Beyond Weird?

Is the Universe always looking?

Is the quantum world fuzzy and uncertain?

Everyone has heard of Schrödinger's cat: Schrödinger is driving along when he is pulled over by a policeman. The officer looks the car over and asks Schrödinger if he has anything in the boot. "A cat," Schrödinger replies. The policeman opens the boot and yells, "Hey! This cat is dead!" Schrödinger replies angrily, "Well, he is now."

It illustrates what a good job Schrödinger did in finding an image catchy enough to become a cultural meme.

One might even say that he was too successful. The cat is still hauled out today as if to imply that we're as puzzled as ever by the mere fact that the quantum world at small scales turns into the world of classical physics at human scales.

The fact is, however, that this so-called quantum-classical transition is now largely understood. Things have moved on, and we can state much more precisely than Schrödinger and his contemporaries could why and how quantum becomes classical. The answer is both elegant and rather astonishing.

For quantum physics is not replaced by another sort of physics at large scales. It actually gives rise to classical physics. Our everyday, common sense reality is, in this view, simply what quantum mechanics looks like when you're 10 feet tall. You might say that it is quantum all the way up.

The question, then, is not why the quantum world is "weird," but why ours doesn't look like that, too.

In Schrödinger's day, traversing the quantum-classical transition seemed like crossing an ocean between two continents: Drawing a border somewhere in the open sea might be an arbitrary exercise, but the continents are undeniably distinct. The land of the quantum, Schrödinger said, is random and unpredictable, yet the classical realm is orderly and deterministic because it depends only on statistical regularities among that atomic-scale chaos.

Schrödinger dreamed up his "diabolical" thought experiment in 1935. It was intended as a challenge to Niels Bohr's interpretation of quantum mechanics, toward which Schrödinger shared a great deal of Albert Einstein's skepticism.

It was all very well for Bohr to impose a strict separation of quantum and classical, and to make observation the process by which they are distinguished—but what, then, if the quantum and the macroscopic are coupled without any observation taking place? Schrödinger was looking for what he called a "ridiculous case", in which we are confronted by a superposition of macroscopic states that seems not just bizarre (like a large object being in "2 places at once"), but logically incompatible.

Einstein raised the prospect of a keg of gunpowder being in a superposition of exploded and unexploded states, and Schrödinger upped the ante with his cat, whose life or death is yoked to a quantum event such as the radioactive decay of an atom. If, as Bohr said, the state of the atom is undetermined (in a superposition) until we look, then so must be the state of the cat.

Schrödinger's cat forces us to rethink the question of what distinguishes quantum from classical behavior. Why should we accept Bohr's insistence that they're fundamentally different things unless we can specify what that difference is?

We might then be inclined to point to features that classical objects like coffee cups have, but that quantum objects don't necessarily have: well-defined positions and velocities, or characteristics that are localized on the object itself and not spread out mysteriously through space. Or we might say that the classical world is defined by certainties while the quantum world is (until a classical measurement impinges on it) no more than a tapestry of probabilities, with individual measurement outcomes determined by chance. At the root of the distinction, though, lies the fact that quantum objects have a wave nature. That is to say, the equation Schrödinger devised in 1924 to quantify their behavior tells us that they should be described as if they were waves, albeit waves of a peculiar, abstract sort that are indicative only of probabilities.

It is this waviness that gives rise to distinctly quantum phenomena like interference, superposition, and entanglement. These behaviors become possible when there is a well-defined relationship between the quantum "waves": in effect, when they are in step. This coordination is called "coherence."

The concept comes from the science of ordinary waves. Here, too, orderly wave interference (like that from double slits, as per image above) happens only if there's coherence in the oscillations of the interfering waves. If there is not, there can be no systematic coincidence of peaks and troughs and no regular interference pattern, but just random, featureless variations in the resulting wave amplitude.

Likewise, if the quantum wave functions of two states are not coherent, they cannot interfere, nor can they maintain a superposition. A loss of coherence (decoherence) therefore destroys these fundamentally quantum properties, and the states behave more like distinct classical systems. Macroscopic, classical objects don't display quantum interference or exist in superpositions of states because their wave functions are not coherent.

