

The Cat With Two Tails

In the strange world of quantum mechanics, the same tiny object can be in two places at once. Keith Schwab is building a not-so-tiny machine that can do that, too.



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Imagine a cat—let’s call him Erwin—sitting on the edge of a sofa. The cat’s tail is swinging back and forth: now towards the television set, now away from it.



CAN ERWIN BE AT ONLY ONE PLACE AT ONE TIME?

Next, take a picture of the cat, setting your shutter speed as fast as possible to avoid a blurry image. In the moment of time captured on film, Erwin’s tail will be pointing toward the television, or not. But it won’t be pointing in both directions at once.

Tails, after all—like the rest of cats, and like every other object in the universe—can only be in one place at one time. Right?

Wrong, says Cornell University’s Keith Schwab, recipient of an FQXi grant worth \$85,000 for a project titled “Production and Study of Macroscopic Mechanical Entanglements.” At least in the case of itsy-bitsy kitties.

Cat Facts

Schwab says there’s no generally understood rule that excludes objects from occupying multiple positions in space simultaneously; it’s just that they aren’t found to do so when the objects are the size of everyday items.

Electrons and other subatomic particles are a different matter. Since the

dawn of the quantum age, it has been understood that, within limits, a subatomic particle can be in more than one spot at the same time. This is such an odd claim that it bears repeating: It is a well-established fact that subatomic particles can be in more than one place at the same time.

“Someone who has never heard of this before might think, well, is this some crackpot stuff? This doesn’t sound like the physical universe that I know about,” Schwab laughs. “It turns out, though, that the basic theory of nature that is quantum mechanics absolutely allows these possibilities.”

In fact, it requires them. In quantum mechanics – the theory of atomic and subatomic behavior that is one of the great achievements of 20th century science – statistics reign supreme. For example, the Schrödinger Equation treats a particle as having a range of possible locations, designated by its “wave function.” Exactly where within its designated range the particle will actually be discovered cannot be known ahead of time; only its chances can.

That’s because a wave function is not a material wave, like the kind that crash on beaches, but a probability wave – a mathematical description of the likelihood that something will be here rather than there. Nevertheless, the wave-function metaphor helps us imagine that a subatomic particle like an electron becomes wave-shaped when no one is looking. In this view, what was a discrete ‘particle’ (the electron), now spreads across a region of space, with the hump in the middle of the wave corresponding to the most likely region to find the particle, and the rest of the wave showing other, less-likely but still possible, electron locations.

Notably, while in the wave state, a particle need not decide exactly where it

is, allowing the object to do something seemingly incoherent: to be in two spots at once.

“It’s not as if being in two places at once was something fanciful that people liked to think about,” Schwab says. “It’s actually the only conclusion you can come up with. We’re forced into it.

“And we see in many experiments with small particles like light, electrons, neutrons . . . we can actually see that, indeed, they are in two places at the same time.”

Superposition

The question for physicists, then, is not whether electrons, photons and the like can be in two places at once, but why cats can’t.

This is the best thing you can do in physics. These kinds of experiments change people’s idea of reality.

- Keith Schwab

“A large number of people have heard about Schrödinger’s cat,” says Dartmouth University’s Miles Blencoe, one of the three co-investigators on Schwab’s project. “Quantum mechanics predicts that for any object — in that instance a cat, but you could take any object — you can have a state where it’s in two places at once. That’s called ‘superposition.’ The question is: why don’t we see these superpositions in our everyday life?”

Austrian physicist Erwin Schrödinger famously entangled cats and quantum thought experiments by wondering what would happen if Erwin were placed inside a box with a poison vial broken only if a sample atom decays. Since the idea of superposition dictates that until the

box is opened, the atom must be regarded as existing in both states, is the cat likewise both alive and dead?

