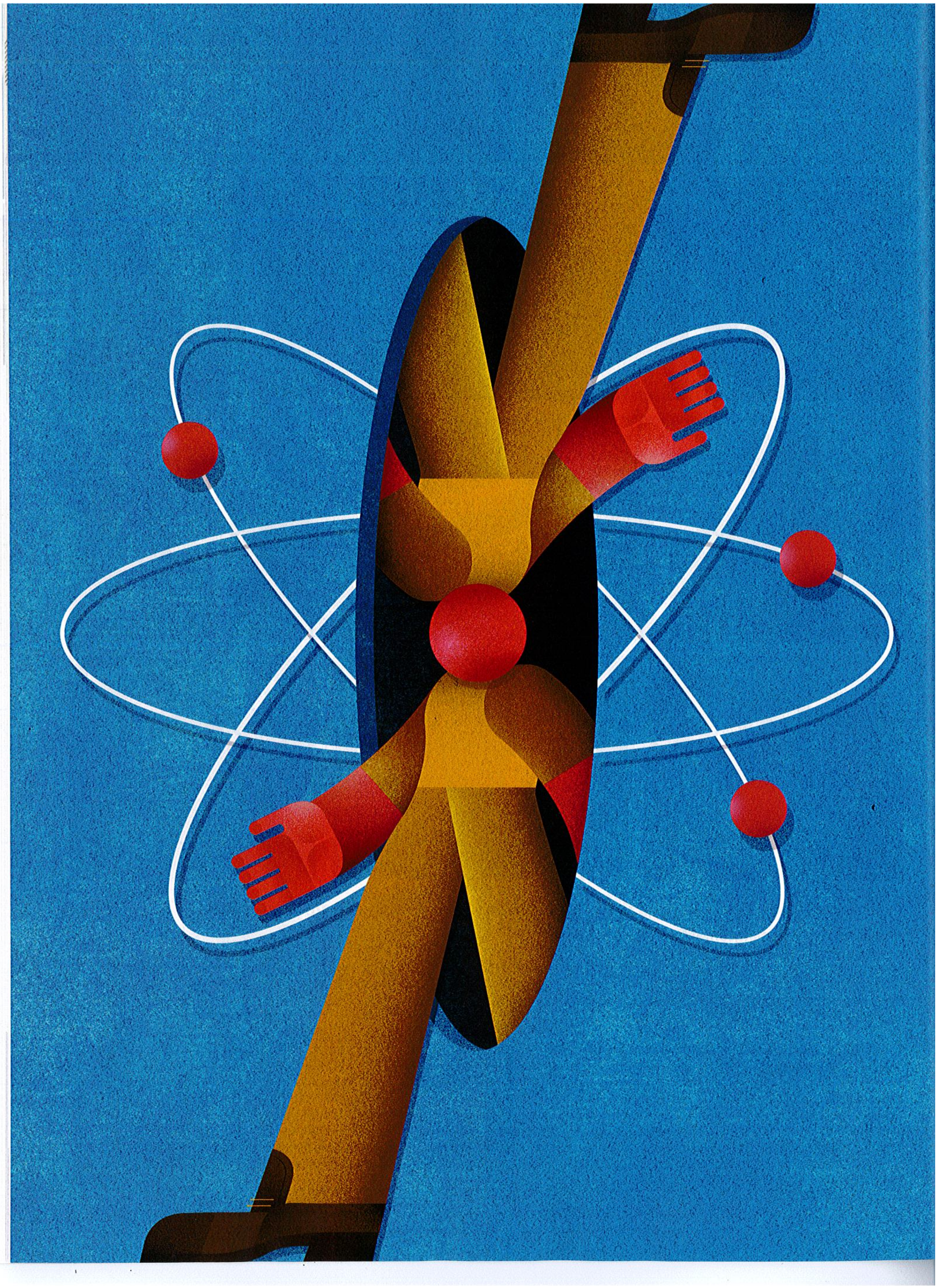

PHYSICS

CROSSING THE QUANTUM DIVIDE

The universe according to quantum mechanics is strange and probabilistic, but our everyday reality seems nailed down. New experiments aim to probe where—and why—one realm passes into the other

