Speaking in ripples

Unseen influences may explain the mysteries of quantum reality, says Anil Ananthaswamy

SAM CHIVERS

IN OCTOBER 1951, physicist David Bohm left the US for Brazil. Branded a communist sympathiser, he had been arrested for refusing to testify to the US Congress. Acquitted, he was still stripped of his Princeton professorship. His departure began an exile that would last until his death, as a naturalised British citizen, four decades later.

The theory Bohm was nurturing as he left his native shores has spent even longer in the cold. In part, that's down to politics. But his ideas also seemed scientifically beyond the pale. Bohm proposed there was a hidden reality to quantum theory, meaning its crazy predictions of a world that doesn't exist until you choose to look at it are just that: crazy.

That went against the established grain, and still does. But more than six decades on, Bohm is getting a fresh hearing, as new experiments are hinting that he might have been on to something. If so, some aspects of reality would become easier to fathom, while others would be harder to stomach. Forget standard quantum weirdness – the world Bohm revealed is a more profoundly and mysteriously interconnected place than we ever imagined.

It wasn't always distasteful to suggest that reality is, well, real. Before quantum physics, our understanding was governed by classical theories in which reality exists regardless of observers. Newton's laws of motion, for example, say we live in a clockwork, deterministic world that behaves in well-defined, predictable ways independently from what we are doing.

The thin end of the wedge came in 1905, when Albert Einstein said that the photoelectric effect, in which certain metals give out electrons when illuminated, can only be explained if light is made up of quantum particles – photons, as they came to be called.

The thing was, light was known to be a wave. In the early 1800s, Thomas Young had done a version of the now classic double-slit experiment, in which light is shone at two parallel slits. The interference pattern formed on a screen beyond is what we would expect if waves of light were spreading outwards from both slits – behaviour that seems impossible if it is made of single particles.

So which is it then – particle or wave? Both, as versions of Young's experiment have since confirmed. These involve light so dim that only one photon at a time passes through the double slit. Each photon lands on the screen at some seemingly random spot. Over time, however, these positions turn out not to be random; rather, the accumulated spots form an interference pattern, as if each photon were going through both slits and interfering with itself.

Try to detect the photons' path through one or the other slit, however, and the interference pattern disappears. Not only is light's nature fundamentally ambiguous, but its guise seems determined by what we choose to measure. And as a young French physicist named Louis de Broglie proposed in 1924, it's not just light. Experiments soon confirmed all the quantum particles that make up material reality have this dual nature, too.

Finding that reality's true character is slippery is still a big step away from saying it doesn't exist when we aren't looking. Yet this is exactly what orthodox quantum mechanics says. In this picture, often called the Copenhagen interpretation after the Danish city where it took shape, a quantum object is represented by a mathematical wave function that allows us to make probabilistic predictions of what we will find when we measure things. Only on measurement does this wave function "collapse" to reveal something localised in space and time. In the words of Werner Heisenberg, a pioneer of the Copenhagen interpretation, "the idea of an objective real world whose smallest parts exist objectively in the same sense as stones or trees exist, independently of whether or not we observe them… is impossible". That remains the dominant view to this day.

> "Reality's nature is slippery, but that's a big step from saying it doesn't exist"

Yet it's not the only possible interpretation (see "The many guises of quantum theory", page 31). De Broglie suggested another: that particles are real and have equally real waves associated with them. In this picture, when a particle goes through one of the double slits, its "pilot" wave goes through both, interferes with itself, and then guides the particle to a location on the screen.

De Broglie presented his ideas at the 1927 Solvay Conference in Brussels, a legendary gathering of the early quantum greats. But he had not developed the theory mathematically, and it received a lukewarm reception. He quietly dropped the idea, becoming an adherent of the Copenhagen interpretation.

David Bohm was unaware of de Broglie's work when, in the early 1950s, he developed a mathematically solid theory in which a wave with properties identical to that of the wave function guides particles around. "This › wave is a pilot wave," says physicist Sheldon Goldstein of Rutgers University in New Jersey, "It choreographs the motion of the particles."

Bohm's theory made exactly the same predictions as standard quantum theory. But the fact that you could only predict outcomes of experiments probabilistically was because you lacked knowledge about the particles' initial state, not because nature doesn't exist when you're not looking. Bohm's ideas made de Broglie revisit and revise his own pilot-wave theory. He developed a two-wave theory in which every particle rides a pilot wave, which in turn interacts with another wave that behaves like a wave function.