Notice how I phrased that. It remains meaningful to think of these objects as having wave functions. They are, after all, made of quantum objects and so can be expressed as a combination of the corresponding wave functions. It's just that the wave functions of distinct states of macroscopic objects, such as a coffee cup being in this place and that place, are not coherent. Quantum coherence is essentially what permits "quantumness."

There is no reason (that we yet know of) why, in principle, objects cannot remain in coherent quantum states no matter how big they are—provided that no observation/measurement is made on them. But it seems that measurement somehow does destroy quantum coherence, forcing us to speak of the wave function as having "collapsed." If we can understand how measurement unravels coherence, then we would be able to bring measurement itself within the scope of quantum theory, rather than making it a boundary where the theory stops.

The crucial factor in understanding quantum decoherence is the ubiquitous entity present but largely ignored in all scientific studies: the surrounding environment. Every real system in the universe sits somewhere, surrounded by other stuff and interacting with it. Schrödinger's cat might be placed inside a sealed box, but there must be air in there for the cat to have a chance of staying alive, while resting on a surface of some kind, exchanging heat with it.

In quantum mechanics, the environment has a central role in how things happen. It turns out to be precisely what conjures the illusion of classical physics out of the quantum soup.

It's often suggested that quantum states such as superpositions are delicate and fragile. Put them in a noisy environment (the story goes), and all that jiggling and shaking by the surroundings destroys these frail quantum states, collapsing wave functions and shattering superpositions. But this isn't quite right. Indeed, why should quantum states be fragile if quantum mechanics supplies the most fundamental description of the universe? What kinds of laws are these, if they give up the ghost so easily?

The truth is that they don't. Quantum superpositions of states aren't fragile. On the contrary, they are highly contagious and apt to spread out rapidly. And that is what seems to destroy them.

If a quantum system in a superposed state interacts with another particle, the two become linked into a composite superposition. That is exactly what quantum entanglement is: a superposed state of two particles, whose interaction has turned them into a single quantum entity. It's no different for a quantum particle off which, say, a photon of light bounces: The photon and the particle may then become entangled. Likewise, if the particle bumps into an air molecule, the interaction places the two entities in an entangled state. This is, in fact, the only thing that can happen in such an interaction, according to quantum mechanics. You might say that, as a result, the quantumness —the coherence— spreads a little further.

In theory, there is no end to this process. That entangled air molecule hits another, and the second molecule gets captured in an entangled state, too. As time passes, the initial quantum system becomes more and more entangled with its environment. In effect, we then no longer have a well-defined quantum system embedded in an environment. Rather, system and environment have merged into a single superposition.

Quantum superpositions are not, then, really destroyed by the environment, but on the contrary infect the environment with their quantumness, turning the whole world steadily into one big quantum state.

This spreading is the very thing that destroys the manifestation of a superposition in the original quantum system. Because the superposition is now a shared property of the system and its environment, we can no longer “see” the superposition just by looking at the little part of it. We can’t see the wood for the trees. What we understand to be decoherence is not actually a loss of superposition but a loss of our ability to detect it in the original system.

Only by looking closely at the states of all these entangled particles in the system and its surroundings can we deduce that they’re in a coherent superposition. And how can we hope to do that—to monitor every reflected photon, every colliding air molecule? We can’t, because once the quantumness has leaked out into the environment, in general, we’ll never be able to concentrate the superposition back on to the original system.

Decoherence, then, is a gradual and real physical event that occurs at a particular rate. For some relatively simple systems, we can use quantum mechanics to calculate that rate: to work out how long it takes for decoherence to sabotage the possibility of observing, let’s say, interference between the wave functions of a quantum object in two different positions. The farther apart in space those two positions are, the faster the coherence between them will become entangled with, and leak away into, the environment.

Take a microscopic dust grain floating in the air of my room, a 1/100 mm across. How quickly do two positions of the grain decohere if their separation is (e.g) about the same size as the width of the grain itself, so they won’t overlap? Ignore photons for now—let’s say the room is dark—and just think about the interactions between the grain and all the air molecules around it. Quantum calculations show that decoherence then takes about 10^{-31} seconds.

That’s so short that we can almost say that decoherence is instantaneous. It happens in less than a millionth of the time it takes for a photon to pass, at the speed of light, from one side of a single proton to the other. If you think you can see a quantum superposition of nonoverlapping position states of a dust grain in my room, think again.