By Tim Folger

Illustration by Maria Corte

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MOST OF SIMON GRÖBLACHER'S HANDIWORK IS INVISIBLE TO THE NAKED EYE. One of the mechanical devices he fashioned in his laboratory at Delft University of Technology in the Netherlands is just a few millionths of a meter long—not much bigger than a bacterium—and 250 nanometers thick—about a thousandth of the thickness of a sheet of paper. Gröblacher no doubt could continue to shrink his designs, but he has a different goal: he wants to scale things *up,* not down. "What we're trying to do is make things that are really, really big," he says as he brings up images of hardware on his computer. Keep in mind that for Gröblacher, an experimental physicist, "really, really big" means something just barely visible without a microscope, "a millimeter by a millimeter in size."

IN BRIEF

The microscopic and macroscopic worlds do not blend seamlessly: the probabilistic nature of quantum mechanics reigns over the first, whereas the second observes more logical "classical" rules.

Physicists have long been stymied over the question of where one realm ends and the other begins, but upcoming experiments offer hope of testing different theories.

One possibility, called continuous spontaneous localization, suggests that quantum probabilities randomly collapse into classical certainties. If true, these collapses would also create a sea of background vibrations in the universe that experiments could detect.

By working on that less than humongous scale, Gröblacher hopes to address an extraordinary question: Can a single macroscopic object be in two places at once? Could something the size of a pinhead, say, exist both here and there at the same time? That seemingly impossible condition is actually the norm for atoms, photons and all other particles. According to the surreal laws of quantum theory, reality at its most basic level defies our commonsense assumptions: Particles do not have fixed positions, energies or any other definite properties—at least while no one is looking. They exist in numerous states simultaneously.

But for reasons physicists do not understand, the reality we see is different. Our world—even the parts we cannot observe directly—appears to be distinctly *un*quantum. Really big things—meaning anything from a virus on up—always manifest in one place and one place only; there is just one Gröblacher talking to one jet-lagged, scribbling journalist in his Delft lab. And therein lies a mystery: Why, if everything is built on a quantum blur of matter and energy, do we not experience quantum weirdness ourselves? Where does the quantum world end and the so-called classical world of Newtonian physics begin? Is there a rift in reality, a scale beyond which quantum effects simply cease? Or does quantum mechanics reign everywhere, and we are somehow blind to it?

"We know the microworld is quantum, and we know in one way or another, we are classical—whatever that means," says Angelo Bassi, a theoretical physicist at the University of Trieste in Italy. "We are ignorant about the true nature of matter in between the micro and the macro." That no-man's-land has baffled physicists since the birth of quantum theory a century ago. But in recent years Gröblacher and other physicists have started running exquisitely sensitive tabletop experiments that may one day reveal how objects make the startling transition from quantum to quotidian. Whether those efforts will resolve the mysteries of quantum theory or deepen them, no one can yet say. But in probing the wild and woolly quantum borderlands, researchers stand a chance of discovering a whole new realm of physics.

THE MEASUREMENT PROBLEM

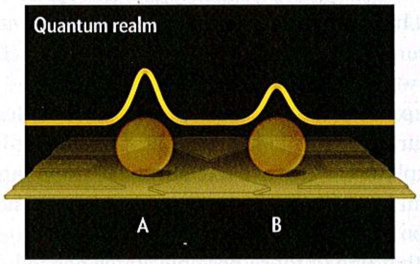
FOR ALL ITS PARADOXES, quantum mechanics is the most powerful and exacting scientific theory ever devised. The theory's predictions match experiment with ridiculous precision—to better than parts-per-trillion accuracy in some cases. By revolutionizing our understanding of atomic structure, it transformed every facet of science, from biology to astrophysics. Without quantum theory, there would be no electronics industry, no cell phones, no Google. Yet the theory has one glaring shortcoming, says Stephen L. Adler, a theoretical physicist at the Institute for Advanced Study in Princeton, N.J.: "In quantum mechanics, things don't happen."

