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WHAT DOES QUANTUM MECHANICS SAY ABOUT REALITY?

First major survey of physicists finds interpretations in conflict. By Elizabeth Gibney

Quantum mechanics is one of the most successful theories in science – and makes much of modern life possible. Technologies ranging from computer chips to medical-imaging machines rely on the application of equations, first sketched out a century ago, that describe the behaviour of objects at the microscopic scale.

But researchers still disagree widely on how best to describe the physical reality that lies behind the mathematics, as a *Nature* survey reveals.

At an event to mark the 100th anniversary of quantum mechanics last month, lauded specialists in quantum physics argued politely – but firmly – about the issue. “There is no quantum world,” said physicist Anton Zeilinger, at the University of Vienna, outlining

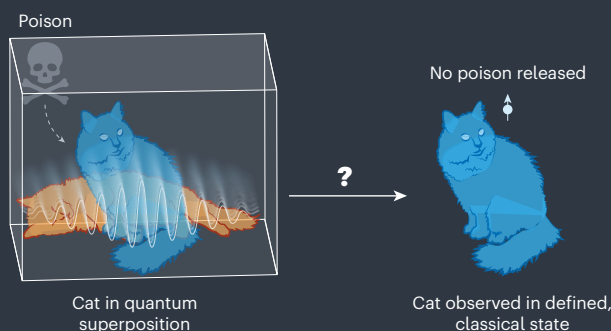
QUANTUM MECHANICS: FIVE INTERPRETATIONS

Here are five broad approaches to interpreting quantum mechanics — and how they address the quantum measurement problem. In quantum theory, an unobserved system can be described as being in a superposition of multiple possible states at once, for example in different locations. Its quantum state is given by a wavefunction, which evolves according to Schrödinger's equation in a smooth, predictable way. But when interacting with measuring equipment, the system acquires a well-defined state, unknowable in advance. Its wavefunction 'collapses', as some say. How to make sense of this?

The 'Schrödinger's cat' thought experiment showcases the conundrum. Here, whether poison is released — potentially killing a cat in a box — depends on radiation being emitted, a random quantum event. Until the box is opened, the cat can be described as a superposition of alive and dead; on looking inside the box, it is in only one of the two states.

Copenhagen interpretation

This view holds that the observer, and their classical world, are distinct from the quantum systems they can interact with. The particle has properties only when measured by an observer; they are not predefined.



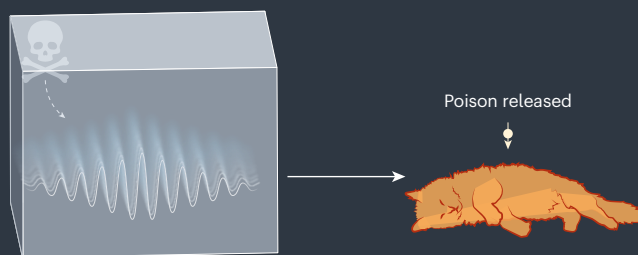
Pros: Practical — it describes experimental observations well.

Cons: Avoids explaining precisely what a measurement is and how it triggers change between quantum and classical worlds, or why outcomes should be predictable from the wavefunction.

How it addresses 'Schrödinger's cat': Measurement simply forces a quantum object into a defined state: an explanation not everyone finds satisfying.* Some modern Copenhagen interpretations take an epistemic approach (see below), and therefore see no conundrum.

Epistemic approaches

Quantum states represent only information; they encode the probabilities of obtaining different outcomes on measurement. An example is relational quantum mechanics, in which the quantum states of a system can be defined only in relation to another specific system. Another is QBism, in which quantum states are always defined from the point of view of a specific observer or 'agent'.



Pros: Explains thought-experiment paradoxes in which the observers of a quantum system obtain different outcomes. Allows for entanglement (when quantum states of two particles become inseparable, so that measurements of their properties are correlated even across large distances) to be something non-physical, which avoids the need for faster-than-light influences that would conflict with relativity.