For microscopic objects, we really can avoid decoherence. It is why we really can do experiments on atoms, subatomic particles, and photons that reveal them to be in quantum superpositions. For a large molecule (the size of a protein), decoherence happens within 10^{-19} seconds if it were floating in the air around us, but in a perfect vacuum at the same temperature, it could stay coherent for more than a week.

Decoherence destroys the possibility of observing macroscopic superpositions, including Schrödinger’s live/dead cat. And this has nothing to do with observation in the normal sense: We don’t need a conscious mind to “observe” in order to “collapse the wave function.” All we need is for the environment to disperse the quantum coherence. We obtain classical uniqueness from quantum multiplicity when decoherence has taken its toll.

Einstein once expressed his exasperation at Bohr’s position on quantum weirdness to the young physicist Abraham Pais. “I recall,” Pais wrote, “that during one walk Einstein suddenly stopped, turned to me and asked whether I really believed that the moon exists only when I look at it.” With an understanding of decoherence, we have an answer to Einstein’s question. Yes, it is there when no one observes it, because the environment is already, and without cease, “observing/measuring” it. All of the photons of sunlight that bounce off the moon are agents of decoherence, and are more than adequate to fix its position in space and give it a sharp outline. The universe is always looking!

This post is adapted from Philip Ball’s new book.

An Experimental Boost for Quantum Weirdness

After a century of debate, an alternative theory that favored classical reality has finally met its ruin.

In 2005, a student working in the fluid physicist Yves Couder's laboratory in Paris discovered by chance that tiny oil droplets bounced when plopped onto the surface of a vibrating oil bath. Moreover, as the droplets bounced, they started to bunny-hop around the liquid's surface. The droplets were "surfing on their own wave," as he put it—kicking up the wave as they bounced and then getting propelled around by the slanted contours of the wave.

As he watched the surfing droplets, Couder realized that they exactly embodied an early, largely forgotten vision of the quantum world devised by the French physicist Louis de Broglie.

A century ago, de Broglie refused to give up on a classical understanding of reality even as the unsettling outcomes of the first particle experiments suggested to most physicists that reality, at the quantum scale, is not as it seems. The standard "Copenhagen interpretation" of quantum mechanics, originated at that time by the Danish physicist Niels Bohr, broke with the past by declaring that nothing at the quantum scale is "real" until it is observed.

Facts on the ground, like particles' locations, are mere matters of chance, defined by a spread-out probability wave, until the moment of observation/measurement, when the wave mysteriously collapses to a point, the particle hops to, and a single reality sets in. In the 1920s, Bohr persuaded most of his contemporaries to embrace the weirdness of a probabilistic universe, the inherent fuzziness of nature, and the puzzling wave-particle duality of all things.

But some physicists objected, Albert Einstein and de Broglie among them. Einstein doubted that God "plays dice." De Broglie insisted that everything at the quantum scale was perfectly normal and aboveboard. He devised a version of quantum theory that treated both the wave and the particle aspects of light, electrons, and everything else as entirely tangible. His "pilot wave" theory envisioned concrete particles, always with definite locations, that are guided through space by real pilot waves—much like the waves propelling Couder's bouncing droplets.

De Broglie couldn't nail down the physical nature of the pilot wave, however, as he struggled to extend his description to more than one particle. At the celebrated 1927 Solvay Conference, a gathering of luminaries to debate the meaning of quantum mechanics, Bohr's more radical views carried the day.

De Broglie's pilot-wave vision of the quantum world was forgotten 78 years later, when the Paris droplets started bouncing. Suddenly, Couder + his colleagues had an "analogue system" for experimentally exploring de Broglie's idea.

Straightaway, they saw the droplets exhibit surprisingly quantumlike behaviors, only traversing certain "quantized" orbits around the center of their liquid baths, for instance, and sometimes randomly jumping between orbits, as electrons do in atoms. There, and in bouncing-droplet labs that soon sprang up at the Massachusetts Institute of Technology and elsewhere, droplets were seen to tunnel through barriers and perform other acts previously thought to be uniquely quantum. In reproducing quantum phenomena without any of the mystery, the bouncing-droplet experiments rekindled in some physicists de Broglie's old dream of a reality at the quantum scale that consists of pilot waves and particles instead of probability waves and conundrums.