Separate Realms

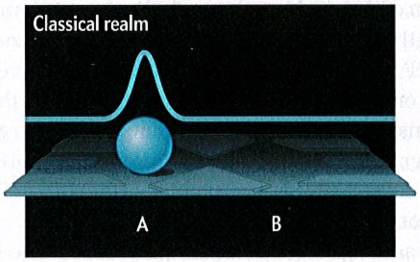
Quantum mechanics produces some bizarre effects in the microscopic world, but we do not see these phenomena in our macroscopic, "classical" reality. Why is that? Scientists have never understood why and how the universe crosses over between these realms, but several theories, as depicted here, offer possible explanations.

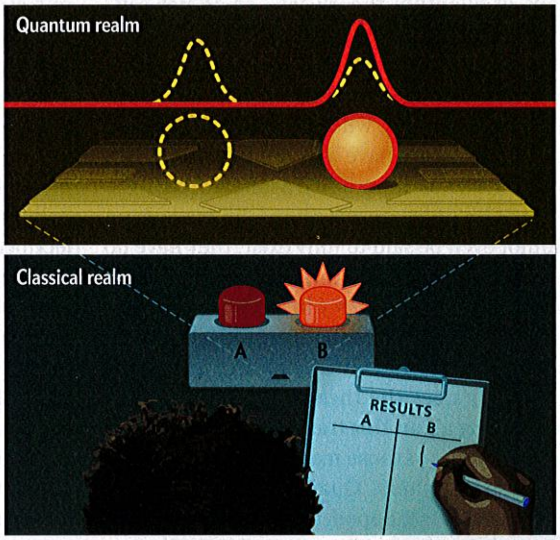
Quantum vs. Classical

According to quantum mechanics, particles do not exist in definite states—here or there, having this energy or that—but rather take on all possible states and positions. The theory describes particles with equations called wave functions, which are combinations, or "superpositions," of multiple waves. The amplitude of each peak in a wave function denotes the probability of a particle being found in any specific circumstances—for instance, at point A or B, as shown.



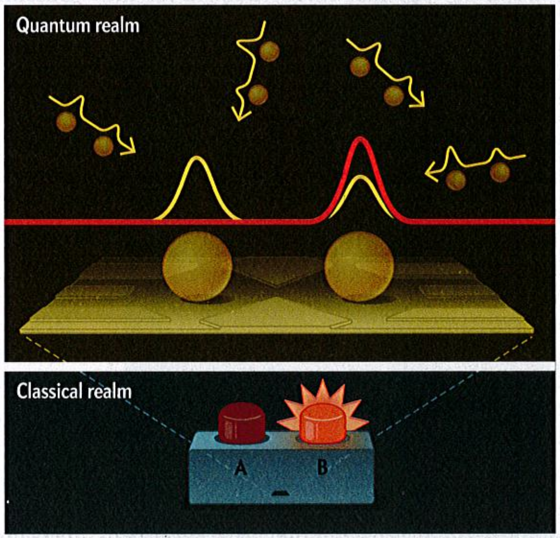
Strangely, when scientists make a measurement of a particle, this act appears to reduce all the quantum possibilities to one, seemingly chosen at random. The experiment will find the particle at point A, for example, and the particle enters the classical realm, ceasing to be in a superposition.





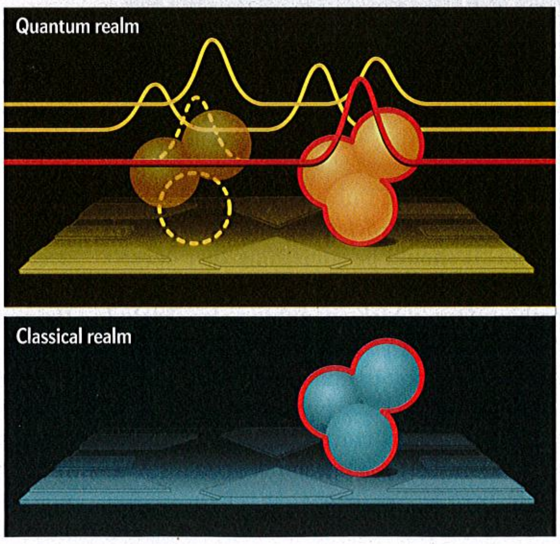
Collapse at Measurement

One theory for how the universe crosses over from quantum to classical is that the act of measurement intervenes. Particles can linger in quantum superpositions (*dotted yellow lines*) as long as no one looks too closely, but once humans make a measurement, the particle is forced to "choose" a specific state (*solid red lines*). How this happens, and why human measurement should take on such a significance in physics, remains mystifying.



