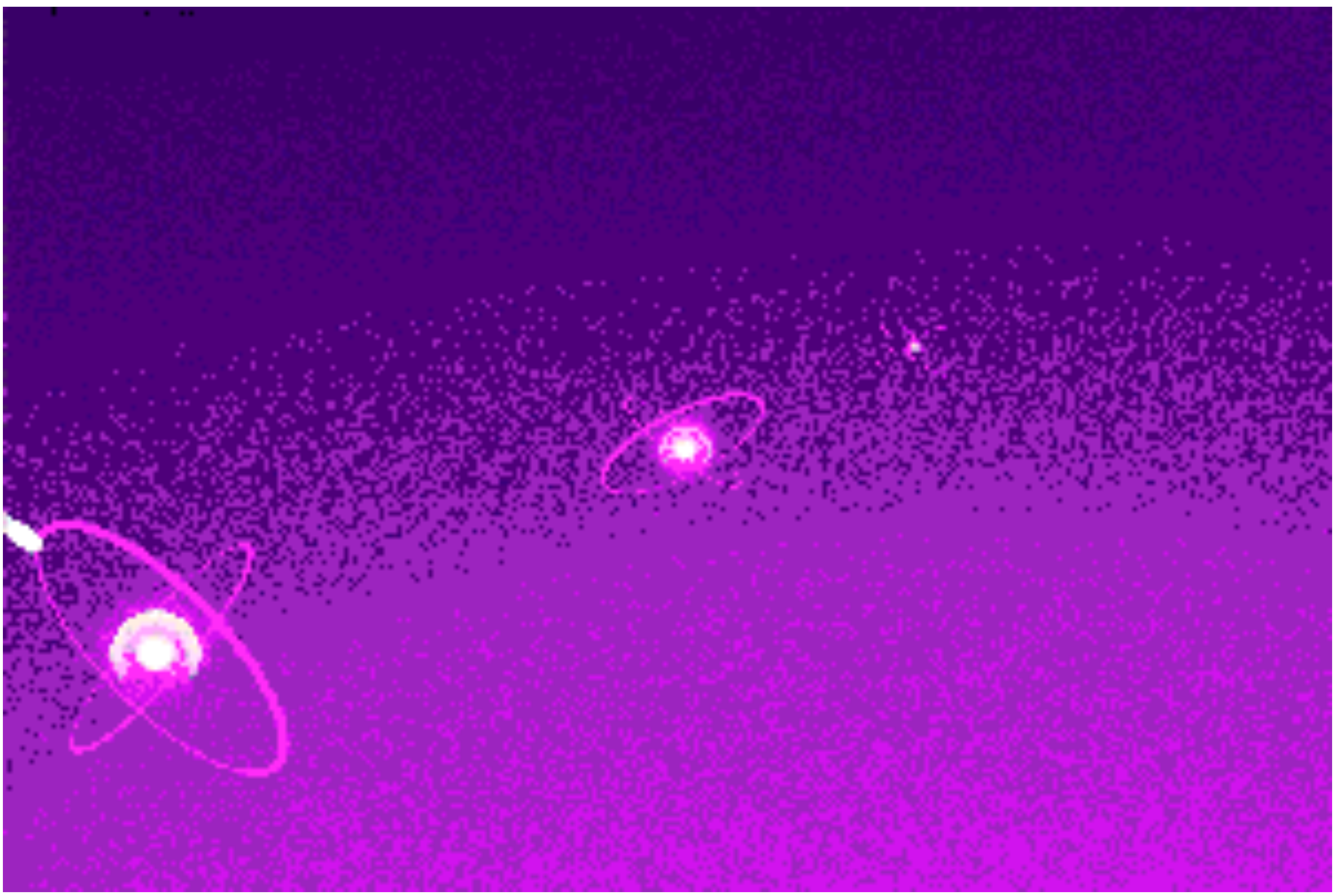
A new understanding of causality could fix quantum theory's fatal flaw

Quantum theory fails to explain how the reality we experience emerges from the world of particles. A new take on quantum cause and effect could bridge the gap



The ball rolls across the floor because it was kicked, just as Earth orbits the sun because it is tugged by gravity. The connection between [cause and effect](#) is fundamental to how we understand the world – or at least, it is for the world we see, governed by classical physics.