Cons: Reality can never be viewed from an objective perspective; some forms of these theories give up on being able to describe an external reality at all.

How it addresses 'Schrödinger's cat': The wavefunction is viewed as just a mathematical tool; its collapse is not a physical process, so there is no paradox involving reality.

*In practice, it would be extremely hard to isolate the quantum state of a cat-sized object from that of its noisy environment; its state would have been resolved as alive or dead before measurement.

his view that quantum states exist only in his head and that they describe information, rather than reality. "I disagree," replied Alain Aspect, a physicist at the University of Paris-Saclay, who shared the 2022 Nobel prize with Zeilinger for work on quantum phenomena.

To gain a snapshot of how the wider community interprets quantum physics in its centenary year, *Nature* carried out the largest ever survey on the subject. We e-mailed more than 15,000 researchers whose recent papers involved quantum mechanics, and also invited attendees of the centenary meeting, held on the German island of Heligoland, to take the survey.

The responses — numbering more than 1,100, mainly from physicists — showed how widely researchers vary in their understanding of the most fundamental features of quantum experiments (see 'Favoured explanations of quantum theory').

As did Aspect and Zeilinger, respondents differed radically on whether the

wavefunction — the mathematical description of an object's quantum state — represents something real (36%) or is simply a useful tool (47%) or something that describes subjective beliefs about experimental outcomes (8%; see 'What is the wavefunction?'). This suggests that there is a significant divide between researchers who hold 'realist' views, which project equations onto the real world, and those with 'epistemic' ones, which say that quantum physics is concerned only with information.

The community was also split on whether there is a boundary between the quantum and classical worlds (45% of respondents said yes, 45% no and 10% were not sure). Some baulked at the set-up of our questions, and more than 100 respondents gave their own interpretations (the survey, methodology and an anonymized version of the full data are available online).

"I find it remarkable that people who are very knowledgeable about quantum theory can be convinced of completely opposite

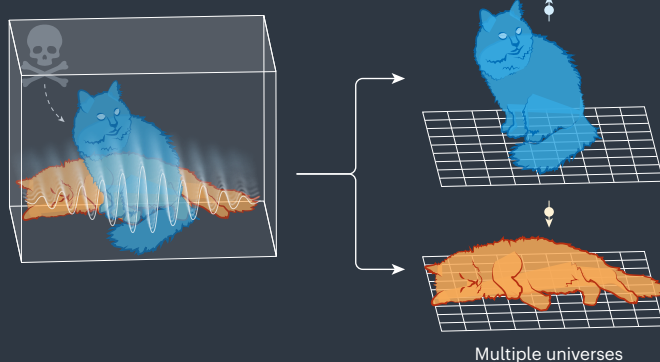
views," says Gemma De les Coves, a theoretical physicist at the Pompeu Fabra University in Barcelona, Spain.

Nature asked researchers what they thought was the best interpretation of quantum phenomena and interactions — that is, their favourite of the various attempts scientists have made to relate the mathematics of the theory to the real world. The largest chunk of responses, 36%, favoured the Copenhagen interpretation — a practical and often-taught approach. But the survey also showed that several, more radical, viewpoints have a healthy following.

Asked about their confidence in their answer, only 24% of respondents thought their favoured interpretation was correct; others considered it merely adequate or a useful tool in some circumstances. What's more, some scientists who seemed to be in the same camp didn't give the same answers to follow-up questions, suggesting inconsistent or disparate understandings

Many worlds

The wavefunction describes something corresponding to physical reality. When an observer makes a measurement, they obtain a result from their vantage point in one world; but the wavefunction never actually collapses. Instead, the wavefunction branches into multiple universes, each describing a different measurement outcome.