Decoherence

Another theory posits that a particle's environment is to blame for moving it from the quantum world to the classical. As long as a particle is undisturbed by any outside influence, so the thinking goes, it can remain in superposition. But when the wave functions of other particles or objects nearby meet with its own, they interfere, causing the particle's many quantum possibilities to collapse into a single classical reality.



Continuous Spontaneous Localization

Another possibility is that the collapse of the wave function to a single possibility is a random event, not caused by human or environmental interference. The chances of any one particle collapsing at any given time are extremely small, but in macroscopic objects containing multitudes of atoms, the collapse of at least one is inevitable, which then causes the entire structure to collapse.

Illustrations by Jen Christiansen

Adler's cryptic comment refers to what the basic equations of quantum theory say—or do not say—about the nature of reality. Known as wave functions, the equations assign probabilities to an object's chances of being found in various states. Unlike Newtonian physics, where apples, planets and everything else always have well-defined properties, quantum physics is inherently probabilistic. In a sense, particles that are described by wave functions cannot even be said to fully exist; they have no fixed locations, speeds or energies—only probabilities. But everything changes when scientists take a measurement. Then real, tangible properties arise, as if conjured up by merely attempting to observe them. Not only does the theory not say *why* measurements bring about this transformation—it does not tell us why one of those many possibilities manifests instead of others. Quantum mechanics describes what *might* happen as the outcome of a measurement but not what *will* happen. In other words, the theory provides no mechanism for the transition from the probable to the actual.

To "make things happen" in quantum mechanics, one of the theory's legendary founders argued for an almost metaphysical hack. In the late 1920s Werner Heisenberg formulated and spread the notion that the very act of measurement makes the wave function of a particle "collapse"—the many potential outcomes instantaneously reduce to a single observed result. The only flaw with the idea is that there is nothing in the equations of quantum theory that says a collapse occurs or offers a physical process to explain it. Heisenberg's "solution" essentially introduced a new mystery into physics: What exactly happens when a wave function collapses? That quantum conundrum is now known as the measurement problem.

Physicists may have gotten used to the collapse idea over the past 90 years, but they have never really liked it. The notion that a human action—measurement—plays a central role in our most fundamental theory of how the universe works does not sit well with anyone partial to the concept of an objective reality.

"Fundamentally, I have an ideal of what a physical theory should be," says Nobel laureate physicist Steven Weinberg of the University of Texas at Austin. (Weinberg serves on *Scientific American*'s board of advisers.) "It should be something that doesn't refer in any specific way to human beings. It should be something from which everything else—including anything you can say systematically about chemistry, or biology, or human affairs—can be derived. It shouldn't have human beings at the beginning in the laws of nature. And yet I don't see any way of formulating quantum mechanics without an interpretive postulate that refers to what happens when people choose to measure one thing or another thing."

CHOOSE YOUR INTERPRETATION

ONE SLEIGHT-OF-HAND WAY OUT of the measurement problem is to assume that collapse simply does not happen. In the early 1970s H. Dieter Zeh, now an emeritus professor at the University of Heidelberg in Germany, proposed a process that yields the *appearance* of collapse while preserving the full quantum multiplicity of the wave function. In the real world, Zeh argued, the wave function of any particular object becomes hopelessly enmeshed with that of everything else in its environment, making it impossible to keep track of all the countless quantum interactions going on around us. In quantum parlance, the wave functions become "entangled"—a special kind of correlation that preserves connectedness even over huge distances. An observer can only ever hope to look at a single small part of that vast entangled system, so any particular measurement captures just a sliver of the quantum world.

Zeh called this process "decoherence," and it has become the go-to explanation among physicists for why we do not witness quantum phenomena on a macroscopic level. It describes how an intact wave function—which comprises all the possible physical states a particle might have—decoheres as it mingles with the wave functions of other quantum systems around it. If the decoherence model is right, we ourselves live among the strands of that entangled quantum web but see only part of it.