Notoriously, everything gets murkier in the underlying realm of atoms and subatomic particles described by quantum theory. But, as a fundamental physicist who develops algorithms to extract cause and effect from correlations, I have long believed that causality could help us solve the mystery at the heart of quantum mechanics: the confounding notion that quantum systems like electrons exist in a state of uncertainty until an observer measures them.

This is why I am intrigued by a fresh attempt to rid quantum theory of this so-called observer problem. Building on insights from existing interpretations and recently developed models of quantum causality, this new take uses the precise mathematics of cause and effect to show how interactions between and within quantum systems can determine which of the many possible ways they could change over time actually happen, without any reference to the mysterious power of observers.

'Dark photon' theory of light aims to tear up a century of physics

What it amounts to is a quietly radical rethink of reality. In this view, quantum causality is the most essential aspect of reality from which the cosmos springs. Remarkably, this view seems to resolve several quantum paradoxes in one fell swoop. Perhaps the biggest indication that it might be on the right track is that it could also provide a plausible route to the long-sought holy grail of physics: a theory that unifies quantum theory with Albert Einstein's theory of general relativity.

A confusing theory

Quantum mechanics is, without doubt, one of our most successful scientific theories. It describes the often counterintuitive behaviour of subatomic particles with incredible accuracy, precisely predicting the outcomes of countless experiments. It is also the source of endless confusion, however, because ever since it was first devised, it has resisted attempts to make sense of what it means for our understanding of reality.

Our frustrations boil down to the vagueness of the concept of "measurement" at the heart of the theory. Until we measure a particle, its properties are best described by the Schrödinger equation and its famous "wave function", which paints those properties as a kind of fog of possible alternatives. This allows us to calculate the odds on which of them we will see when a particle is measured. But it can't tell us the outcome of any measurement. Until we make one, all we have is probabilities.

The upshot is that the observer who performs the measurement is all-important. The gnawing problem is that it isn’t at all clear what qualifies as an observer. With no precise definition, quantum theory offers no answer to the key question of how and why the world we see – where particles have definite properties – emerges from the quantum fog.

In the reality we experience, one thing always leads to another

Sibylle Pietrek/Plain Picture

That’s why many physicists view quantum theory as it is typically understood to be deeply unsatisfying. “The current situation with quantum mechanics is that it’s a theory that predicts very well and explains very badly,” says Nick

Ormrod at the Perimeter Institute for Theoretical Physics in Waterloo, Canada. We can't just fall back on the phrase "because we measure it", he says, particularly as many suspect that the vagueness of quantum theory is a big part of why physicists struggle to apply it in contexts where no observers are present, such as the very early universe or the fabric of space-time.

What we require, then, is an interpretation that removes the need for observers. In fact, we already have several on the table (see "The meaning of quantum theory", below). And while they are imperfect, Ormrod and his colleague Jonathan Barrett at the University of Oxford wondered if two of them might be refined to build a more coherent, observer-independent take on quantum theory.

Consistent histories

The first of those proposals is known as the consistent histories interpretation, which was developed in the 1980s. Rather than treating measurement as a special process, it instead focuses on all the ways a quantum system could feasibly evolve over time – in other words, what happens between measurements. It identifies sequences of properties that the system (that is, a set of particles, for example) could have at different times, known as "histories", and assigns probabilities to them, so long as they are internally consistent, meaning they can be calculated according to the standard rules of logic and classical probability. Crucially, and somewhat surprisingly, it turns out that all quantum phenomena can be modelled this way: there is no need for measurement or observers.

In this view, the act of measurement is just one way of accessing a history, seemingly removing its mysterious power to select an outcome from quantum uncertainty. But there is a catch: there isn't just one consistent history a quantum system could follow, but many. The framework doesn't contain anything that tells us which represents the properties the system really had at any given time, which means it doesn't explain why we get the world we see. "You have to just sort of choose the right one and that choice feels a bit ad hoc," says Ormrod.

The radical idea that space-time remembers could upend cosmology

There are new hints that the fabric of space-time may be made of "memory cells" that record the whole history of the universe. If true, it could explain the nature of dark matter and much more

The second interpretation, known as relational quantum mechanics, developed in the 1990s, is simpler to state: the properties of a quantum system exist only at the point of its interaction with another such system. This means that any physical system can act as an observer and, more importantly, that reality isn't absolute, but is relative to the observer – whether people or particles. Think, for example, of a sunset: it only makes sense to talk about a sunset if we acknowledge it as something observed by a particular person in a certain position on Earth's surface. In that sense, a sunset is relative. In the relational interpretation of quantum mechanics, every aspect of reality must be seen in a similar light.

