

Quantum weirdness isn't weird – if we accept objects don't exist

We can grasp the truth about the quantum world, says physicist Carlo Rovelli – as long as we abandon our most cherished assumption about what's real and what's not

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By



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HERE is a chair in front of me. A nice red wooden chair with four legs, a seat to sit on, a rest to support the sitter's back. Does this chair exist by itself?

Of course it does: it exists regardless of me. But wait: we call it a chair because we sit on it. Would there be the concept of a chair without its relation to us, without sitting humankind?

Maybe not, but even if someone were unaware of a chair's intended function, its components would still exist, for instance the smooth red wood it is made of. What does "red" mean, though? It refers to an interaction between the wood, light scattering off it and particular receptors in our eyes.

Most animals don't see colours like humans, though.

Regardless of that, the atoms of the wood are there, even in the absence of our receptors or the light that may bounce off those atoms. Dig down deep enough, and things have properties that are independent of anything else, right?

Perhaps not. [Quantum physics](#), which describes the bizarre behaviour of the physical world at the most elementary level we know, may be telling us the opposite. Things don't have properties exclusive to themselves: their properties only exist by virtue of their relationship to other things, just like there are really no "chairs" without someone around to interact with them and see them as such. Coming to terms with this idea may clarify the persistently mysterious nature of the quantum world. It might even help make other mysteries, such as the nature of our conscious experience, a little bit less mysterious.

Quantum theory remains puzzling despite a century of total success. The theory is routinely used in condensed-matter, nuclear and particle physics, in astrophysics, chemistry, electronics and much else, and hasn't been found wanting so far. But if you stop and think about what it really tells us about the nature of the world, you cannot avoid becoming perplexed. This is a topic of lively debate in physics and philosophy departments.

A contentious question, in particular, is what the “wave function” – or the more abstract version of this notion, the “quantum state” – really represents. The wave function of an electron, for instance, is an entity diffused in space that we can use to compute the probability of finding the electron at a given position. This notion is often given prominence in the teaching of quantum mechanics. But is the wave function a [genuine, actual picture of reality](#)? Or is it only a tool to tell us what might happen next, like a weather forecast that helps us anticipate where rain might fall?

Interpreting the wave function as the “real stuff” of the world creates difficulties. In our calculations, the wave function jumps (or “collapses” – in the jargon of the theory) when we measure something. When we detect an electron somewhere, for instance, its wave function suddenly concentrates there. But why should nature care if there is anybody measuring anything?

This difficulty was famously expressed by physicist [Erwin Schrödinger](#) in pictorial terms. Before we observe it, the wave function of a cat might be a superposition of a sleeping cat and an awake cat (in Schrödinger’s version, the cat was dead or alive, but it isn’t nice to joke about dying cats). Such a superposition is the source of quantum effects called interference that don’t happen if the cat is either awake or asleep. But how does the cat feel in such a superposition?

How, indeed, would you feel if you were in such a quantum superposition?

Different ideas try to make sense of this strangeness inherent in the wave function picture. They all lead somewhere disconcerting. The [many worlds interpretation](#), for instance, claims that the cat is both sleeping and awake; if you look at it, reality splits into parallel worlds in which two equally real copies of you see those two states of the cat. The "hidden variables" interpretation assumes that some [physical influence is pulling the strings](#), determining what happens – but working on a non-local level of reality that is inaccessible to us. "Physical collapse" interpretations speculate that collapse isn't anything to do with observations, but rather [due to a natural phenomenon going on all the time](#) – which so far, however, hasn't been observed.

There is an alternative to all these unpalatable conclusions. To understand it, it helps to recall a quirk of history – two, in fact.

The first is that, when Schrödinger introduced the wave function in 1926, quantum theory already existed in its full glory, without any wave function. After a first breakthrough by Werner Heisenberg, the formulation of the theory was completed by Max Born with Heisenberg and Pascual Jordan, and independently by Paul Dirac, in 1925.

