Bringing Schrödinger’s Cat to Life

by Philip Yam, *staff writer*

I am sorry that I ever had anything to do with quantum theory,” Erwin Schrödinger reportedly complained to a colleague. The Austrian physicist was not lamenting the fate of his now famous cat, which he figuratively placed in a box with a vial of poison in 1935. Rather he was commenting on the strange implications of quantum mechanics, the science behind electrons, atoms, photons and other things submicroscopic. With his feline, Schrödinger attempted to illustrate the problem: according to quantum mechanics, particles jump from point to point, occupy several places at once and seem to communicate faster than the speed of light. So why don’t cats—or baseballs or planets or people, for that matter—do the same things? After all, they are made of atoms. Instead they obey the predictable, classical laws quantified by Isaac Newton. When does the quantum world give way to the physics of everyday life? “That’s one of the $64,000 questions,” chuckles David Pritchard of the Massachusetts Institute of Technology.

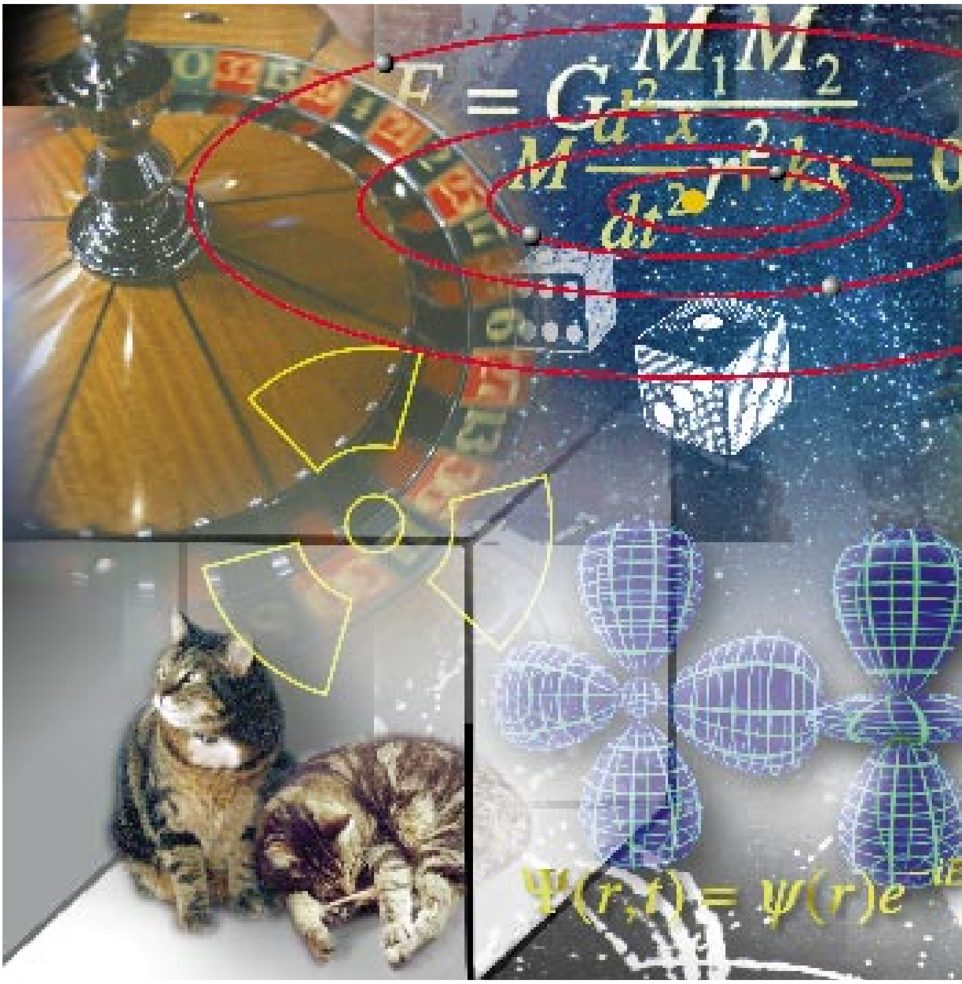
Pritchard and other experimentalists have begun to peek at the boundary between quantum and classical realms. By cooling particles with laser beams or by moving them through special cavities, physicists have in the past year created small-scale Schrödinger’s cats. These “cats” were individual electrons and atoms made to reside in two places simultaneously, and electromagnetic fields excited to vibrate in two different ways at once. Not only do they show how readily the weird gives way to the familiar, but in dramatic fashion they illustrate a barrier to quantum computing—a technology, still largely speculative, that some researchers hope could solve problems that are now impossibly difficult.