Part of the insight of this question is that it gets right at the question of how large a system can become and still exhibit quantum effects. Consider the classic double-slit experiment, first run over two centuries ago to settle the question of whether light was a particle or a wave (spoiler alert: it's both!). In this experiment, light particles (photons) are shined on a barrier with two slit openings. The light coming through each slit causes a "diffraction pattern" on a screen behind the barrier, with telltale alternating light and dark bars corresponding to destructive and constructive interference.

Now the rub: the same pattern is produced when photons are sent through one particle at a time. The only way this can happen – the reigning interpretation goes – is if each individual particle has, upon meeting the barrier, traveled through both slits at once, interfering with itself on the other side.

"You can fire electrons at a whisker of metal," Schwab says, "and they will go both ways around the whisker. You can shine light at beam splitter and it will head both ways. And you can do the double-slit experiment with single particles — that's the ultimate experiment that showed us, yeah, there's something really weird here."

In the past few decades, the double-slit experiment has been successfully performed on increasingly larger objects, including atoms and whole molecules. In 1999, a team led by Anton Zeilinger – a co-investigator on this experiment – famously succeeded in demonstrating quantum effects with a fullerene molecule, which has a whopping 60 or 70 atoms.

So if a molecule of almost 100 atoms can be made to exist in a superposition state—why not something even larger? What about, say, ten billion atoms?

"We're going to try to show experimentally that we can make a very small mechanical device be in two places at the same time," says Schwab. "That's really the gist of it."

Qbit Cat

Schwab has already distinguished himself as an experimentalist in the strange world of quantum phenomena. At UC Berkeley, he did significant work on superfluids; at Caltech, he measured the fundamental unit of heat flow, a first and critical step toward the manufacture of ultra-small devices. As a result of these advances,

Fortune magazine listed him among the "Top Ten Innovators" for 2003. He has even been the subject of a documentary film called *The Uncertainty Principle* by writer/director Toni Sherwood.



STUDYING MACROSCOPIC MECHANICAL ENTANGLEMENTS
Keith Schwab

In a basement lab at Cornell, Schwab and his coworkers cool a small space to a thousandth of a degree above absolute zero. This is done to isolate the experiment as much as possible from the "thermal bath" of our everyday environment: even a stray bump from an air molecule can cause a superposition state to 'decohere,' meaning the objects that make it up will have definite locations again. Into this deep cold goes a proverbial cat's whisker: a tiny sliver of silicon, about ten billion atoms in size.

"We use all the techniques of silicon valley to microfabricate the device," Schwab says. "There's a little wire that can vibrate at radio frequencies, and then there's a piece of electronics in there, where we make the superposition."

The little wire is called a "nanomechanical resonator," and the piece of electronics is known as a "Cooper-Pair Box," a superconducting island that can be placed in a superposition of both positive and negative charge.

"[Cooper-Pair Boxes] have already been tried and tested," Blencoe says. "They're devices you can control that behave quantum mechanically. They have no problem at all with being in two charged states at once."

Now for the intriguing part. With the Cooper-Pair Box in a linear combination of state 1 (positive charge) and state 2 (negative charge), the silicon whisker next to it must be both attracted and

repelled. In physics lexicon, the nanomechanical resonator is said to become entangled with the box, entering a superposition of its own.

Think again of the cat on the sofa. If its tail were Schwab's nanomechanical resonator, and the television set the Cooper-Pair Box, at the moment of entanglement the tail would be doing the seeming impossible: pointing both toward and away from the TV.

"The mechanics have to respond to both positive and negative charges," Schwab says, "so it actually has to split into two pieces."

Entangled Tails

If the experiment is a success, the resonator will be the largest object to have been teased into a "Cat State," the colloquial term for superposition. At ten billion atoms, the resonator will dwarf the fullerene molecule in size, which already dwarfs the single atom experiments that preceded it.

The natural question, then, is: If ten billion works, what about twenty?

"The trajectory of people who work on this stuff is to try and work with bigger and bigger objects," Schwab says. "The question is, will it work? And, if it does work, how far can we push this?"