But a recent series of bouncing-droplet findings has crushed this dream. The results indicate that Couder's most striking demonstration of quantumlike phenomena, in 2005, "the experiment that got me hooked on this problem," the fluid dynamicist Paul Milewski said, was in error. Repeat runs of the experiment, called the "double-slit experiment," have contradicted Couder's initial results and revealed the double-slit experiment to be the breaking point of both the bouncing-droplet analogy and de Broglie's pilot-wave vision of quantum mechanics.

Improbably, the person who put the irreparable crack in de Broglie's idea is Niels Bohr's grandson, the fluid physicist Tomas Bohr. A professor at the Technical University of Denmark who, as a child, enjoyed puzzling over riddles posed by his grandfather, Tomas Bohr heard about Couder's bouncing-droplet experiments and was immediately intrigued. "I felt a genuine interest in trying to see whether you could really get a deterministic quantum mechanics," he said about his decision to enter the fray. Given his family history, he added, "maybe I also felt some obligation. I felt I should really try to see if it was true or not."

The physicist Richard Feynman called the double-slit experiment "impossible, *absolutely* impossible, to explain it in any classical way," and said it "has in it the heart of quantum mechanics. In reality, it contains the *only* mystery."

Here, particles are shot toward two slits in a barrier. The ones that pass through the slits hit a sensor some distance away on the other side. Where any one particle ends up is always a surprise, but if you shoot many particles toward the slits, you start to see stripes develop in their detected locations, indicating places where they can and cannot go. The stripy pattern suggests that each particle is actually a wave that encounters the slitted barrier and passes through both slits at once, producing two wave fronts that converge and interfere, cresting in some places and canceling out in between. Each particle materializes in the sensor at the location of one of the crests of this strange probability wave.

Stranger still, when you add a second sensor and detect which slit each particle passes through, the interference stripes disappear, as if the probability wave, known as the wave function, has collapsed. This time, particles pass straight through their chosen slits to either of two spots on the far sensor.

To explain the double-slit experiment, a Copenhagenist will point to quantum uncertainty, arguing that the trajectory of each particle cannot be exactly known and is thus defined only probabilistically, by a wave function. After passing through both slits, as any wave would, and interfering on the other side, the wave function representing the particle's possible locations is "collapsed" by the sensor, which seems to select a single reality from among the possibilities.

To de Broglie, the double-slit experiment didn't require an abstract, mysteriously collapsing wave function. Instead, he conceived of a real particle riding on a real pilot wave. The particle passes like driftwood through one slit or the other in the double-slit screen, even as the pilot wave passes through both. On the other side, the particle goes where the two wave fronts of the pilot wave constructively interfere and doesn't go where they cancel out. De Broglie never actually derived dynamical equations to describe this complicated wave-particle-slit interplay. But with bouncing droplets in hand, Couder and Emmanuel Fort, moved quickly to perform the double-slit experiment, reporting their astonishing results in *Physical Review Letters* in 2006.

After recording the trajectories of 75 bouncing droplets through a double-slit barrier, Couder and Fort thought they detected rough stripes in the droplets' final locations, an interference-like pattern that seemed as if it could only come from the pilot wave. Double-slit interference, considered "impossible to explain in any classical way," was happening without mystery before everyone's eyes. Drawn by the potential quantum implications, the fluid dynamicist John Bush started up a bouncing-droplet lab of his own at MIT and led others to the cause. Tomas Bohr heard Couder talk about his results in 2011 and discussed the experiments with Bush. He teamed up with Anders Andersen, to study bouncing droplets further. "We really became fascinated with, in particular, the double-slit experiment".

Bohr/Andersen's group in Denmark, Bush's team at MIT, and quantum physicist Herman Batelaan at the University of Nebraska all set out to repeat the bouncing-droplet double-slit experiment. After perfecting their experimental setups, getting rid of air currents, and setting oil droplets bouncing on pilot waves toward two slits, none of the teams saw the interference-like pattern reported by Couder and Fort. Droplets went through the slits in almost straight lines, and no stripes appeared. The French pair's mistake is now attributed to noise, faulty methodology and insufficient statistics.

Bush's detailed double-slit studies, showed no hint of interference, but he still thinks it might be possible to generate an interference pattern with pilot waves when the right combination of parameters is found, like the right frequency for the vibrating fluid bath, or a necessary addition of noise. Milewski shares this hope. However, in the Denmark group's paper reporting their null double-slit results, Tomas Bohr presented a thought experiment that appears to demolish de Broglie's pilot-wave picture completely.