Spooky influences

Both of these pictures also explained another central feature of the quantum world – the way "entangled" quantum objects seem to influence each other's states instantaneously at a distance. Standard Copenhagen quantum mechanics provides no explanation for this non-locality, or "spooky action", as Einstein dismissively referred to it. In the alternative picture, though, if particles are entangled, a common pilot wave guides them, and any change in the position or momentum of one particle instantly changes the pilot wave, thus influencing all the other particles. "The fact that Bohmian mechanics is non-local is not a defect of the theory," says Roderich Tumulka, Goldstein's colleague at Rutgers. "It is a feature that a true theory has to have."

In another world, Bohm's work might have been seen as a breakthrough. But by the time the idea was published in 1952, he was already in exile. "A lot of the reception of Bohm's theory is tied up with that," says David Albert, a philosopher of physics at Columbia University in New York City. It didn't help that Einstein, then in his twilight years and a vocal critic of quantum theory, dismissed it too. In a letter to Max Born, another quantum pioneer, he wrote: "Bohm believes (as de Broglie did, by the way, 25 years ago) that he is able to interpret the quantum theory in deterministic terms... That seems too cheap to me." Bohmian mechanics entered the twilight zone of scientific theories – not quite dead, but not really a live concern either.

And there it has largely stayed, bar the odd finding that, if anything, hindered its revival. In 1992, for example, a thought experiment by physicist Marlan Scully of Texas A&M University and his colleagues showed that the theory made it possible for a particle to be measured passing through one slit in a double-slit experiment, but then land on the screen at a position that implied it had passed through the other. "Tersely: Bohm trajectories are not realistic, they are surrealistic," they wrote.

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The many guises of quantum theory

Why does reality only seem to coalesce into a definite state when you make a measurement? The answer depends on your preferred view of the quantum world

Copenhagen interpretation
The "shut up and calculate" view: the quantum world does not exist in any meaningful sense without measurements.

Many worlds interpretation
Make a measurement and the universe splits, taking you into the parallel world where you got the result you did.

Objective collapse
Spread-out quantum states are collapsing into definite states all the time. Your clodhopping measurement just helps things on their way.

Quantum Bayesianism
Quantum uncertainty is not intrinsic to reality – it has to do with your own lack of knowledge about whatever you are attempting to measure.

Information
When you measure something, you extract some physical form of information from it, forcing it into a high-definition state.

Bohmian mechanics
Reality is guided by pilot waves; measurement just discovers what reality is up to, in the same way as classical physics (see main story).

It was a series of unlikely experiments involving oil droplets that started to change some minds. In 2005, Yves Couder and Emmanuel Fort at Denis Diderot University in Paris stumbled upon a physical analogue of pilot waves. They discovered that if they let a millimetre-sized droplet of silicone oil fall on to a bath of the same oil that was vibrating up and down, the droplet would bounce indefinitely on the surface. And not just that: when it bounced the first time, it created a wave that it encountered on the next bounce, which gave the droplet a horizontal as well as a vertical kick. The bouncing droplet started wandering across the oil bath, guided by the very wave that it had created and helped sustain with each bounce.

The interesting thing was what happened when this wave-particle system encountered a barrier, a fraction of a millimetre below the surface, with two gaps in it: a double slit. The walking droplet went over one or the other slit, while its pilot wave went over both, and the wave pattern that emerged on the other side guided the droplet on. The researchers collected 75 such trajectories, and their analysis suggested the formation of an interference pattern on the far side of the slits. Despite there only ever being one particle-like droplet in the apparatus at any time, its pilot wave was causing it to acquire seemingly wave-like behaviour. If you couldn't see the wave, the pattern built up over time would make you think the droplets had gone through both slits (*Physical Review Letters*, vol 97, p 154101).

It was clearly only an analogy, and attempts by other teams to repeat the work suggest that the supposed interference pattern might have been the product of air currents, as well as inadequate statistics. More recently, John Bush and his colleagues at the Massachusetts Institute of Technology have performed a more rigorous version of the experiment, with proper shielding from air currents. They found, once again, that the bouncing droplet creates a pilot wave that guides it on – and they discovered a second wave pattern. Created by the interaction of the droplet with the edge of the circular bath, this pattern in the droplet's position emerges over time and has properties that mimic the wave function. This is just as in de Broglie's more complex version of pilot-wave theory (*Journal of Fluid Mechanics*, DOI: 10.1017/jfm.2016.537).

The bouncing droplet experiments have allowed Couder's and Bush's teams to observe behaviour usually seen only in quantum systems. For example, the statistics of the droplet's seemingly chaotic movements bear an uncanny resemblance to those of an electron moving inside a corral of atoms. "Now we have a macroscopic realisation of the physical picture suggested by de Broglie, and it exhibits many of the allegedly inscrutable features of quantum mechanics," says Bush. "That's a hell of a coincidence."