Not all physicists believe that decoherence settles the measurement problem. For one thing, it still fails to explain why we see one strand of the quantum web and not others. "You still have to invoke the collapse postulate, which takes an entangled state and says that one of those possible states has to be selected, and that is usually done by fiat," says Miles P. Blencowe, a theoretical physicist at Dartmouth College. For Blencowe and others, the process does not capture the way we experience things. "I believe we have this one world that is evolving," he says. "How do you go from an entangled state to this perception of the world as always finding one unique path into the future? Many quantum mechanicians would feel that there needs to be a collapse to restore this oneness about the world as it evolves rather than this web of entanglement that keeps enlarging." Adler's assessment of decoherence is more blunt: "It doesn't supply a mechanism [for collapse] at all. It doesn't solve the problem, period."

Six decades ago a doctoral candidate at Princeton University proposed an even more radical solution to the collapse problem. In his 1957 Ph.D. thesis, Hugh Everett argued that the wave function neither collapses nor decoheres. Rather all its components are physically real, parts of an endlessly branching panoply of universes. Everett's "many worlds" interpretation, as it is called, has become popular among cosmologists, who have other reasons to think we might inhabit a multiverse. But no one has ever managed to experimentally distinguish the many-worlds idea from standard quantum theory.

The same holds for other interpretations of quantum mechanics. French physicist Louis de Broglie, one of the founders of quantum theory, sought to eliminate the need for collapse by introducing the notion of "pilot waves" that guide the paths of electrons and all other particles. In de Broglie's version of quantum theory, which American physicist David Bohm further developed in the 1950s, there is no mysterious collapse; measurements simply show the interactions of pilot waves and their associated particles. But again, no one has yet found experimental evidence that distinguishes de Broglie and Bohm's pilot-wave view of reality from Everett's many worlds or any of the other dozen or so different takes on quantum mechanics. In the end, quantum partisans choose their favorite description of reality based on aesthetics. "I still come back to the fact that we have this one world that is evolving," Blencowe says. "For that, one really needs some sort of collapse, which is more than just a rule for the results of experiments but is some actual process."

TESTING COLLAPSE

THE CITY OF DELFT might qualify as an entangled quantum system. Its placid canals and medieval brick buildings overlap in space and time with cars, bicyclists, cell-phone shops and students staggering home from all-night parties along the same narrow streets painter Johannes Vermeer once walked. Gröblacher's lab lies about two kilometers south of the old town center and what feels like several hundred years into the future. On a warm spring morning, he shows a visitor one of the "really, really big" things he and his colleagues have built: a millimeter-size membrane tethered to a silicon chip, just barely visible to the naked eye.

