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The illusion of reality in a quantum world

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HOW would you like to be quantum? It would certainly have its advantages. Imagine, for a start, if you could be in two places at once. Jet off to the beach and stay in the office at the same time. Do the weekend shopping and mow the front lawn simultaneously. Sure, you say, dream on.

Well then, here's the shocking bit: you really could be quantum. After all, you are made of atoms and molecules that obey the rules of quantum theory. They can be in different states, spinning this way and that, all at the same time. They can be here, there and everywhere in between. The big question is why atoms can experience the full weirdness of quantum mechanics, whereas you and I evidently cannot. "In short, how does the well-behaved, everyday classical world emerge from the schizophrenic quantum realm," asks Johannes Kofler, a specialist in quantum theory from Caslav Brukner's group at the University of Vienna, Austria.

We may finally have the answer. For years physicists have tried to pin down the elusive boundary between the quantum and classical worlds. Now Kofler, Brukner and others have shown that this boundary may not exist. That's right, the quantum world never breaks down. If that's true, we're left with a mind-numbing prospect: the world could be quantum, but we are blind to it. This result challenges our very notions of how classical reality arises.

Quantum theory, for its part, is a supremely effective description of the microscopic world of atoms and their constituents. Disturbingly, however, it also reveals a profoundly counter-intuitive reality in which, for instance, a particle can exist in a "superposition" of states where it can do two or more things at once.

In 1935, Erwin Schrödinger came up with his famous thought experiment to highlight a consequence of this. He imagined a cat shut in a box together with a vial of poison. The decay of a radioactive atom could prompt a hammer to smash the vial and kill the cat. Crucially, if the atom was in a superposition in which it simultaneously did and did not decay, the cat would be both dead and alive at the same time. The only way to know would be to open the box. This thought experiment catapulted quantum weirdness out of the microscopic realm and into the everyday world, where researchers had no choice but to deal with it.

Physicists call these macro-scale superpositions - ones containing many atoms or other quantum entities - Schrödinger cat states, or simply "cats". In the past decade, these cats have helped researchers probe the transition between the quantum and classical worlds. They have also begun to explain why we don't see everyday objects in two states at once, and whether there's a chance we ever will.

Traditionally, there have been two competing views on this question. A minority of researchers believe there is a threshold size at which quantum reality "collapses" into everyday reality. In other words, when a cat gets big enough, some fundamental property of nature forces it to choose one particular state over the others. Roger Penrose of the University of Oxford thinks this transition may be triggered by the effects of gravity. Physicists at the University of California, Santa Barbara, and elsewhere have been preparing intricate experiments to test this idea (New Scientist, 9 March 2002, p 27).

The more mainstream view is that quantum behaviour only manifests itself when two states in a superposition interfere with each other. However, when a quantum object leaves an impression on a large number of atoms - a detector, your eye or even the surrounding environment - the ability of the states in the superposition to interfere with each other is very rapidly lost. According to this phenomenon, known as "decoherence", quantum effects disappear as soon as an object ceases to be isolated from its environment. Take the most familiar example: when you observe a quantum particle, or lift the lid on Schrödinger's cat, it is forced to pick a state. What's more, the bigger an object is, the more likely it will be to run into other particles such as photons and oxygen molecules, and thus decohere.

One way to shine a light on the mysterious quantum-classical transition is to create bigger and bigger cats and see when and how they dissolve. In the late 1990s, a team led by Markus Arndt and Anton Zeilinger at the University of Vienna did just that by observing a large buckminsterfullerene molecule made up of 60 carbon atoms pass through two slits in an opaque screen simultaneously - a sure sign of its quantum properties since the molecule was in two places at once. They have since repeated the experiment with larger objects such as carbon-70 and biomolecules spanning a few nanometres, and have even proposed using viruses, which are much larger (New Scientist, 15 May 2004, p 30).