Maybe – but there was still the problem of those contradictory, surrealist particle paths the alternative theory seems to allow. Last year, a refined version of the double-slit experiment conducted by Aephraim Steinberg of the University of Toronto, Canada, and his colleagues suggested that might not be quite such a problem after all. Brace yourself, because this is where things get really weird.

First, the researchers created pairs of photons with entangled polarisations. One photon of each pair was sent through the double slit, which was designed so that if the photon was vertically polarised it would go through slit A, and if horizontally polarised through slit B. The second photon served as a probe: thanks to the entanglement, measuring its polarisation was akin to knowing the polarisation of the photon passing through the slits, and thus which slit it must have gone through (see "Really surreal", below left).

This set-up gave the team two bites at the same cherry: they were able to determine the travelling photon's position as it went through the apparatus, and could also measure the polarisation state of the associated probe photon. They did this with tens of thousands of photon pairs, and found that, on average, at the moment a photon passed through slit A, the probe photon would be vertically polarised, as expected. But at the screen, things were a lot more ambiguous. When a travelling photon was measured at a position on the screen corresponding to ›

Really surreal

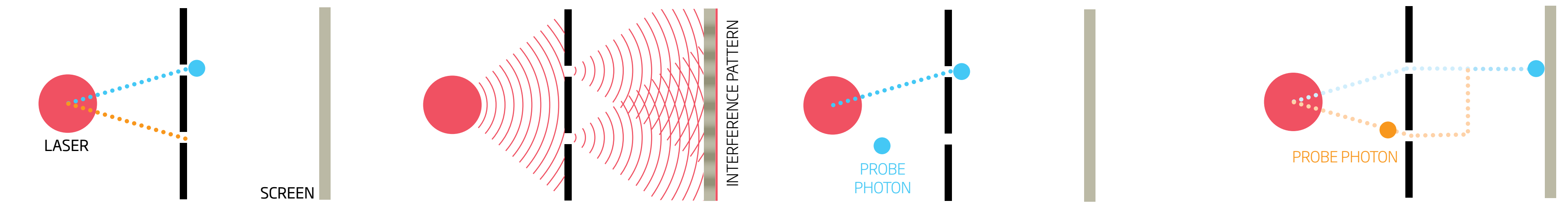
Quantum double-slit experiments tell us that nothing is quite as it seems

Measurements at the slits detect single photons passing through one slit or the other: **light is made of particles**

Allow the photons to reach the screen and an interference pattern develops over time: **light is a wave**, and it passes through both slits

Now introduce an entangled "probe" photon that tells us which slit its partner photon passed through. Measure at the slits again, and the states of the two photons must agree

Take measurements at the screen, however, and half the time they disagree: the state of the probe suggests the travelling photon went through one slit, but its position on the screen implies it passed through the other – **a seemingly surreal trajectory**



having passed through slit A, half the time the polarisation of the probe photon was horizontal – suggesting that the travelling photon had passed through slit B. These were seemingly surreal trajectories, unmasked (*Science Advances*, vol 2, p e1501466).

Reality regained

What's happening? In a word, non-locality. The experiment shows that the moving photon is constantly changing the polarisation of the probe photon. Look at the probe photon at the moment the moving photon goes through a slit, and there is no contradiction. But look at it the moment the moving photon hits the screen and, half of the time, its polarisation state has changed. This sort of non-locality is admissible in standard quantum theory, but it is baked into Bohm's version. The experiment is by no means a proof of Bohm's theory, but it shows that its prediction of surreal trajectories cannot be used to debunk it.

So Bohmian mechanics can and should remain a contender, says Albert. "Any realist picture is preferable to any anti-realist picture," he says.

But winning hearts and minds will still be a struggle. For a start, Bohmian mechanics is formulated to replicate the predictions of standard quantum mechanics: experimentally, it's almost impossible to tell them apart. Also, the theory is mathematically fleshed out only for particles travelling far slower than the speed of light. Quantum mechanics, in contrast, has been extended to embrace relativistic particles travelling close to the speed of light, and so forms the basis of quantum field theory and the standard model of particle physics. "Clean, worked-out Bohmian versions of those things do not exist," says Goldstein.

For David Kaiser, a physicist and historian of science at MIT, that may be the theory's Achilles heel. "My aesthetic concern is that it feels, in the original description at least, horribly non-relativistic, anti-relativistic," he says.