The mystery about the quantum-classical transition stems from a crucial quality of quantum particles—they can undulate and travel like waves (and vice versa: light can bounce around as a particle called a photon). As such, they can be described by a wave function, which Schrödinger devised in 1926. A sort of quantum Social Security number, the wave function incorporates everything there is to know about a particle, summing up its range of all possible positions and movements.

Taken at face value, a wave function indicates that a particle resides in all those possibilities at once. Invariably, however, an observation reveals only one of those states. How or even why a particular result emerges after a measurement is the point of Schrödinger’s thought experiment: in addition to the cat and the poison, a radioactive atom goes into the box. Within an hour, the atom has an even chance of decaying; the decay would trigger a hammer that smashes open the vial of antifeline serum.

The Measurement Problem

According to quantum mechanics, the unobserved radioactive atom remains in a funny state of being decayed and not decayed. This state, called a superposition, is something quantum objects enter quite readily. Electrons can occupy several energy levels, or orbitals, simultaneously; a single photon, after passing through a beam splitter, appears



DIGITAL COMPOSITION BY JEFF BRICE; WIGNER FUNCTION OF ATOMIC-MATTER WAVE THROUGH DOUBLE SLIT COURTESY OF MATTHIAS FREYBERGER, UNIVERSITY OF ULM

Recent experiments have begun to demonstrate how the weird world of quantum mechanics gives way to the familiarity of everyday experience

to traverse two paths at the same time. Particles in a well-defined superposition are said to be coherent.

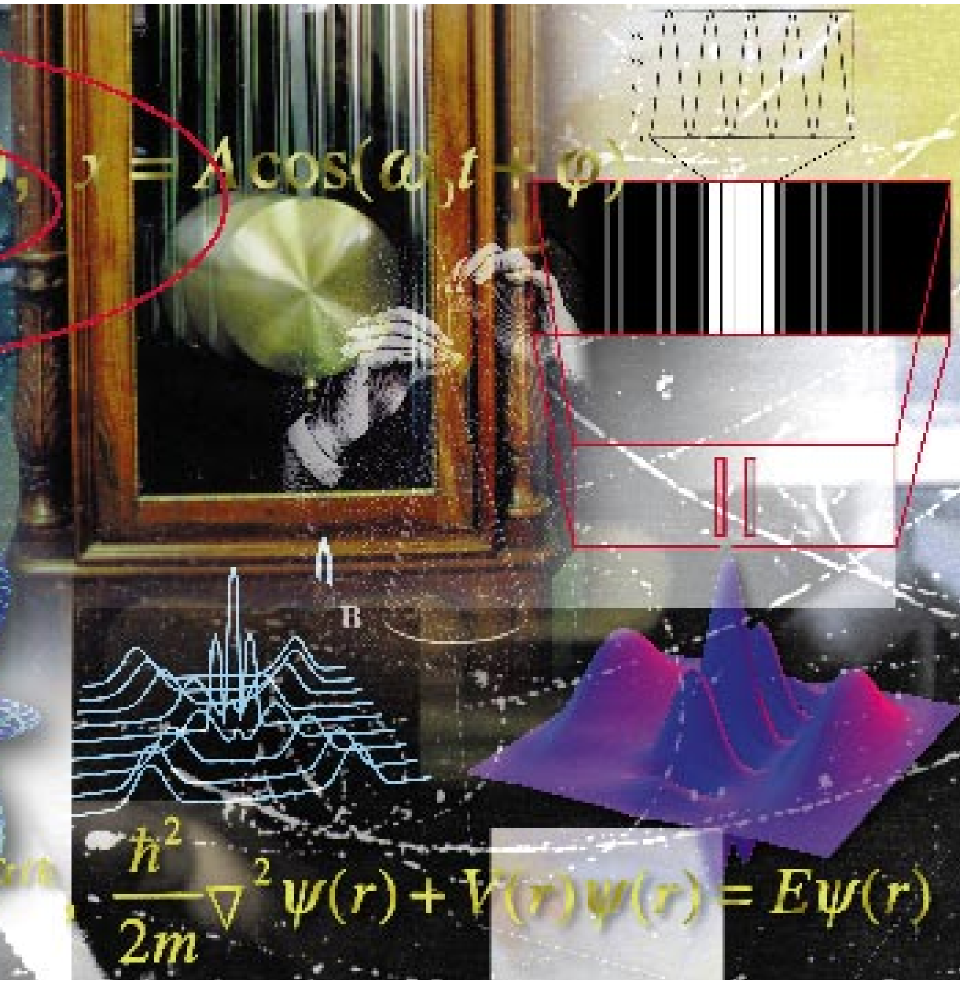
But what happens when quantum objects are coupled to a macroscopic one, like a cat? Extending quantum logic, the cat should also remain in a coherent superposition of states and be dead and alive simultaneously. Obviously, this is patently absurd: our senses tell us that cats are either dead or alive, not both or neither. In prosaic terms, the cat is really a measuring device, like a Geiger counter or a voltmeter. The question is, then, Shouldn't measuring devices enter the same indefinite state that the quantum particles they are designed to detect do?