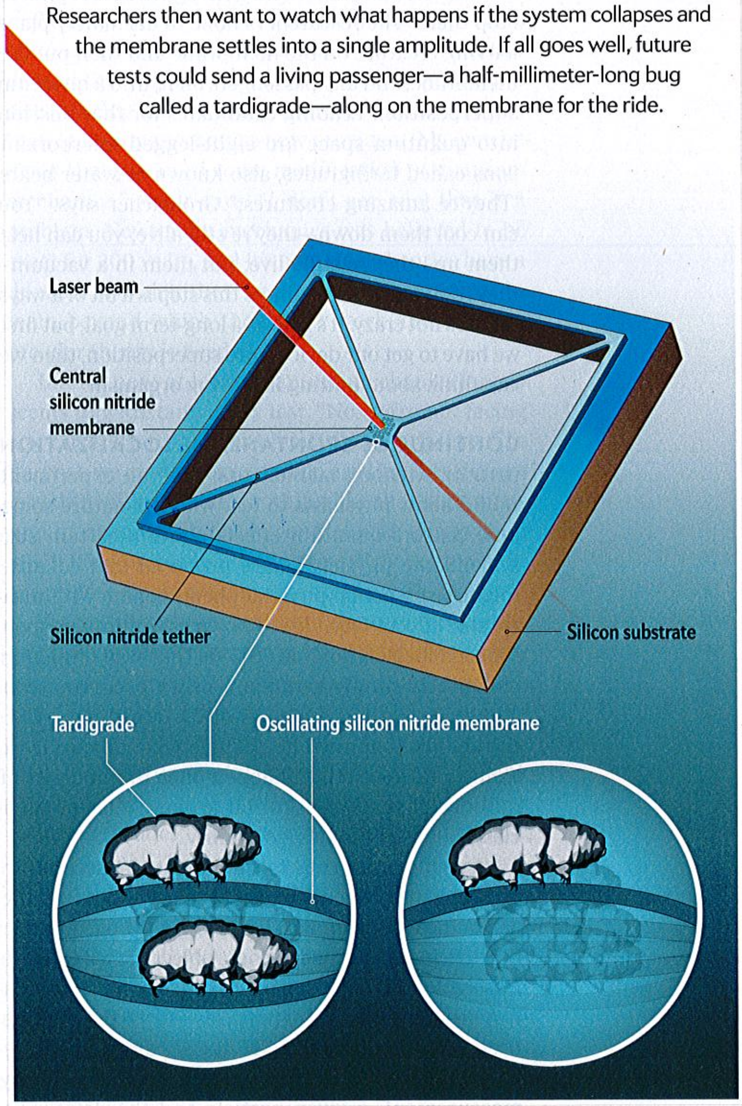
Seen up close (or blown up on a poster in the hallway outside Gröblacher's office), the membrane resembles a minuscule trampoline. It is made of silicon nitride, a durable ceramic material that was used for engine bearings in the space shuttles, and holds a highly reflective mirror at its center. A single jolt from a component on the chip can set the membrane vibrating for minutes at a time. Such membranes are "really good oscillators," Gröblacher says. "To put that in perspective, it would be like pushing someone on a swing, and the person would go back and forth, with one single push, for 10 years." Despite its Lilliputian dimensions, the membrane is extraordinarily robust. "We really put a lot of stress in it—six gigapascals" says Richard Norte, one of Gröblacher's collaborators. "It's about 10,000 times the stress you'd have in a bicycle tire, in something that's only about eight times thicker than the width of DNA."

Those robust qualities make the membrane an ideal place to study quantum phenomena—it vibrates reliably at room temperature without breaking down. Gröblacher and Norte plan to eventually use a laser to nudge the membrane into a superposition—a quantum state where the membrane could be simultaneously oscillating at two different amplitudes. The membrane's ability to wiggle for minutes on end should, in principle, allow such quantum states to persist long enough to see what happens when—or if—the membrane collapses into a single classical state.

"That is exactly what you need to create some sort

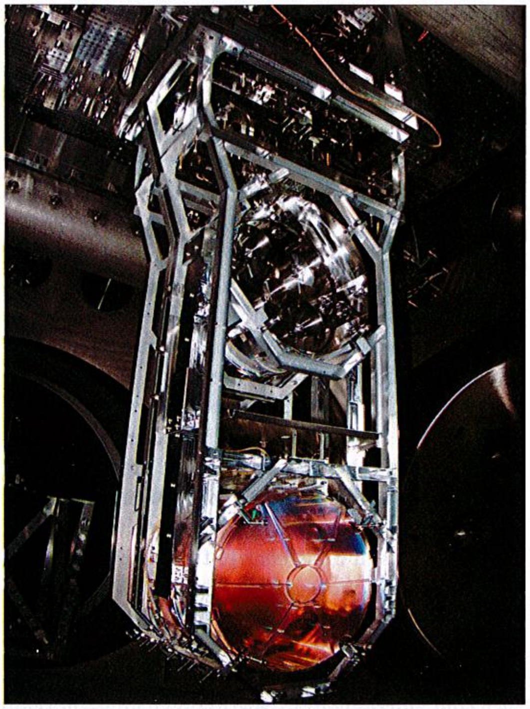
Tabletop Test

Physicists want to see if macroscopic objects can behave in quantum ways. One planned experiment will feature a millimeter-size membrane that looks like a tiny trampoline. Attached to a silicon chip, the membrane can be jolted into long-lasting vibrations. Ultimately scientists plan to use a laser to push the membrane into a quantum superposition. In the experiment, the membrane could be vibrating at two different amplitudes at once. Researchers then want to watch what happens if the system collapses and the membrane settles into a single amplitude. If all goes well, future tests could send a living passenger—a half-millimeter-long bug called a tardigrade—along on the membrane for the ride.



of quantumness," Gröblacher says. "You don't want to have it interact with its environment, because that induces decoherence—supposedly. So you want a really well-isolated system, get it in a quantum state, then switch on your own decoherence, something you control—a laser. We're still not at the point where we can actually create a superposition of the oscillations of the system. But in a few years that's what we're aiming for."