“Abandon the notion of a wave function that mirrors reality and we can make sense of quantum theory”

This formulation is extraordinarily elegant. It can be summarised by saying that a quantum system is governed by exactly the same variables and equations as in classical physics, with the addition of a single extra equation: $xp - px = i\hbar$. Here x is the position and p the momentum of the system, i is the square-root of -1 and \hbar is the Planck constant, the fundamental constant of nature that defines the scale of the quantum realm. Virtually all the phenomena predicted by quantum theory, from Heisenberg’s famous [uncertainty principle](#) to the atomic bomb, from the laser to quantum computers, follow from this one equation that states that multiplying two physical quantities in a different order gives a different result.

In this language, the theory isn’t about a wave function. It is about facts. The electron is here, the electron is there; the cat is asleep, the cat is awake.

Introducing the wave function, Schrödinger didn’t add predictive power to the theory. The wave function helps to visualise phenomena, for example the wave-like “orbitals” of electrons around the atomic nucleus that you might see in chemistry textbooks. But visualisation can be misleading: the pre-Copernican idea of epicycles carrying the heavenly bodies revolving around Earth, or the 19th-century idea of

heat as a “caloric fluid”, were easy to visualise, but clarity was obtained by abandoning them.



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The second historical quirk is the way Niels Bohr, another founder of quantum physics, synthesised what quantum theory seemed to be telling us. He wrote “the description of a quantum system cannot be separated from the measuring instruments that interact with it”. This idea is called contextuality. It correctly captures the core of the theory, but Bohr’s formulation is misleading because it seems to make “measuring instruments” necessary. In Bohr’s time, quantum systems were indeed studied only in physicists’ labs. But today, almost a century of successes later, we are confident

that quantum theory [applies to everything in the universe](#) – to processes in our next-door neighbour galaxy Andromeda, for example, where we can't be sure anyone is "measuring". Bohr's contextuality observation needs to be generalised and the need for a measurer removed.

This can be done by saying that the description of a physical system cannot be separated from the other physical systems that interact with it. Abandon the notion of a real wave function that mirrors reality and take this statement seriously, and we have a way to make sense of quantum theory.

Properties of a quantum system exist only at the point of interacting with something else, and refer only to interactions. An electron isn't spread like a wave between one interaction and the next: rather, it has no position at all. Schrödinger himself later in life gave up the idea that reality is described by his wave function. "It is better to consider a particle not as a permanent entity, but rather as an instantaneous event. Sometimes these events form chains that give the illusion of being permanent," he wrote. A particle is a sequence of distinct, instantaneous interactions. Its position or any other property exists only in the context of an interaction.

Furthermore, the properties of a system aren't absolute: they are relative to the interacting system. We make a mistake if

we assume that they can be attributed to one single system. In the quantum realm, all facts are relative facts. For instance, it makes no sense in the absolute to ask about the state of Schrödinger's cat. With respect to itself, the cat is either awake or asleep. With respect to the observer outside a box where the cat is hidden, it may be that neither is true: as long as the cat isn't interacting with the observer, the question of its state has no meaning.

This is the central idea of the [relational interpretation](#) of quantum mechanics. I [proposed the basic idea in 1996](#), and it has since slowly attracted attention, first with philosophers and then with a growing number of physicists, who have developed and clarified it. It avoids many worlds, hidden variables and the like, at the price of accepting that the properties of all things are relational: they express how things interact, not how things are.

This reading of quantum phenomena gets rid of the misleading notions of measurements and observers that fog our understanding of the theory. The properties of a system are determined when the system interacts with any other system, whatever this other system is: there are no special systems that are observers. The properties realised in this manner, however, are only relative to the interacting system: they have no consequences for further systems of the universe.

A chair is the way it interacts with its surroundings. To talk about the properties of the chair by itself, when it isn't interacting with anything, is meaningless. All of the properties we commonly use to characterise a chair – its colour, its comfort, its weight – are defined through interactions with something else. And so it is for the properties of the single atoms or elementary particles forming the chair.