For the Danish physicist Niels Bohr, a founder of quantum theory (and to whom Schrödinger's regretful comment was directed), the answer was that measurements must be made with a classical apparatus. In what has come to be called the standard, or Copenhagen, interpretation of quantum mechanics, Bohr postulated that macroscopic detectors never achieve any fuzzy superposition, but he did not explain exactly why not. "He wanted to mandate 'classical' by hand," says Wojciech Zurek of Los Alamos National Laboratory. "Measurements simply became." Bohr also recognized that the boundary between the classical and the quantum can shift depending on how the experiment is arranged. Furthermore, size doesn't necessarily matter: superpositions can persist on scales much larger than the atomic.

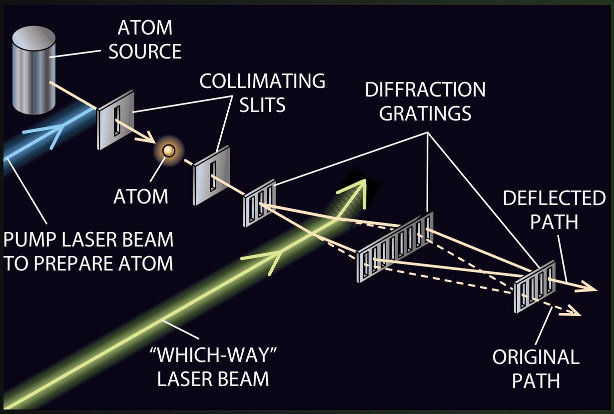
In November 1995 Pritchard and his M.I.T. colleagues crystallized the fuzziness of measurement. The team sent a narrow stream of sodium atoms through an interferometer, a device that gives a particle two paths to travel. The paths recombined, and each atom, acting as a wave, "interfered" with itself, producing a pattern of light and dark fringes on an observing screen (identical to what is seen when a laser shines through two slits). The standard formulation of quantum mechanics states that the atom took both paths simultaneously, so that the atom's entire movement from source to screen was a superposition of an atom moving through two paths.

The team then directed a laser at one of the paths. This process destroyed the interference fringes, because a laser photon scattering off the atom would indicate which path the atom took. (Quantum rules forbid "which-way" information and interference from coexisting.)