The problem with this view, according to Ormrod, is that it lacks the sort of precisely defined mathematical framework required to properly scrutinise it. I agree with him. There is currently no formalism that provides a clear-cut definition of ambiguous notions such as "interaction" and "relative". As such, it isn't obvious exactly what relational quantum mechanics tells us about reality, or how it might change the way we approach efforts to construct a coherent theory of quantum gravity.

Which is where cause and effect comes in. Now, you might think it seems odd to apply classical notions of how things influence each other to the quantum world, which doesn't play by the same rules. But to me, and to some other physicists, it has always made sense given that causal reasoning possesses extraordinary explanatory power. "You can't do physics without using cause and effect," says Robin Lorenz, a researcher in causality and quantum computing at Quantinuum. "Causality is the bread and butter of the sciences." What's more – and this is vital – these days, we have a better understanding of how cause and effect operate in the quantum regime.

What Ormrod and Barrett realised is that we can marry the tantalising insights from the consistent histories interpretation and relational quantum mechanics, then overcome their flaws by underpinning them with recently developed models of quantum causality – and by elevating those causal structures to fundamental status.

A new interpretation of quantum theory sees reality as being made up of "causal bubbles"

MICHAL CIZEK/AFP/Getty Images

In a paper released in 2024, they showed that if we consider quantum systems as a network of “causal bubbles” with specific mathematical rules for how subsystems within a bubble influence one another, the “correct” sequence of properties a given bubble has or had over time naturally emerges. In other words, the causal structure of the system determines how it evolves – that is, what properties it has at any given moment – in a way that matches what we would predict with standard quantum theory, but without needing to appeal to the mysterious powers of external observers. “By analysing a quantum causal structure, you can always derive a unique set of consistent histories,” says Ormrod.

Truly grasping the appeal of this model requires some advanced mathematical skills. To get a sense of what it amounts to, however, Ormrod suggests thinking of a spider’s web. The spider doesn’t begin with a set of points and connect them with threads. Rather, it begins with the threads, laying them down one after another – and where they interact, points form.

The key thing is that points in the spider’s web aren’t fundamental. They are by-products of how the threads are woven. “The points only exist because of the pieces of thread,” says Ormrod. “They emerge from the threads. The threads are actually the conceptually fundamental thing.”

In the same way, Ormrod and Barrett suggest, causation is the fundamental “thread” from which quantum reality emerges. The properties of particles are the points, the places where causal influences interact. But the causal structure – the threads – comes first. The properties of a quantum system – what we might call reality – emerge from causality, rather than from the mysterious and ill-defined process of measurement.

The paradox of Wigner's friend

In any case, there are already reasons to think they are onto something with this new interpretation, which is sufficiently novel that it doesn't yet have a name. One is that it can resolve a troubling conundrum that has, in recent years, brought the observer problem into sharper focus. First devised as a thought experiment and later recreated with particles in the lab, the Wigner's friend paradox demonstrates that two observers – Wigner observing his friend making measurements on a quantum system in a lab from the outside – can have two contradictory experiences of reality. The implication is that quantum theory insists there is no such thing as objective, observer-independent reality, and renders the standard interpretation extremely problematic.

In Ormrod and Barrett's framework, the Wigner's friend paradox dissolves. The key is that the notion of a "definite outcome" is tied to causal structure, not to observation. Inside the lab, the friend is embedded in one causal bubble:

the particle influences the apparatus, which influences their sensory experience. Within that causal bubble, the outcome is definite. From outside, however, Wigner is in a different causal bubble. What we learn from Ormrod and Barrett's take on quantum theory is that, in this scenario, the friend's measurement exerts a quantum influence on Wigner's outcome, which precludes it from being part of the consistent history in his causal bubble. Relative to the bubble that includes Wigner's outcome, the friend doesn't obtain any measurement outcome at all.