And Gröblacher and his colleagues do not plan to stop there. The researchers hope to ultimately place a living creature on the membrane and then put the membrane, and any passengers on it, into a quantum superposition. Leading candidates for that mission into quantum space are eight-legged microorganisms called tardigrades, also known as water bears. "They're amazing creatures," Gröblacher says. "You can cool them down—they're still alive; you can heat them up—they're still alive; put them in a vacuum—they're still alive." He admits this step is a bit of a ways off. "It's not crazy. It's nice as a long-term goal, but first we have to get our devices into superposition, then we can think about putting in a living organism."


MIRRORS at LIGO showed no evidence of having been nudged by quantum jiggles predicted by CSL theory.

LIGO LABORATORY California Institute of Technology and Massachusetts Institute of Technology

CONTINUOUS SPONTANEOUS LOCALIZATION

WITH OR WITHOUT TARDIGRADES, such an experiment would allow physicists to test whether nature somehow censors quantum effects above a certain size scale. Some physicists have proposed that collapse might be an actual physical phenomenon, with measurable effects. One idea—known as continuous spontaneous localization, or CSL—is that wave function collapse is simply a random event occurring constantly in the microscopic world. According to CSL, the chance that any one particle will collapse is extremely rare—it might happen once in hundreds of millions of years—but for large aggregates of particles, collapse becomes a certainty.

"A single proton has to wait about 10^{16} seconds to see a collapse, so it happens only a few times over the age of the universe," Bassi says. But the huge number of particles in any macroscopic object makes collapse inevitable. "If you take a table, which contains roughly Avogadro's number of particles—10^{24}—the collapse occurs almost immediately." If CSL is real, measurement and observation have no role in collapse. In any measurement, a given particle and the devices recording it become part of an immense quantum array that very rapidly collapses. Although it seems as if the particle went from a superposition to an actual position during a measurement, this transformation happened as soon as the particle interacted with the devices, before the measurement occurred.

If collapse turns out to be a real physical phenomenon, the practical consequences could be significant. For one thing, it might limit the nascent technology of quantum computers. "Ideally, you would like to make bigger and bigger quantum computers," Bassi says. "But you would not able to run quantum algorithms, because the collapse would kill everything." For decades most physicists have regarded collapse as an essentially untestable aspect of quantum theory. But CSL and other collapse models have changed that. The CSL model, for example, predicts that the action of collapse imparts a slight jiggle to particles, creating an omnipresent background vibration that might be detectable in experiments. "The collapse [in CSL] is something universal for micro and macro systems," Bassi says. "Every time there is a collapse, you move the particle a little." He and other physicists have searched for such evidence in surprising places. They have combed through the calibration data for the Laser Interferometer Gravitational-Wave Observatory (LIGO), an instrument capable of registering motions 10,000 times as small as the width of a proton.

In February 2016 LIGO reported detecting a gravitational wave for the first time. The wave—a ripple in spacetime caused by two distant colliding black holes—stretched and squeezed the space between two mirrors at the experiment's twin sites in Washington State and Louisiana. This passing wave shifted the positions of LIGO's mirrors by just four-thousandths the diameter of a proton, in perfect agreement with predictions by Einstein's general theory of relativity. But Bassi and his colleagues found no evidence in LIGO's data for any additional motion caused by the kind of quantum nudges predicted by CSL. The result did not surprise them. If quantum collapse is an actual physical phenomenon, it is an extraordinarily weak one. The question was: How weak? Now they have put extremely precise bounds on the effect. "If you apply the model to the mirror at LIGO, the mirror should move more than expected, but the mirror doesn't move much. Therefore, the collapse noise can't be too strong," Bassi says.

Physicists have also hunted for signs of collapse in experiments designed to look for dark matter—hypothetical particles thought to account for up to 85 percent of the matter in the universe. One such experiment, sheltered in the Spanish Pyrenees, uses germanium detectors to search for signs of dark matter particles zipping through and generating a flash of x-rays. A collapsing wave function should likewise create a flash, but experimenters have seen no such emissions.