Remarkably, however, there is no agreement on something as fundamental as what is the biggest Schrödinger cat created so far. To define this more precisely, Florian Marquardt of the Ludwig-Maximilian University in Munich, Germany, and his colleagues Benjamin Abel and Jan von Delft have come up with a new measure of a cat's size: just count the number of operations on individual particles required to change one state of a superposition into another. To change a carbon-70 molecule at one slit into carbon-70 at another, for instance, you have to move 70 atoms, so carbon-70 is a bigger cat than carbon-60.

It isn't always that simple, however. Physicists have also created other kinds of cats such as superconducting quantum interference devices, or SQUIDs. In this gizmo, an electrical current travels both clockwise and anticlockwise around a superconducting circuit at the same time. The superposition involves billions of electrons, so does that make it a bigger cat than carbon-70?

Not necessarily. Electrons travel around a SQUID in duos known as Cooper pairs. Thanks to Marquardt's model, you don't need to move billions of electrons to change one state into the other; shifting just a few Cooper pairs from the clockwise current will make an anticlockwise current - as long as they have enough energy or are travelling fast enough. "Despite the fact that the SQUID supports a macroscopically measurable current, it may in fact be a small cat," says Marquardt.

The upshot of all this is that just adding more particles to a superposition won't help us build cats that are big enough to show quantum effects in everyday life. So how do we make bigger cats? A team led by Keith Burnett at the University of Oxford has devised a rough guide for experimenters. Burnett and his collaborators developed a model of another type of cat made from a Bose-Einstein condensate - a large number of supercooled atoms, mostly in one quantum state, which behave as a single entity, like a company of soldiers marching in lockstep (see "How to make a fat cat").

Through two doors at once

To be able to construct a superposition, they found that the states - represented by the atoms' different movements - needed to have similar energies and be tightly linked. Otherwise the system would simply settle on one state or the other. That suggests you couldn't be in a superposition of working in the office and napping on the beach, say, but you might be able to walk through two different doors in your office. More practically, Burnett's model suggests ways to prepare a superconducting circuit so it can stay in two states at once. "It's because it is difficult to achieve these conditions that it is so difficult to make fat cats," says David Hallwood, a team member from Oxford.

OK, but in principle, is there any limit to how big a cat can be? Could a person really be in a superposition in which they go through two doors simultaneously? "In theory, yes, if you could keep them perfectly isolated from their surroundings," says Marquardt. Just one problem: the idea that quantum laws apply on human scales has not been proved before.

That's where Kofler and Brukner come in. They have developed a model made up of a large number of particles such as atoms, each with a "spin" similar to the angular momentum that planets and figure skaters possess when they rotate - except that quantum particles can have angular momentum without actually rotating. The researchers then create a superposition of two states: one in which the particles' spins are aligned in one direction, and one with them aligned in a different direction.

Surprisingly, the researchers worked out that there is nothing to prevent them from creating such a superposition in theory, even if the spins are infinite in magnitude - so an unlimited number of particles could be in superposition. That means there is no definite point at which an object fails to obey the laws of quantum theory, implying that the quantum-classical boundary does not exist. In other words, if you were sufficiently isolated from your environment to ward off decoherence, you and everything around you could be quantum.

But there's a catch, and it has to do with whether you could ever actually see these quantum effects. According to Kofler and Brukner, people have overlooked another factor that complements decoherence.

Their model shows there is a difference between a quantum superposition of spins and a mere classical mixture of spinning atoms in separate boxes, some pointing to the north and some to the east, for example. Think of a sphere with an arrow, or spin vector, pointing from its centre to the North Pole and another spin vector pointing from the centre towards the east. The sphere represents the collection of spin states, not any physical object.

In the classical world, the probability that any given box will contain a north-spinning or east-spinning particle can be represented on the surface of the sphere as peaks at the north and the east, but nothing in between. A quantum superposition can also be represented as a wavy pattern, with peaks at north and east, but it will have ripples over the whole sphere because of interference between the spin states.