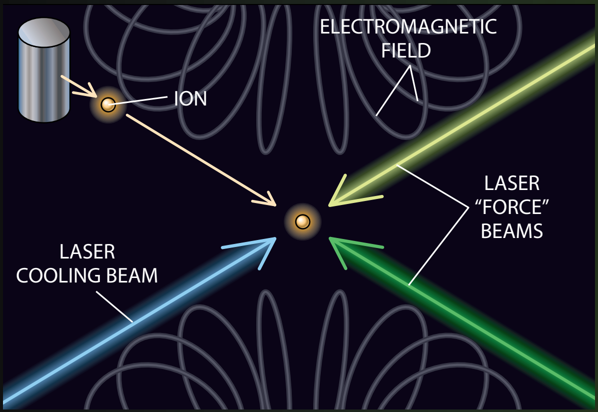
On the surface, this scattering would seem to constitute a measurement that destroys the coherence. Yet the team showed that the coherence could be "recovered"—that is, the interference pattern restored—by changing the separation between the paths to some quarter multiple of the laser photon's wavelength. At those fractions, it was not possible to tell from which path the photon scattered. "Coherence is not really lost," Pritchard elucidates. "The atom



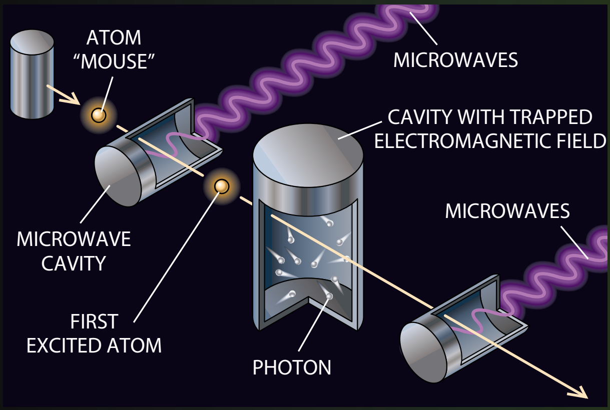
FRAMEWORK OF PHYSICS must somehow connect the exotica of quantum mechanics—its dead-and-alive cats, orbitals, oscillating ions and matter waves—with the more intuitive counterparts from classical physics: probabilities, planetary motions, pendulum swinging and double-slit, light-wave interference.



FUZZINESS OF QUANTUM MEASUREMENT is demonstrated with sodium atoms split and recombined to produce an interference pattern (*not shown*). A laser deflecting off an atom would reveal which path the atom took and thereby eliminate interference. But the pattern reemerges if the path lengths are varied, showing how deeply quantum systems can become "entangled" with classical apparatus.



SCHRÖDINGER'S CAT made from a beryllium ion is first trapped by an electromagnetic field and then cooled with a laser. Laser "force" beams prepare the ion in a superposition of two spin states. These states are then eased apart so that the ion resides in two places at once.



CAT-AND-MOUSE EXPERIMENT is done with a trapped electromagnetic field (confined photons). A rubidium atom is excited by microwaves into a superposition of two states. As it passes through the center cavity, it relays its superposed state to the electromagnetic field. A second atom serves as the "mouse" that probes the resulting state of the field. (The second microwave cavity, identical to the first, provides a way to create quantum interference and is essential to measurements.)

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became entangled with a larger system." That is, the quantum state of the atom became coupled with the measuring device, which in this case was the photon.

Like many previous experiments, Pritchard's work, which is a realization of a proposal made by the late Richard Feynman many years ago, deepens the mysteries underlying quantum physics rather than resolving them. It demonstrates that the measuring apparatus can have an ambiguous definition. In the case of Schrödinger's cat, then, is the measurement the lifting of the lid? Or when light reaches the eye and is processed by the mind? Or a discharge of static from the cat's fur?

A recent spate of Schrödinger's cat experiments have begun to address these questions. Not all physicists concur that they are looking at bona fide quantum cats—"kitten" is the term often used, depending on the desired level of cuteness. In any event, the attempts do indicate that the quantum-classical changeover—sometimes called the collapse of the wave function or the state-vector reduction—has finally begun to move out of the realm of thought experiments and into real-world study.