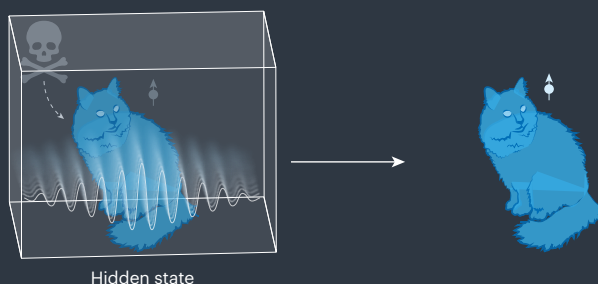
Pros: Removes the measurement problem. Explains outcomes of measurements on entangled particles by having each combination of correlated results exist in a different world, rather than requiring a physical influence to travel across space-time.

Cons: Allows for an enormous number of realities. Not clear whether it can account for our ability to predict that some outcomes are more likely than others.

How it addresses 'Schrödinger's cat': Each branched universe features a copy of the observer who sees a definite measurement outcome, with 'alive' and 'dead' possibilities existing in separate worlds.

Bohmian

Point-like particles follow definite trajectories and their properties have defined values. The wavefunction also describes a physical reality, serving as a pilot wave that guides the particles. The full state of a particle, described by its position as well as its wave, can never be fully known; it is in part hidden.



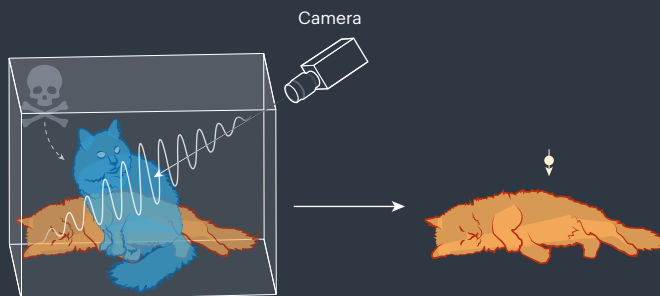
Pros: Signifies that nature is not inherently random; properties with determined values exist before measurement.

Cons: To explain entanglement, pilot-wave interactions can have instantaneous effects. If these effects happen faster than the speed of light, Bohmian mechanics becomes difficult to reconcile with Einstein's special theory of relativity.

How it addresses 'Schrödinger's cat': The wavefunction is only part of the system: pilot waves act as guides for the cat, which has a definite (hidden) state. This predetermined outcome is revealed on measurement.

Spontaneous collapse

Interprets quantum mechanics as an approximation to a different theory, in which Schrödinger's equation is modified such that the wavefunction collapses by itself without the need for measurement.



Pros: Solves the measurement problem.

Cons: So far, no experiments have found evidence for modifications to Schrödinger's equation. Like other theories involving an instantaneous physical collapse, it is difficult to reconcile with special relativity.

How it addresses 'Schrödinger's cat': When the cat's state is observed, its quantum state becomes entangled with the measuring equipment (here, a camera). Any large collection of quantum objects such as this inevitably collapses to a defined state, according to the tweaked Schrödinger's equation*.

of the interpretation they chose.

"That was a big surprise to me," says Renato Renner, a theoretical physicist at the Swiss Federal Institute of Technology (ETH) in Zurich. The implication is that many quantum researchers simply use quantum theory without engaging deeply with what it means – the 'shut up and calculate' approach, he says, using a phrase coined by US physicist David Mermin. But Renner, who works on the foundations of quantum mechanics, is quick to stress that there is nothing wrong with just doing calculations. "We wouldn't have a quantum computer if everyone was like me," he says.

Copenhagen still reigns supreme

Over the past century, researchers have proposed many ways to interpret the reality behind the mathematics of quantum mechanics, which seems to throw up jarring paradoxes. In quantum theory, an object's behaviour is characterized by its wavefunction:

a mathematical expression calculated using an equation devised by Austrian physicist Erwin Schrödinger in 1926. The wavefunction describes a quantum state and how it evolves as a cloud of probabilities. As long as it remains unobserved, a particle seems to spread out like a wave; interfering with itself and other particles to be in a 'superposition' of states, as though in many places or having multiple values of an attribute at once. But an observation of a particle's properties – a measurement – shocks this hazy existence into a single state with definite values. This is sometimes referred to as the 'collapse' of the wavefunction.