"In principle there shouldn't be any limit" to how large an object you can get into a Cat State, says Marcus Aspelmeyer, an FQXi Awardee and co-investigator on Schwab's team, who is also working with Zeilinger at the University of Vienna on a different approach to the same question, using optically cooled mirrors (see "[Through the Looking Glass](#)"). "It's just a question of creativity of the experimenter and money of the funding agencies."

In the opto-mechanical experiment, a tiny mirror being cooled with photons becomes entangled with them as well, causing it to fall into a superposition. The difference is in method — optical interaction versus electronic interaction — as well as in scale. The mirror is a hundred micrometers by fifty micrometers wide, far larger than even Schwab's nanomechanical whisker.

"Yeah, it's enormous," Aspelmeyer says happily. "You see it with the bare eye."

"It's quite cool," he adds.

When devices being coaxed into Cat States become large enough that we can see them without microscopes, an imaginary but palpable border has been crossed: Now, one must accept the idea that an actual "there it is, sitting in the

apparatus" object, rather than a more abstract entity like a neutron, can be made to bilocate.

"It's extremely challenging and fun work," Aspelmeier says, "because this is simply a riddle that nature poses to us: how can that possibly be? And I truly believe that in a couple of years from now, because of such experiments, we will understand nature better."

Big Electric Cat

For now, it is unclear how large an object can be Cat-States, even in principle. After all, *something* prevents everyday items from falling into superposition.

It may simply be that macroscopic objects are perpetually interacting with their environments, in everything from photon collisions to the emission of gravitational waves, and therefore constantly giving off the kind of information that causes Cat States to decohere. If constant interaction is the mechanism that causes "spontaneous localization," then the problem of getting really big things into Cat States reduces to simply isolating them from their environment – by dropping experimental temperatures even closer to absolute zero, say. (Of course, there is no way to isolate an object from gravitation.)

Conversely, localization may not be solvable by even hypothetical future technologies, because the universe simply won't allow it. For instance, there may be some as-yet undiscovered nonlinearity to quantum mechanics itself.

"This is the interesting question," Blencoe says. "In principle, does quantum mechanics allow arbitrary large objects to be in superposition states? The current theory of quantum mechanics

we have, in principle, allows such states to exist. So the question is whether it is just very hard to do it . . . or whether there is some new, undiscovered form of quantum mechanics that forbids it." The potentially significant implications of Schwab's work range from sensing devices to quantum computers. But for the moment, the work is purely exploratory, a probing of nature in the strange, coun-

terintuitive realm of the very small for the simple purpose of understanding how it works.

"In my opinion, this is the best thing you can do in physics," Schwab says. "These kinds of experiments change people's idea of reality."

Entangled Tails

The problem with Cat States is that they decohere when you test for them.

Returning to our cat-sofa-TV metaphor, when you photograph Erwin on his couch, the act of taking the picture itself will cause his tail to choose one direction or the other. It's the same with Schwab's nanomechanical resonator: As soon as someone peeks, the Cooper-Pair Box will be either positively or negatively charged, and the whisker will either be pointing toward or away.

So what good is an experiment if you can't read the results?

"Yeah. That's a trick," Schwab admits. "If you put a position detector there, you'll collapse the system to one or the other state. So you can't look to see where the mechanics is. You have to ask another question and infer the fact that it was in two places at once."

Luckily, this inference can be reliably made, based on the fact that there will be multiple data signatures caused by the interaction of the Cooper-Pair Box with the whisker. However, making this inference invites a slew of epistemological questions that have hounded quantum cats since the theory was first introduced: Can an object really be said to be in two places if, at any time you look at it, it is only in one place? Is the superposition really happening when Schwab isn't testing for its presence? Indeed, how do we know anything is happening when we aren't observing it?

"Now were talking what your basic philosophy of all this is," Schwab says.

"My point of view is equally as valid and screwed up as anyone else's. As an experimentalist, though, I believe that the apparatus is downstairs doing something, even when I'm not hanging out making measurements."

But, he points out, nobody really knows.

"You read Feynman's lectures," he says. "First page: Nobody gets quantum mechanics. Just so you know that."