Here, Kitty, Kitty

In 1991 Carlos Stroud and John Yeazell of the University of Rochester were experimenting with what are called Rydberg atoms, after the Swedish spectroscopist Johannes Rydberg, discoverer of the binding-energy relation between an electron and a nucleus. Ordinarily, electrons orbit the nucleus at a distance of less than a nanometer; in Rydberg atoms the outer electron's orbit has swollen several 1,000-fold. This bloating can be accomplished with brief bursts of laser light, which effectively put the electron in many outer orbitals simultaneously. Physically, the superposition of energy levels manifests itself as a "wave packet" that circles the nucleus at an atomically huge distance of about half a micron. The packet represents the probability of the excited electron's location.

While swelling potassium atoms, the Rochester workers noticed that after a few orbits, the wave packet would disperse, only to come back to life again as two smaller packets on opposite ends of its large orbit. With his colleague Michael W. Noel, Stroud showed last September that the two packets constituted a Schrödinger's cat state—a single electron in two locations.

MICHAEL NOEL AND CARLOS STROUD *University of Rochester*

WRITING ON AN ATOM is theoretically plausible. An electron in a superposition of 2,500 energy levels has a wave function sufficiently complex to encode a message. Words are written by assigning color and saturation to the amplitude and phase of the wave function.

An electron, though, is essentially a mere point. Closer to the macroscopic realm is an ion (a charged atom), which consists of many elementary particles. In May 1996 Chris Monroe, David J. Wineland and their colleagues at the National Institute of Standards and Technology (NIST) in Boulder, Colo., created a Schrödinger's cat out of a beryllium ion. They first trapped the ion with electromagnetic fields, then hit it with a laser beam that stifled the ion's thermal jitters and thereby cooled it to within a millikelvin of absolute zero. Then the researchers fired two laser beams, each of a slightly different frequency, at the ion to manipulate its spin, an intrinsic, quantum feature that points either up or down. With the lasers, the researchers made the ion take on a superposition of spin-up and spin-down states.

So much for the preparations; next came the more macroscopic part. By manipulating the tuning of the two lasers, the NIST team could swing the spin-up state to and fro in space, and the spin-down state fro and to. A snapshot would show the ion in the spin-up state at one physical location and simultaneously in the spin-down state at a second position. The states were 80 nanometers apart—large on the atomic scale. "We made one ion occupy two places that are very far separated compared with the size of the original ion," Monroe says.

Last December, Michel Brune, Serge Haroche, Jean-Michel Raimond and their colleagues at the Ecole Normale Supérieure (ENS) in Paris took matters a step further. "We were able to monitor the washing-out of quantum features," Haroche explains. To see how the superposition collapsed to one state or another, they in effect dangled a quantum mouse in front of their Schrödinger's cat to check whether it was alive or dead.

The cat was a trapped electromagnetic field (a bunch of microwave photons in a cavity). The researchers sent into the cavity a Rydberg atom that had been excited into a superposition of two different energy states. The Rydberg atom transferred its superposed state to the resident electromagnetic field, putting it into a superposition of two different phase, or vibrational, states. With its two phases, the field thus resembled the Schrödinger's cat in its odd superposition between life and death.

For the mouse, the ENS team fired another Rydberg atom into the cavity. The electromagnetic field then transferred information about its superposed phases to the atom. The physicists compared the second atom with the first to glean superposition information about the electromagnetic field.

More interesting, however, was the team's ability to control crucial variables and to determine how coherent states become classical ones. By varying the interval between the two atoms sent into the cavity (from 30 to 250 microseconds), they could see how the collapse of the superposition varied as a function of time, and by enlarging the electromagnetic field (by putting more photons in the cavity), they could see how the collapse changed with size. "This is the first time we can observe the progressive evolution of quantum to classical behavior," Haroche says.

"This is a breathtaking experiment," Zurek enthuses. "Seeing a Schrödinger's cat is always surprising, but being able to see the cat forced to make a choice between 'dead' and 'alive,' to observe for the first time quantum weirdness going away, is the real coup." Moreover, the ENS results jibed with most theorists' technical expectations. "What it tells me," Zurek remarks, "is that the simple equations we've been writing down seem to be a good approximation."

Losing Coherence

Zurek is the leading advocate of a theory called decoherence, which is based on the idea that the environment destroys quantum coherence. He formulated it in the 1980s (although some of it harkens back to Bohr and other quantum founders) and with various collaborators has been investigating its consequences ever since.