It gets stranger: putting two particles into a state of joint superposition can lead to entanglement, which means that their quantum states remain intertwined even when the particles are far apart.

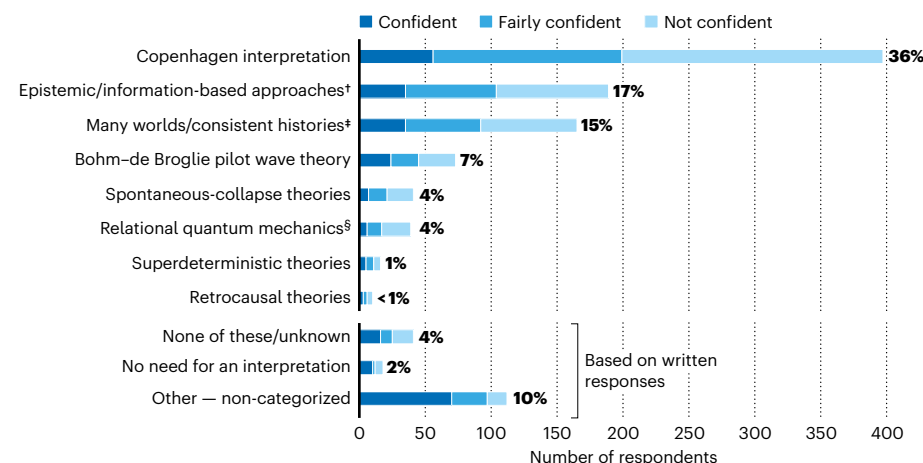
The German physicist Werner Heisenberg, who helped to craft the mathematics behind quantum mechanics in 1925, and his mentor,

Danish physicist Niels Bohr, got around the alien wave-particle duality largely by accepting that classical ways of understanding the world were limited, and that people could only know what observation told them. For Bohr, it was OK that an object varied between acting like a particle and like a wave, because these were concepts borrowed from classical physics that could be revealed only one at a time, by experiment. The experimenter lived in the world of classical physics and was separate from the quantum system they were measuring.

Heisenberg and Bohr not only took the view that it was impossible to talk about an object's location until it had been observed by experiment, but also argued that an unobserved particle's properties really were fundamentally unfixed until measurement – rather than being defined, but not known to experimenters. This picture famously troubled Einstein, who persisted in the view that there was a pre-existing reality that it was science's job to measure.

FAVoured EXPLANATIONS OF QUANTUM THEORY

The Copenhagen interpretation of quantum mechanics was chosen by more than one-third of the 1,101 respondents to *Nature's* survey*. But many respondents were not confident in their chosen answer.



*Questions: "Which of the following, in your opinion, provides the best interpretation of quantum phenomena and interactions?", followed by: "How confident are you in your answer above about the best interpretation?", with these options:

Confident: I think this is the correct interpretation.
Fairly confident: I think this is an adequate interpretation.
Not confident: I think this is just the best interpretation I am aware of or one that is useful as a tool in certain situations.

†Includes six respondents (<1% who selected 'Other' and wrote in 'QBism', which is an epistemic theory.

‡These categories were inappropriately grouped together in the survey; see Correction note for details.

§Also an epistemic approach.

Decades later, an amalgamation of Heisenberg's and Bohr's not-always-unified views became known as the Copenhagen interpretation, after the university at which the duo did their seminal work. Those views remain the most popular vision of quantum mechanics today, according to *Nature's* survey. For Časlav Brukner, a quantum physicist at the University of Vienna, this interpretation's strong showing "reflects its continued utility in guiding everyday quantum practice". Almost half of the experimental physicists who responded to the survey favoured this interpretation, compared with 33% of the theorists. "It is the simplest we have," says Décio Krause, a philosopher at the Federal University of Rio de Janeiro, Brazil, who studies the foundations of physics, and who responded to the survey. Despite its issues, the alternatives "present other problems which, to me, are worse", he says.

