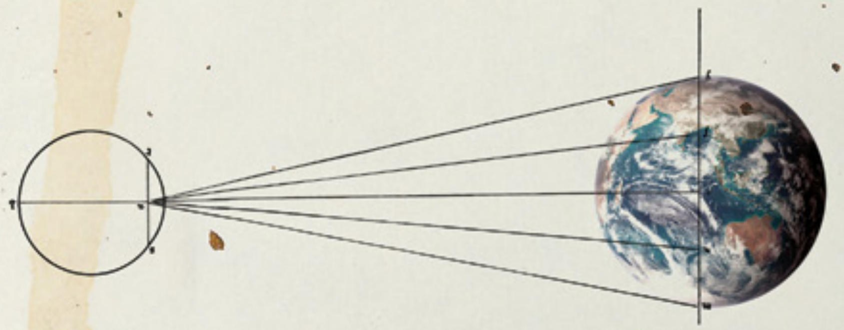
Vlatko Vedral made his name developing a novel way of quantifying entanglement and applying it to macroscopic physical systems. He did his undergraduate and graduate studies at Imperial College London. Since June 2009 he has been in an entangled state of professorship at the University of Oxford and at the National University of Singapore. Besides physics, Vedral enjoys spending time with his three children and playing his Yamaha electric guitar with the Marshall amp turned up to 11.



PHYSICS

LIVING IN A QUANTUM WORLD

Quantum mechanics is not just about teeny particles. It applies to things of all sizes: birds, plants, maybe even people

By Vlatko Vedral

ACCORDING TO STANDARD PHYSICS TEXTBOOKS, QUANTUM MECHANICS IS THE THEORY OF THE MICROSCOPIC world. It describes particles, atoms and molecules but gives way to ordinary classical physics on the macroscopic scales of pears, people and planets. Somewhere between molecules and pears lies a boundary where the strangeness of quantum behavior ends and the familiarity of classical physics begins. The impression that quantum mechanics is limited to the microworld permeates the public understanding of science. For instance, Columbia University physicist Brian Greene writes on the first page of his hugely successful (and otherwise excellent) book *The Elegant Universe* that quantum mechanics "provides a theoretical framework for understanding the universe on the smallest of scales." Classical physics, which comprises any theory that is not quantum, including Albert Einstein's theories of relativity, handles the largest of scales.

Yet this convenient partitioning of the world is a myth. Few modern physicists think that classical phys-

IN BRIEF

Quantum mechanics is commonly said to be a theory of microscopic things: molecules, atoms, subatomic particles.

Nearly all physicists, though, think it applies to everything, no matter what the size.

The reason its distinctive features tend to be hidden is not a simple matter of scale.

Over the past several years experimentalists have seen quantum effects in a growing number of macroscopic systems.

The quintessential quantum effect, entanglement, can occur in large systems as well as warm ones—including living organisms—even though molecular jiggling might be expected to disrupt entanglement.

Illustration by Justin Van Genderen

ics has equal status with quantum mechanics; it is but a useful approximation of a world that is quantum at all scales. Although quantum effects may be harder to see in the macroworld, the reason has nothing to do with size per se but with the way that quantum systems interact with one another. Until the past decade, experimentalists had not confirmed that quantum behavior persists on a macroscopic scale. Today, however, they routinely do. These effects are more pervasive than anyone ever suspected. They may operate in the cells of our body.

Even those of us who make a career of studying these effects have yet to assimilate what they are telling us about the workings of nature. Quantum behavior eludes visualization and common sense. It forces us to rethink how we look at the universe and accept a new and unfamiliar picture of our world.

A TANGLED TALE

TO A QUANTUM PHYSICIST, classical physics is a black-and-white image of a Technicolor world. Our classical categories fail to capture that world in all its richness. In the old textbook view, the rich hues get washed out with increasing size. Individual particles are quantum; en masse they are classical. But the first clues that size is not the determining factor go back to one of the most famous thought experiments in physics, Schrödinger's cat.

Erwin Schrödinger came up with his morbid scenario in 1935 to illustrate how the microworld and macroworld couple to each other, preventing arbitrary lines from being drawn between them. Quantum mechanics says that a radioactive atom can be both decayed and not decayed at the same time. If the atom is linked to a bottle of cat poison, so that the cat dies if the atom decays, then the animal gets left in the same quantum limbo as the atom. The weirdness of the one infects the other. Size does not matter. The puzzle was why cat owners only ever see their pets as alive or dead.

In the modern point of view, the world looks classical because the complex interactions that an object has with its surroundings conspire to conceal quantum effects from our view. Information about a cat's state of health, for example, rapidly leaks into its environment in the form of photons and an exchange of heat. Distinctive quantum phenomena involve combinations of different classical states (such as both dead and alive), and these combinations tend to dissipate. The leakage of information is the essence of a process known as decoherence [see "100 Years of Quantum Mysteries," by Max Tegmark and John Archibald Wheeler; SCIENTIFIC AMERICAN, February 2001].

A QUANTUM PARADOX

Observing the Observer

The idea that quantum mechanics applies to everything in the universe, even to us humans, can lead to some strange conclusions. Consider this variant of the iconic Schrödinger cat thought experiment that Nobel laureate Eugene P. Wigner came up with in 1961 and David Deutsch of the University of Oxford elaborated on in 1986.