The destabilizing environment essentially refers to anything that could be affected by—and hence inadvertently "measure"—the state of the quantum system: a single photon, a vibration of a molecule, particles of air. The environment is not simply "noise" in this theory; it acts as an apparatus that constantly monitors the system.

The ENS experiment makes that effect clear. "The system decoheres because the system leaks information," Zurek notes. Some photons can escape the cavity and hence betray the state of the remaining ones to the rest of the universe. "So in a sense, Schrödinger's cat is having kittens crawling out," Zurek says.

Having the environment define the quantum-classical boundary has the advantage of removing some of the mystical aspects of quantum theory that certain authors have promulgated. It does away with any special need for a consciousness or new physical forces to effect a classical outcome. It also explains why size per se is not the cause of decoherence: large systems, like real-life cats, would never enter a superposition, because all the particles that make up a feline influence a vast number of environmental parameters that make coherence impossible. Given a one-gram bob on a pendulum and a few reasonable assumptions, the interference terms in the system's wave function drop to about $2.7^{-1,000}$ of their original value in a nanosecond—a virtually instantaneous disappearance of quantum weirdness. "The old intuition going back to Bohr is on the money," although now there is a physical mechanism to substantiate his mandate, Zurek concludes.

Still, Zurek's decoherence model is flawed in some eyes. "In my view, decoherence doesn't select a particular outcome," opines Anthony J. Leggett of the University of Illinois. "In real life, you get definite macroscopic outcomes."

Zurek argues that the environment does indeed dictate the quantum possibilities that end up in the real world. The process, which he refers to as environment-induced superselection, or einselection, tosses out the unrealistic, quantum states and retains only those states that can withstand the scrutiny of the environment and thus might become classical. "The selection is done by the environment, so you will not be able to predict which of the allowed possibilities will become real," Zurek observes.

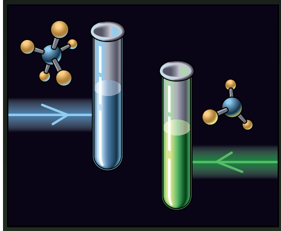
The explanation feels less than satisfying. Zurek's approach is "very appealing. It allows you to calculate things, to see how the interference fringes wash out as the superposition gets bigger," NIST's Monroe says. "But there's still something funny about it. He's sweeping things under the rug, but it's hard to say what rug." The problem is that decoherence—and in fact any theory about the quantum-classical transition—is necessarily ad hoc. Quantum superpositions must somehow yield outcomes that conform to our everyday sense of reality. That leads to circuitous logic: the results seen in the macroscopic world arise out of the quantum world because those results are the ones we see. A solution of sorts, advocated by a few prominent cosmologists, is the unwieldy "many worlds" interpretation, which holds that all possibilities stipulated by the wave function do in fact happen. They go on to exist in parallel universes. The idea, however, is untestable, for the parallel universes remain forever inaccessible to one another.

Jobs for Quantum Cats

Researchers have proposed and demonstrated several technologies exploiting entangled and superposed quantum states, such as quantum computing. A few other schemes include the following:

Quantum Chemistry

Using lasers, researchers can place molecules in a superposition of reaction pathways; then they can control the chemical process by adjusting the degree of interference. Last December workers separated isotopes with a similar technique. Obstacles include less than practical efficiency levels and difficulty in controlling phase characteristics of the laser.



Quantum Key Cryptography

A much better prospect than quantum computing is quantum key cryptography. Legitimate communicators create shared keys using the polarization of photons. Eavesdropping on these keys would immediately be noticed, because it would disrupt the key photons' states. Quantum cryptography has been shown to function over several kilometers in optical fibers.

Radical Reworkings

The problems with decoherence and the many-worlds idea have led a sizable minority to support a view called GRW theory, according to Leggett. The concept was put forward in 1986 by GianCarlo Ghirardi and Tullio Weber of the University of Trieste and Alberto Rimini of the University of Pavia.