But others argue that Copenhagen's emergence as the default comes from historical accident, rather than its strengths. Critics say it allows physicists to sidestep deeper questions.

One concerns the 'measurement problem', asking how a measurement can trigger objects to switch from existing in quantum states that describe probabilities, to having the defined properties of the classical world.

Another unclear feature is whether the wavefunction represents something real (an answer selected by 29% of those who favoured the Copenhagen interpretation) or just information about the probabilities of finding various values when measured (picked by 63% of this group). "I'm disappointed but not surprised at the popularity of Copenhagen," says Elise Crull, a philosopher of physics at the City University of New York. "My feeling is that physicists haven't reflected."

The Copenhagen interpretation's philosophical underpinnings have become so normalized as to seem like no interpretation at all, adds Robert Spekkens, who studies quantum foundations at the Perimeter Institute for Theoretical Physics in Waterloo, Canada. Many advocates are "just drinking the Kool-Aid of the Copenhagen philosophy without examining it", he says.

Survey respondents who have carried out research in philosophy or quantum foundations, studying the assumptions and principles behind quantum physics, were the least likely to favour the Copenhagen interpretation, with just 20% selecting it. "If I use quantum mechanics in my lab every day, I don't need to go past Copenhagen," says Carlo Rovelli, a theoretical physicist at Aix-Marseille University in France. But as soon as researchers apply thought experiments that probe more deeply, "Copenhagen is not enough", he says.

What else is on the menu?

In the years after the Second World War and the development of the atomic bomb, physicists began to exploit the uses of quantum mechanics, and the US government poured cash into the field. Philosophical investigation was put on the back burner. The Copenhagen interpretation came to dominate mainstream physics, but still, some physicists found it unsatisfying and came up with alternatives (see 'Quantum mechanics: five interpretations').

In 1952, US physicist David Bohm resurfaced an idea first touted in 1927 by French physicist Louis de Broglie, namely that the strange dual nature of quantum objects made sense if they were point-like particles with paths determined by 'pilot' waves. 'Bohmian' mechanics had the advantage of explaining interference

effects while restoring determinism, the idea that the properties of particles do have set values before being measured. *Nature's* survey found that 7% of respondents considered this interpretation the most convincing.

Then, in 1957, US physicist Hugh Everett came up with a wilder alternative, one that 15% of survey respondents favoured. Everett's interpretation, later dubbed 'many worlds', says that the wavefunction corresponds to something real. That is, a particle really is, in a sense, in multiple places at once. From their vantage point in one world, an observer measuring the particle would see only one outcome, but the wavefunction never really collapses. Instead it branches into many universes, one for each different outcome. "It requires a dramatic readjustment of our intuitions about the world, but to me that's just what we should expect from a fundamental theory of reality," says Sean Carroll, a physicist and philosopher at Johns Hopkins University in Baltimore, Maryland, who responded to the survey.

In the late 1980s, 'spontaneous collapse' theories attempted to resolve issues such as the quantum measurement problem. Versions of these tweak the Schrödinger equation, so that, rather than requiring an observer or measurement to collapse, the wavefunction occasionally does so by itself. In some of these models, putting quantum objects together amplifies the likelihood of collapse, meaning that bringing a particle into a superposition with measuring equipment makes the loss of the combined quantum state inevitable. Around 4% of respondents chose these sorts of theories.