In this hypothetical "*gedanken*" version of the double-slit experiment, the particles, before arriving at the slitted barrier, have to pass to either side of a central dividing wall. In standard quantum mechanics, this wall can be very long, and it won't matter, because the wave function representing the possible paths of a particle will simply go both ways around the wall, pass through both slits, and interfere.

But in de Broglie's picture, and likewise in the bouncing-droplet experiments, the driving force of the whole operation—the particle—can go only one way or the other, losing contact with the part of the pilot wave that passes to the other side of the wall. Unsustained by the particle or droplet, the wave front disperses long before reaching its slit, and there's no interference pattern. The Danish researchers verified these arguments with computer simulations.

In explaining his decision to keep studying bouncing droplets, Bush said, “I never liked *gedanken* experiments. The beauty of this situation is you can actually do the experiment.” But the dividing-wall thought experiment highlights, in starkly simple form, the inherent problem with de Broglie’s idea.

In a quantum reality driven by local interactions between a particle and a pilot wave, you lose the necessary symmetry to produce double-slit interference and other nonlocal quantum phenomena. An ethereal, nonlocal wave function is needed that can travel unimpeded on both sides of any wall. “To get the real quantum-mechanical result, it’s really important that the possible paths of the particle enter in a democratic way,” Tomas Bohr said.

But with pilot waves, “since one of these sides in the experiment carries a particle and one doesn’t, you’ll never get that right. You’re breaking this very important symmetry in quantum mechanics.”

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Experts note that the simplest version of de Broglie’s theory was bound to fail. In describing individual particles guided by corresponding pilot waves, de Broglie didn’t account for the way multiple interacting particles become “entangled,” or defined by a single, joint, nonlocal wave function that keeps their properties correlated even after the particles have traveled light-years apart.

Experiments with entangled photons starting in the 1970s proved that quantum mechanics must be nonlocal. A theory of local interactions between a particle and its pilot wave like de Broglie’s would need to get a whole lot weirder in the jump from one particle to two to account for nonlocal entanglement.

Until his death in 1987, de Broglie questioned the arguments about nonlocality and entanglement, and continued to believe that real pilot waves might somehow stir up the necessary long-distance connections. That improbable dream, shared by some bouncing-droplet experimenters, might have been allowed to stubbornly persist until now, but with pilot waves unable to even generate double-slit interference in the case of single particles, the dream collapses like a scrutinized wave function.

Early on, de Broglie did offer a kind of compromise, a version of his theory that was promulgated again in 1952 by the physicist David Bohm, and which is now known as Bohmian mechanics or de Broglie-Bohm theory. In this picture, there’s an abstract wave function that extends through space—an entity that’s just as mysterious in this theoretical framework as it is in the Copenhagen interpretation—as well as real particles somewhere in it.

Proofs in the 1970s showed that de Broglie-Bohm theory makes exactly the same predictions as standard quantum mechanics. However, with one element of classical reality restored, concrete particles, new mysteries arise, like how or why a mathematical wave function that is spread everywhere in space is bolted in certain places to physical particles. “Quantum mechanics is not less weird from that perspective,” Tomas Bohr said. Most physicists agree, but it’s really just a matter of taste, since the experimental predictions are identical.

Tomas Bohr attributes his grandfather’s certainty that nature is incurably weird at the quantum scale to Niels Bohr’s most important physics research: his 1913 calculations of the electronic energy levels of the hydrogen atom. Bohr realized that when electrons jump between orbits, releasing quantized packets of light, there was no mechanical picture of the situation that made sense. He couldn’t relate the electrons’ energy levels to their rotational motion.

Even causality failed, because electrons seemingly know before they jump where they are going to land, in order to emit a photon of the correct energy. “He was probably more aware than most of how weird that whole thing was,” Tomas Bohr said. “He was just somehow philosophically inclined in such a way that he was ready to accept that nature was that strange, and most people were not.”

In the past few years, Tomas has often wondered what his grandfather would have said about the bouncing-droplet experiments. “I think he would have been very interested,” he said, adding with a laugh, “He would probably have been much quicker than me to figure out what he thought about it. But he would have thought it was an ingenious thing, that you could generate such a system, because it is surprisingly close to what de Broglie was talking about.”