Goldstein and his colleagues have been trying since the mid-1990s to marry Bohm's ideas with Einstein's special relativity. The hardest part is to accommodate the instantaneous interactions of Bohmian mechanics. That's at odds with relativity's limit on how fast influences can spread – namely, the speed of light. What's more, relativity does not distinguish points in space as being in any one present. Goldstein and his colleagues have tried to get around this, showing that a Bohmian wave function can create structures or "foliations" in space-time, and that events on any one foliation are simultaneous, leading to non-locality. It's the most sophisticated approach yet – but also very much still a work in progress.

When Goldstein started learning standard quantum mechanics in the 1960s, he was seduced by its mystery and spookiness, he says – only to realise gradually that Bohm's ideas made more sense. Besides, he says, Bohm's ideas have their own sense of mystery: the way in which every entangled particle influences every other particle in the universe, and the fact that the wave function is a new kind of entity. "You have still got romance," he says. "It's in the right place now. Not misplaced."

In the end, though, it's not about winning over minds, but being open to the Bohmian picture, says Steinberg. "The best thing experiments like ours can do is to remind people that the interpretation exists," he says. "People aren't aware of it, and we want to bring more attention to it." Bush feels similarly about his walking-droplet experiments. "That's why I'm a believer in this venture, even if its sole result is to get young people to question their views on quantum mechanics," he says. ■

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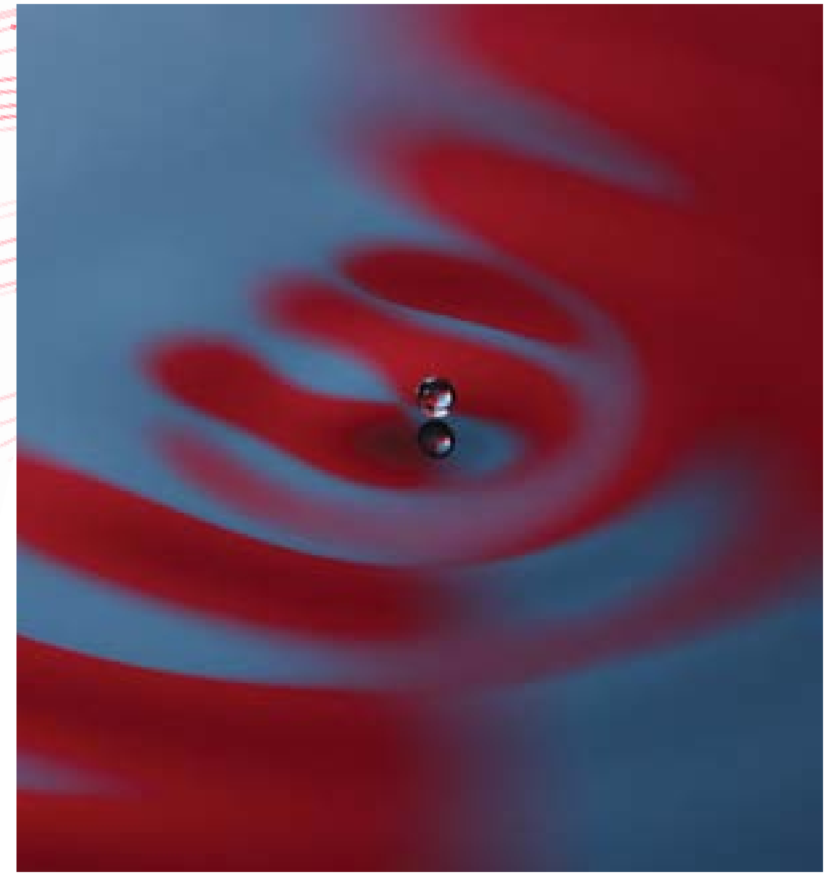

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BRAIN DEATH

Quantum mechanics gives a bizarre twist to that old trope about a monkey at a typewriter with infinite time. Ditch the monkey, and consider quantum fluctuations in an everlasting universe. They could at some point spontaneously form anything, even a brain. If one such "Boltzmann brain" exists, it's likely that many others do. In fact, if we live in such a universe, it's likely that our brains are this kind.

That sounds nonsensical. "If a theory predicts that the majority of observers are Boltzmann brains, that's bad for the theory," says Roderich Tumulka at Rutgers University.

Standard quantum mechanics says that an infinitely enduring universe exists in a "superposition" of all possible states, including those with Boltzmann brains. But in Bohmian mechanics (see main story) such a universe evolves towards a static state. The probability of that state being one with Boltzmann brains is minuscule, and even if it is, nothing is changing so the brain can't be functional. "It's much more likely that there are no Boltzmann brains, and then it stays that way," says Tumulka.