Nature's survey suggests that 'epistemic' descriptions, which say that quantum mechanics reveals only knowledge about the world, rather than representing its physical reality, might have gained in popularity. A 2016 survey¹ of 149 physicists found that only around 7% picked epistemic-related interpretations, compared with 17% in our survey (although the precise categories and methodology of the surveys differed). Some of these theories, which build on the original Copenhagen interpretation, emerged in the early 2000s, when applications such as quantum computing and communication began to frame experiments in terms of information. Adherents, such as Zeilinger, view the wavefunction as merely a tool to predict measurement outcomes, with no correspondence to the real world.

The epistemic view is appealing because it is the most cautious, says Ladina Hausmann, a theoretical physicist at the ETH who responded to the survey. "It doesn't require me to assume anything beyond how we use the quantum state in practice," she says.

One epistemic interpretation, known as QBism (which a handful of respondents who selected 'other' wrote down as their preferred interpretation), takes this to the extreme,

stating that observations made by a specific ‘agent’ are entirely personal and valid only for them. The similar ‘relational quantum mechanics’, first outlined by Rovelli in 1996 (and selected by 4% of respondents), says that quantum states always describe only relationships between systems, not the systems themselves.

When asked specific follow-up questions about how to view aspects of quantum mechanics, researchers’ opinions differed sharply, as could be expected from the variety in overall interpretations they favoured.

One question that elicited a mix of answers relates to one of the weirdest aspects of quantum mechanics: that the outcomes of observations on entangled particles are correlated, even if the particles are moved thousands of kilometres apart. This potential for distant connection is referred to as non-locality. The connection doesn’t allow faster-than-light communication. But whether it nevertheless represents a kind of real and instantaneous influence across space-time, such that measuring one particle instantly changes its entangled partner and affects the results of future measurements, is something that respondents disagreed on.

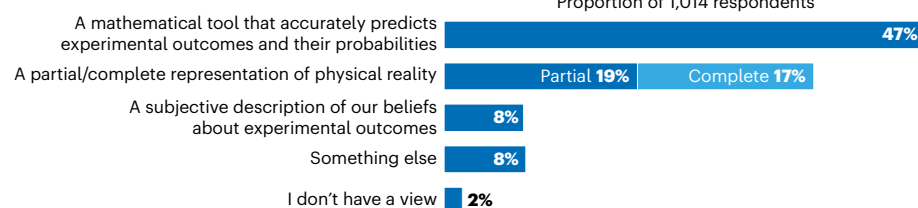
In the survey, 39% of respondents said they thought that such ‘action at a distance’ was real. The remainder either weren’t sure or disagreed in a variety of ways. If respondents answering ‘yes’ meant to imply that a physical influence is travelling faster than light, this would conflict with Einstein’s special theory of relativity, says Flaminia Giacomini, a theoretical physicist at the ETH. “This should worry every serious physicist,” adds Renner. “I’m puzzled.”

However, some respondents, such as those who take epistemic views, might have answered ‘yes’ but have interpreted instantaneous influence to mean merely an instant change in their information, rather than a physical effect, says Giacomini.

Breaking the stalemate

How is it possible to disagree so strongly about the underlying world that quantum theory describes, when everyone does the same calculations? Besides revealing the different attitudes of experimenters and theorists – and the tendency of people who study quantum foundations to avoid the Copenhagen interpretation – the views in *Nature’s* survey didn’t seem to correlate with other factors. One such factor is gender (only 8% of respondents identified as women, which, although low, accords with a finding earlier this year that only 8% of senior authors in *Nature Physics* papers were women²). Where in the world people have worked, and their religion, also seemed to have little effect (although too few answered the last question for the result to be conclusive). The closest that respondents got to consensus was that attempts to interpret the mathematics of quantum mechanics in a physical or an

WHAT IS THE WAVEFUNCTION?



intuitive way are valuable – 86% agreed.

Three-quarters of respondents also thought that quantum theory would be superseded in the future by a more complete theory, although most also thought that elements of it would survive. Although quantum mechanics is among the most experimentally verified theories in history, its mathematics cannot describe gravity, which is instead explained as a curving of space-time by the general theory of relativity. This leads many researchers to think that quantum physics might be incomplete.