The relational interpretation can shed light on various mysteries of the quantum world, such as the strange phenomenon of [entanglement](#), in which two particles seem to communicate with one another instantaneously across great distances. From the relational perspective, there is no instantaneous communication: relative to each particle, there is no fact of the matter about what has happened to the other. It is only when physical communication between the two sides is actually established that correlations become real. At this point, however, there is no more instantaneous communication at a distance.

A question of suppression

The relativity of facts has been beautifully demonstrated by some recent experiments. It is possible to [simulate a complex situation in the laboratory similar to that of the Schrödinger's cat scenario](#). The result shows that, in a precise, technical sense, there are facts that are [true for the](#)

[cat, but not for the external observer.](#)

Why, then, don't we perceive the relativity of facts in everyday life? Why does it only loom so large and problematic when we zoom in on quantum systems? The reason is a well understood phenomenon predicted by quantum theory: decoherence. This is a ubiquitous occurrence that suppresses quantum interference effects whenever very large numbers of particles are involved.

Last year, my colleague Andrea Di Biagio at the Sapienza University of Rome and I showed [that decoherence renders](#) relative facts "stable", diluting quantum interference effects to a level at which they are so subtle as to be practically unobservable. Their dependence on the interacting system becomes irrelevant, because we would need to log a number of details too large for us to observe in order to detect the interference that could reveal the relativity of facts. In the case of the cat, for instance, the suppression of interference between asleep-cat and awake-cat allows us to say that however the cat appears relative to us is also the case relative to any other system: no observation can make the distinction.



Lee Robinson Photography

The relational interpretation doesn't imply that each observer is isolated in their own world. Stability makes reality nearly identical for all. More importantly, all real observers are physical systems and therefore can interact. They can simply ask one another what they have seen, and the theory predicts agreement. Paradoxes appear only if we disregard the fact that any communication between observers is itself at heart a quantum interaction, and therefore suffers always a margin of imprecision due to Heisenberg's uncertainty principle, which says that there are properties of a quantum object that can't be sharply determined together in any one interaction.

“We think about a world of things with absolute properties because this is what we experience”

As hinted at in the opening of this article, it isn't a novelty to realise that aspects of the world are relational. Biology, psychology, economics and many other sciences focus on relations more than entities. Physics itself is already full of relational notions: velocity is only defined with respect to something else, as are electric or gravitational potential and orientation, to name just some examples. The physical world seemed to provide a non-relational substratum formed by substances with absolute properties. Quantum mechanics, I think, is the discovery that this isn't the case: the world is woven by relationships that go all the way down to the smallest physical entities.

An understanding of the world in terms of relations rather than entities might even help us disentangle other thorny issues, for instance the nature of [consciousness](#). If we think of the physical world as if it were made by little stones each with its own properties, the jump from this picture to the subjective experience of mental phenomena is huge. But if the physical nature of the world is better described in terms of how physical systems, simple as well as complex ones, affect one another, perhaps the disjoint will appear less dramatic: products of the mind are just the complex phenomenon formed by the tangled and [richly interwoven](#)

[interactions between the world and the brain.](#)

Our old metaphysical prejudice was that physical reality is made by some fundamental substance with absolute properties. Quantum theory questions this. I think this is fine: our metaphysical prejudices have formed and evolved within the restricted domain of our everyday experience. We are used to thinking about the world in terms of things with absolute properties because this is what we experience, thanks to the stability generated by decoherence. But we shouldn't force what we have discovered about nature to align with these prejudices: rather, our prejudices should be modified by our discoveries about nature.

Quantum theory has altered our understanding of physical reality in ways that are even more profound than the Copernican revolution, when we learned that we live on a madly spinning rock. Digesting the full implications of Nicolaus Copernicus's work has taken centuries. We are only beginning to digest the full implications of the quantum revolution.

How to make sense of quantum theory Explore quantum mysteries live with Carlo Rovelli at our online event on Thursday 1 April: [newscientist.com/events](https://www.newscientist.com/events)