In the GRW scheme, the wave function of a particle spreads out over time. But there is a small probability that the spreading wave "hits" a mysterious "something" in the background. The wave function suddenly becomes localized. Individual particles have only a small chance of a hit, about once every 100 million years. But for a macroscopic cat, the chance that at least one of its roughly 10^{27} particles makes a hit is high, at least once every 100 picoseconds. The cat never really has a chance to enter any kind of superposition. Hence, there is no need for decoherence: the macroscopic state of the cat results from spontaneous microscopic collapses.

A few problems plague this model. One is that the timing factor that triggers the hit is entirely arbitrary; proponents simply choose one that produces reasonable results. More important, though, is the source of the trigger. "Basically, [there is] a sort of universal background noise that cannot itself be described by quantum mechanics," Leggett explains. The noise is not simply random processes in the environment; it has a distinct mathematical flavor. Roger Penrose of the University of Oxford argues in his book *Shadows of the Mind* that the trigger may be gravity, which would neatly sidestep certain technical objections.

Other, more radical proposals abound. The most well known was put forth by the late David Bohm, who postulated that "hidden variables" underpin quantum mechanics. These variables—describing properties that in a way render wave functions as real forces—would eliminate the notion of superpositions and restore a deterministic reality. Like the many-worlds idea, Bohm's theory cannot be verified: the hidden variables by definition remain, well, hidden.

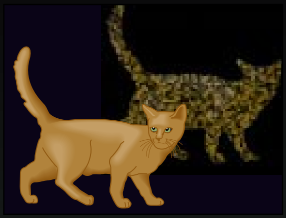
Given such choices, many working physicists are subscribing to decoherence, which makes the fewest leaps of faith even if it arguably fails to resolve the measurement problem fully. "Decoherence does answer the physical aspects of the questions," Zurek says, but does not get to the metaphysical ones, such as how a conscious mind perceives an outcome. "It's not clear if you have the right to expect the answer to all questions, at least until we develop a better understanding of how brain and mind are related," he muses.

Bigger superpositions may enable researchers to start ruling out some theories—GRW and decoherence predict them on different scales, for instance. "What we would like to do is to go to more complex systems and entangle more and more particles" than just the mere 10 trapped before, Haroche of the ENS says. Future NIST experiments are particularly suited to serve as "decoherence monitors," Monroe contends. "We can simulate noise to deliberately cause the superposition to decay." Leggett has proposed using sensors made from superconducting rings (called SQUIDs): it should be possible to set up large currents flowing in opposite directions around the ring simultaneously.

Still, there's a long way to go. "Even in the most spectacular experiments, at most you've shown a superposition for maybe 5,000 particles. That's a long way from the 10^{23} characteristic of the macroscopic world," says Leggett, who nonetheless remains supportive. "My own attitude is that one should just try to do experiments to see if quantum mechanics is still working."

Shrinking transistors, now with features less than a micron in size, may also lead to insights about the quantum-classical changeover. In a few years they may reach dimensions of tens of nanometers, a realm sometimes called the mesoscopic scale. Da Hsuan Feng of Drexel University speculates that quantum mechanics perhaps really doesn't lead to classical

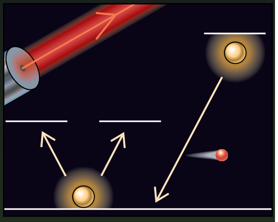
Quantum Teleportation



The idea has less to do with *Star Trek* than with reconstructing destroyed information. The crux is the Einstein-Podolsky-Rosen effect, which shows that two photons can remain entangled, no matter how far apart they are, until a measurement is made (which instantaneously puts both in a definite state). Alice takes one EPR photon, Bob the other. Later, Alice measures her EPR photon with respect to a third photon. Bob can use the relational measurement to re-create Alice's non-EPR photon. Whether Bob truly rematerialized the photon or just created an indistinguishable clone is unclear. Researchers at the University of Innsbruck reportedly demonstrated the phenomenon, which might have use in quantum cryptography.