Researchers who work on quantum foundations say that picking an interpretation comes down to choosing between the sacrifices each entails. To adopt many worlds is to accept that there are an unfathomable number of universes we can probably never access. To be QBist means admitting that quantum theory can’t describe a single reality for all observers

“It’s just embarrassing that we don’t have a story to tell people about what reality is.”

(although without necessarily denying that a shared reality exists). What price someone is willing to pay comes down to not merely physics training, but something personal, says Renner. “It’s a very deeply emotional thing,” he says. Almost half of the respondents to *Nature’s* survey said that physics departments do not give enough attention to quantum foundations (with just 5% saying there was “too much”).

All interpretations, broadly, predict the same results. But that doesn’t mean that ways can’t be found to distinguish them. A 1960s proposal by UK physicist John Bell has already constrained quantum physics. His thought experiments, put into practice in many formats since then, use measurements on entangled particles to prove that quantum physics cannot be both realist and local. Realist means that particles have properties that exist whether they are measured or not, and local means that objects are influenced only by their immediate – rather than distant and unconnected – surroundings.

New ways of probing quantum interpretations continue to emerge. Last month, for instance, physicists studying the phenomenon of quantum tunnelling, in which particles

burrow through barriers that, classically, would be impossible to surmount, argued that the measured speed of the process did not fit with predictions from Bohm’s pilot-wave theory³. Some 58% of respondents to *Nature’s* survey thought that experimental results will help to decide between viable approaches. Some respondents mentioned efforts to scale up superpositions to biological systems. Others referred to probing the interface between quantum physics and gravity.

Some physicists think that exploiting superposition inside quantum computers will reveal more about such phenomena. In 2024, when Hartmut Neven, founder of Google Quantum AI in Santa Barbara, California, announced the firm’s Willow quantum chip, he argued that its ability to perform a calculation that would take longer than the age of the Universe on the fastest classical computer “lends credence to the notion that quantum computation occurs in many parallel universes”. He was referring to a 1997 extension to the many-worlds theory by David Deutsch, a physicist at the University of Oxford, UK.

Agreeing on a single interpretation might be a case of coming up with a new approach altogether. “Once we find the correct interpretation, it will announce itself by virtue of offering more coherence than anything before,” says Spekkens. “I think we should aim for that.”

Whether the current state of affairs is a problem or not depends on who you ask. “It’s just embarrassing that we don’t have a story to tell people about what reality is,” concluded Carlton Caves, a theoretical physicist at the University of New Mexico in Albuquerque, and moderator of the foundations panel at the Heligoland meeting.

Crull disagrees. People are taking the question of interpretations seriously, she says, “and it’s not leading to chaos and it’s not embarrassing. It’s leading to progress, to creativity. There’s a kind of joy there.”

Elizabeth Gibney is a senior reporter for *Nature* based in London. Additional survey analysis by Richard Van Noorden and Jeff Perkel.

1. Sivasundaram, S. & Nielsen, K. H. Preprint at arXiv <https://doi.org/10.48550/arXiv.1612.00676> (2016).
2. Hallas, A. M. *Nature Phys.* **21**, 491–493 (2025).
3. Sharoglazova, V., Puplauskis, M., Mattschas, C., Toebe, C. & Klaers, J. *Nature* **643**, 67–72 (2025).

Correction

This News feature gave the wrong nationality for Erwin Schrödinger. Furthermore, the survey it was based on grouped the 'many worlds' (MW) and 'consistent histories' (CH) interpretations together, with the rationale that both involve the quantum state evolving smoothly and both involve branching into different worlds. In fact, CH does not involve branching into different worlds, so should not have been grouped with MW. Three respondents wrote in free-text boxes that they preferred CH; of these, two had selected 'other' in their answer to the quantum interpretation they preferred, and one had selected the Copenhagen interpretation.