These types of experiments have tightened the constraints on collapse models considerably but not fatally. Last September, Andrea Vinante, a physicist at the University of Southampton in England, along with Bassi and three colleagues, reported the discovery of tentative evidence in support of the CSL model. Vinante's team constructed a miniature cantilever (a horizontal beam fixed at one end), just half a millimeter long and two microns thick and tipped with a small magnet. The researchers carefully shielded the setup from any external vibrations and cooled the cantilever to 40 thousandths of a kelvin above absolute zero to eliminate any possibility of thermally induced movements.

Under those conditions the cantilever should have vibrated ever so slightly because of thermal motion of its particles. But the actual wobble was greater than this predictable motion. The experiment's motion detector—an extremely sensitive instrument called a superconducting quantum-interference device, or SQUID—found that the cantilever and its magnet vibrated like a diving board, bending up and down by a few trillionths of a meter. Eleven years ago Adler calculated that collapsing wave functions might produce vibrations of approximately that size.

"We could see some unexplained noise," says Vinante, describing his experimental results. "It's something that is consistent with what we expect from collapse models, but it could be from an effect we have not understood completely." He and his colleagues are working on upgrades to improve the experiment's sensitivity by at least a factor of 10 and perhaps a factor of 100. "We should be able to either confirm that there is something anomalous or rule out that what we observed was anything interesting." Vinante says it might take another year or two before they have new data. Given the century-long track record of quantum theory's dominance, the odds of discovering a deviation are slim.

But what if one of these experiments does pan out and confirms the phenomenon of quantum collapse? Would that mean an end to the mysteries and paradoxes of the theory? "If collapse really existed, it would divide the world into different scales," says Igor Pikovski, a theoretical physicist at the Harvard-Smithsonian Center for Astrophysics. "Above a certain scale quantum mechanics would cease to be the correct theory. But below that scale everything we know about quantum mechanics would still hold. So the same philosophical questions and interpretations that bug us would still hold for the lower scale. You'd still have many worlds for electrons or atoms—but not for the moon! So it doesn't solve some of the problems—I think it makes it more strange."

Models such as CSL are just preliminary efforts to unify those two realms. Although they are not full-fledged theories yet, they may eventually help physicists develop a more comprehensive model of reality than quantum mechanics now provides. "My own belief is that you need some modification of quantum mechanics," Adler says. "I don't see why that is a problem. Newtonian mechanics was believed to be exact for 200 years, and it's not. Most theories have a domain in which they work, and then there's a domain beyond which they don't work and where a broader theory is needed."

But for now, at least, quantum mechanics largely seems to withstand every test. "No, we're not facing any crisis. That's the problem!" Weinberg says. "In the past, we made progress when existing theories ran into difficulties. There's nothing like that with quantum mechanics: It's not in conflict with observation at all. It's a problem of failing to satisfy the reactionary philosophical preconceptions of people like me."

Yet for all the weirdness of quantum mechanics, most scientists are happy to leave it be. They carry on using the theory to operate their atom smashers and dark matter detectors and rarely stop to ponder what quantum mechanics says—or does not say—about the fundamental nature of reality. "I think most physicists have what seems to me a very healthy attitude," Weinberg says, "to go on using it, to try to push forward the frontiers of our knowledge and leave the philosophical questions for a future generation." More than a few, though, are not willing to wait that long. "Some people will tell you quantum mechanics has taught us that the world is strange, so we have to accept it," Bassi says. "I would say no. If something is strange, then we have to understand better." SA

MORE TO EXPLORE

Mechanical Resonators for Quantum Optomechanics Experiments at Room Temperature. R. A. Norte et al. in *Physical Review Letters,* Vol. 116, No. 14, Article No. 147202; April 8, 2016. Preprint available at https://arxiv.org/abs/1511.06235

Improved Noninterferometric Test of Collapse Models Using Ultracold Cantilevers. A. Vinante et al. in *Physical Review Letters,* Vol. 119, No. 11, Article No. 110401; September 15, 2017. Preprint available at https://arxiv.org/abs/1611.09776

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