Quantum Laser Optics

Lasers ordinarily require a population inversion, a condition in which atoms in an excited state outnumber those in the ground state; the excited atoms emit laser photons as they drop to the ground state. In 1995 researchers sidestepped this requirement. In lasing without inversion, two coupling lasers give ground-state atoms two paths to one higher energy level. Interference between the paths renders the ground-state atoms invisible, and so fewer excited atoms are needed. Such lasers do not require as much power and in principle could emit light in the desirable x-ray region.



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mechanics; rather both descriptions spring from still undiscovered concepts in the physical realm between them.

Quantum Computing

Even if experiments cannot yet tackle the measurement problem fully, they have much to contribute to a very hot field: quantum computing. A classical computer is built of transistors that switch between 0 or 1. In a quantum computer, however, the "transistors" remain in a superposition of 0 *and* 1 (called a quantum bit, or qubit); calculations proceed via interactions between superposed states until a measurement is performed. Then the superpositions collapse, and the machine delivers a final result. In theory, because it could process many possible answers simultaneously, a quantum computer would accomplish in seconds tasks, such as factoring large numbers to break codes, that would take years for a classical machine.

In December 1995 researchers successfully created quantum two-bit systems. Monroe and his colleagues crafted a logic element called a controlled-NOT gate out of a beryllium ion. The ion is trapped and cooled to its lowest vibrational state. This state and the first excited vibrational state constitute one bit. The second bit is the spin of one of the ion's electrons. Laser pulses can force the bits into superpositions and flip the second bit depending on the state of the first bit. Other variations of gates couple two photons via an atom in a cavity or transmit an entangled pair of photons through a network of detectors.

Yet the creation of a useful quantum computer, relying on superpositions of thousands of ions performing billions of operations, remains dubious. The problem? Loss of superposition. The logic gates must be fast enough to work before the qubits lose coherence. Using data from the NIST gate experiment, Haroche and Raimond calculated in an August 1996 *Physics Today* article that given the gate speed of 0.1 millisecond, the bits would have to remain in a superposition for at least a year to complete a meaningful computation (in this case, factoring a 200-digit number).

Other physicists are less pessimistic, since error-correcting codes (which are indispensable in classical computing) might be the solution. "It gives you instructions on how to repair the damage," says David DiVincenzo of the IBM Thomas J. Watson Research Center in Yorktown Heights, N.Y.

Moreover, DiVincenzo points out that a new method of quantum computation, making use of nuclear magnetic resonance (NMR) techniques, could raise coherence times to a second or more. Say a liquid—a cup of coffee—is placed in a magnetic field; because of thermal vibration and other forces, only one out of every million nuclei in the caffeine molecules would line up with the magnetic field. These standouts can be manipulated with radio waves to put their spins in a superposition of up and down. Maintaining coherence is easier here than in the other techniques because the nuclear spins undergoing the superpositions are well protected from the environment by the surrounding turmoil of seething molecules, the mad scramble of which averages out to zero. The calculating caffeine sits effectively in the calm eye of a hurricane. Two groups have recently demonstrated quantum computing by NMR, using a four-qubit version to sum 1 and 1. More complex systems, using perhaps 10 qubits, could be had by the end of the year.

The drawback is readout. With no way to detect individual spins, researchers must measure all the molecules' spins—both qubit and nonqubit ones. Complex molecules capable of sustaining many spins are therefore "noisier" than simpler ones. "They'll be able to do some nice stuff," Monroe says, "but beyond about 10 bits, they'll run into fundamental problems." The output from 10 bits is only 0.001 as strong as that from a single bit; for 20, the output is down by one million. So the NMR technique may not enter a meaningful computational realm of at least 50 bits.

There might be other uses for quantum superpositions, though. Stroud proposes data storage on an atom, because an electron in a Rydberg atom could be made to inhabit a superposition of 2,500 different energy levels. "That means that the electron's wave function can be quite complex, encoding a great deal of information," Stroud expounds. He demonstrated the possibility theoretically by writing "OPTICS" on an atom. Other uses for quantum superposition, such as in cryptography, chemistry and even teleportation, have been demonstrated. Schrödinger's boxed cat may have outwitted the best philosophical minds so far, but it seems to have found plenty of technological reasons to stay put.

Further Reading

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