[A cosmic shape could explain the fundamental nature of the universe]

Physicists have created a 3D shape called the cosmohedron, which can be used to reconstruct the quantum wavefunction of the universe – and potentially do away with the idea of space-time as the underlying fabric of the universe

In other words, both perspectives are correct, but are relative to their causal bubbles. There is no contradiction, because "definiteness" isn't an absolute fact about the world, but a relational fact about causal structures. By making causation, not observation, the foundation, the framework elegantly sidesteps the need to favour one viewpoint. Realising that their framework resolved this paradox "was an amazing moment", says Ormrod.

The other reason to take this new interpretation seriously has to do with the possibility of applying it to fundamental questions about the universe. The thing is, the notion that causality might be more fundamental than the entities it relates to also plays a role in our understanding of general relativity, which casts gravity as the result of mass warping space-time. There is a classic discovery from the 1970s that shows that if you know the causal structure of space-time – roughly, which points can influence which others – you can reconstruct its geometry, distances and even the flow of time. "Causation is playing a very important role in shaping space-time structure," says Ormrod.

How space-time emerges

This means space–time itself may be thought of as emerging from causal order. With that in mind, physicists seeking to reconcile quantum theory and general relativity to form a quantum theory of gravity have long speculated that the universe’s deepest layer may be a causal network, from which both geometry and matter emerge. If this is correct, Ormrod and Barrett’s interpretation is even more striking. On the quantum side, they show how the properties of a quantum system emerge naturally from causal structure. On the relativity side, causal structure already underpins space-time geometry. Taken together, the suggestion is tantalising: what if causality is the common root of both pillars of modern physics, and a foundation on which to unify them?

Carlo Rovelli on what we get wrong about the origins of quantum theory

Conventional accounts of the birth of quantum theory often overlook the pivotal role of one of its luminaries – and this has led to a persistent misunderstanding of what it really means, argues physicist Carlo Rovelli

Other attempts to unite quantum mechanics and relativity have taken very different routes. String theory, for example, imagines the fundamental building blocks as vibrating strings in higher dimensions. It is a bold idea that has inspired decades of research, but it has yet to deliver a complete, testable theory. What makes the causal approach appealing is its simplicity. Instead of inventing exotic new entities, it asks whether the familiar idea of cause and effect could be the missing foundation. If space-time and the properties of quantum systems both emerge from causality, then perhaps cooking up a viable theory of quantum gravity is less about discovering new ingredients and more about rearranging the ingredients we already have. "It seems highly suggestive that we've got these two similar emergence stories in the two theories that we're attempting to unify," says Ormrod.

For now, this is just informed speculation. But what we have with Ormrod and Barrett's new interpretation is the outline of a framework that offers a bold answer to quantum theory's greatest mystery: not just how the theory predicts outcomes, but why those outcomes occur. To me, that alone is remarkable. Because if we take seriously the idea that causality, rather than observation, is the foundation of reality, the bedrock from which the world we see emerges, we may finally be closer to understanding the quantum realm on its own terms.

The meaning of quantum theory

The deepest problem with quantum theory is that it describes a reality in which nothing ever seems to be fixed before we measure it, even though reality as we experience it is composed of objects with definite properties. How and why the latter arises from the former is known as the measurement problem, and while causality may provide an exciting new solution (see main story), it isn't the only one available. Here are some of the main alternatives:

The Copenhagen interpretation simply says that quantum theory doesn't give us any information about what particles are doing before we measure them. It amounts to saying that physicists shouldn't worry about the metaphysical meaning of quantum theory – which is why physicist David Mermin once called it the "shut up and calculate" approach.

If that sounds conservative, the **many–worlds interpretation** is at the other end of the spectrum. This idea, first formulated by physicist Hugh Everett in the late 1950s, says that all possible outcomes of a measurement are realised – just in other universes. The implication that reality is constantly branching is, for some, so strange that it is difficult to swallow.

For a long time, physicists suspected that quantum theory appeared so strange only because it was incomplete. **Hidden-variable theories**, which come in many flavours, say there is some piece of the puzzle we are missing that would explain how and why we get the outcomes we do. However, many of these hypotheses have been ruled out by experiments.

A more recent – and starkly different – approach is **quantum Bayesianism**, also known as QBism. This insists that quantum theory isn't about reality in an objective sense, but only our subjective knowledge of it. When we make a measurement, we update our knowledge of a quantum particle, say, so it makes total sense that it is so hazily defined before we look. The drawback of this framework, for some, is that it abandons any hope of being able to describe the quantum world before we look at it.