Newton meets Schrödinger

Now imagine measuring the spin of this quantum superposition with an increasingly coarse instrument. At some point you will not be able to distinguish some spin directions from others that are close by on the surface. In effect, the wavy pattern on the sphere will appear blurred as you step back from it. Eventually, you see a pattern with peaks in the north and east but not at any of the directions in between - which matches exactly the classical distribution of spins.

"The transition is made smoothly from the quantum case to the classical case," says Kofler. "It's all because we can't distinguish neighbouring quantum states." He stresses that this blurring happens even when the system is completely isolated from its environment so that decoherence does not occur. "In that case, the coarseness of our instruments determines when we can no longer see quantumness," he says.

It all points to an additional mechanism for how classical reality might arise from quantum laws. Until now, the only accepted explanation was that we don't see quantum objects because they decohere. Kofler and Brukner argue that the effect they have identified - the blurred image of the quantum world that our eyes and instruments give us - is what can also translate Schrödinger's equation, which describes the quantum world, into Newton's laws, which describe the everyday, classical world.

Indeed, their model helps show for the first time that what we perceive as classical reality can emerge gradually from quantum laws. "Interesting stuff, and I'd say it's the real thing," says Lawrence Schulman of Clarkson University in New York state. Other researchers agree, though they are cautious about the broader implications. "The real challenge is to explain why classical physics approximately applies over such a wide range of time, epoch and scale in our universe," says Jim Hartle of the University of California, Santa Barbara.

Nevertheless, it would seem that the quantum-classical transition is now fully understood. Reality is fundamentally quantum but looks classical to us as a result of decoherence or the coarseness of our instruments, whichever effect kicks in first. In practice this depends on your set-up. If you could isolate your system so it didn't decohere, coarse-graining might cut in first; otherwise decoherence rules.

Kofler is not so sure that the problem has been cracked, however. "When we talk about quantum states that are 'close together' being blurred into each other, we use terminology that means nothing in the quantum world," he says. That is, we still have a vestige of our classical world in our description of the quantum.

So what about our chances of ever being in two places at once? It seems you'd need absurdly high resolution and near-total isolation to detect this sort of quantum reality. What is more, even if you could, you probably wouldn't experience a double life. "Superpositions are never actually observed, only the consequences," says Marquardt.

Sadly, this means you will probably never see a person going through two doors simultaneously, or get to enjoy the French Riviera while also working a full day at the office. At best you might get to detect some weird effect that shows you have been in a superposition. Then again, if you have been feeling strangely relaxed at work or inexplicably productive on weekends, you might just chalk it up to your quantum self.

How to make a fat cat

Schrödinger cats - macroscopic objects in "superpositions" of different quantum states - are hard to make. If they weren't, chairs and tables and you and I could be in multiple places at once. Now David Hallwood and Keith Burnett of the University of Oxford and Jacob Dunningham of the University of Leeds, UK, have come up with a recipe for researchers.

They imagine a bucket filled with a bunch of supercooled atoms all in the same quantum state, known as a Bose-Einstein condensate. One of the strange properties of this state of matter is that all the atoms remain stationary when you rotate the bucket, rather than move with it. From the bucket's point of view, however, the atoms revolve in the opposite direction. Similarly, if the atoms are in an excited state where they all revolve at the same speed, you can rotate the bucket so that from its view the atoms are not moving. Finally, imagine rotating the bucket at some intermediate speed so that the stationary atoms and the excited atoms have the same speed but are revolving in opposite directions from the bucket's point of view. Those are your states of superposition. "The system doesn't know what state to pick," says Hallwood.

In order to make a fat cat, the energies of the two states need to be similar, and there cannot be others close by in energy. The states must also have a high probability of making the transition from one to the other, but a low probability of going to any other states. This recipe could be useful for building superconducting devices.