Suppose that a very able experimental physicist, Alice, puts her friend Bob inside a room with a cat, a radioactive atom and cat poison that gets released if the atom decays. The point of having a human there is that we can communicate with him. (Getting answers from cats is not that easy.) As far as Alice is concerned, the atom enters into a state of being both decayed and not decayed, so that the cat is both dead and alive. Bob, however, can directly observe the cat and sees it as one or the other. Alice slips a piece of paper under the door asking Bob whether the cat is in a definite state. He answers, "yes."

Note that Alice does *not* ask whether the cat is dead or alive because for her that would force the outcome or, as physicists say, "collapse" the state. She is content observing that her friend sees the cat either alive or dead and does not ask which it is.

Because Alice avoided collapsing the state, quantum theory holds that slipping the paper under the door was a reversible act. She can undo all the steps she took. If the cat was dead, it would now be alive, the poison would be in the bottle, the particle would not have decayed and Bob would have no memory of ever seeing a dead cat.

And yet one trace remains: the piece of paper. Alice can undo the observation in a way that does not also undo the writing on the paper. The paper remains as proof that Bob had observed the cat as definitely alive or dead.

That leads to a startling conclusion. Alice was able to reverse the observation because, as far as she was concerned, she avoided collapsing the state; to her, Bob was in just as indeterminate a state as the cat. But the friend inside the room thought the state did collapse. That person did see a definite outcome; the paper is proof of it. In this way, the experiment demonstrates two seemingly contradictory principles. Alice thinks that quantum mechanics applies to macroscopic objects: not just cats but also Bobs can be in quantum limbo. Bob thinks that cats are only either dead or alive.

Doing such an experiment with an entire human being would be daunting, but physicists can accomplish much the same with simpler systems. Anton Zeilinger and his colleagues at the University of Vienna take a photon and bounce it off a large mirror. If the photon is reflected, the mirror recoils, but if the photon is transmitted, the mirror stays still. The photon plays the role of the decaying atom; it can exist simultaneously in more than one state. The mirror, made up of billions of atoms, acts as the cat and as Bob. Whether it recoils or not is analogous to whether the cat lives or dies and is seen to live or die by Bob. The process can be reversed by reflecting the photon back at the mirror. On smaller scales, teams led by Rainer Blatt of the University of Innsbruck and by David J. Wineland of the National Institute of Standards and Technology in Boulder, Colo., have reversed the measurement of vibrating ions in an ion trap.

In developing this devious thought experiment, Wigner and Deutsch followed in the footsteps of Erwin Schrödinger, Albert Einstein and other theorists who argued that physicists have yet to grasp quantum mechanics in any deep way. For decades most physicists scarcely cared because the foundational issues had no effect on practical applications of the theory. But now that we can perform these experiments for real, the task of understanding quantum mechanics has become all the more urgent. *—V.V.*

Larger things tend to be more susceptible to decoherence than smaller ones, which justifies why physicists can usually get away with regarding quantum mechanics as a theory of the microworld. But in many cases, the information leakage can be slowed or stopped, and then the quantum world reveals itself to us in all its glory. The quintessential quantum effect is entanglement, a term that Schrödinger coined in the same 1935 paper that introduced his cat to the world. Entanglement binds together individual particles into an indivisible whole. A classical system is always divisible, at least in principle; whatever collective properties it has arise from components that themselves have certain properties. But an entangled system cannot be broken down in this way. Entanglement has strange consequences. Even when the entangled particles are far apart, they still behave as a single entity, leading to what Einstein famously called "spooky action at a distance."

Usually physicists talk about entanglement of pairs of elementary particles such as electrons. Such particles can be thought of, crudely, as small spinning tops that rotate either clockwise or counterclockwise, their axes pointing in any given direction: horizontally, vertically, at 45 degrees, and so on. To measure a particle's spin, you must choose a direction and then see whether the particle spins in that direction.

Suppose, for argument's sake, that electrons behaved classically. You might set up one electron to spin in the horizontal clockwise direction and the other in the horizontal counterclockwise direction; that way, their total spin is zero. Their axes remain fixed in space, and when you make a measurement, the outcome depends on whether the direction you choose aligns with the particle's axis. If you measure both of them horizontally, you see both of them spinning in opposite directions; if you measure them vertically, you detect no spin at all for either.

For quantum electrons, however, the situation is astonishingly different. You can set up the particles to have a total spin of zero even when you have not specified what their individual spins are. When you measure one of the particles, you will see it spinning clockwise or counterclockwise at random. It is as though the particle decides which way to spin for itself. Nevertheless, no matter which direction you choose to measure the electrons, providing it is the same for both, they will always spin in opposite ways, one clockwise and the other counterclockwise. How do they know to do so? That remains utterly mysterious. What is more, if you measure one particle horizontally and the other vertically, you will still detect some spin for each; it appears that the particles have no fixed axes of rotation. Therefore, the measurement outcomes match to an extent that classical physics cannot explain.

ACTING AS ONE

MOST DEMONSTRATIONS of entanglement involve at most a handful of particles. Larger batches are harder to isolate from their surroundings. The particles in them are likelier to become entangled with stray particles, obscuring their original interconnections. In accordance with the language of decoherence, too much information leaks out to the environment, causing the system to behave classically. The difficulty of preserving entanglement is a major challenge for those of us seeking to exploit these novel effects for practical use, such as quantum computers.

A neat experiment in 2003 proved that larger systems, too, can remain entangled when the leakage is reduced or somehow counteracted. Gabriel Aeppli of University College London and his colleagues took a piece of lithium fluoride salt and put it in an external magnetic field. You can think of the atoms in the salt as little spinning magnets that try to align themselves with the external field, a response known as magnetic susceptibility. Forces that the atoms exert on one another act as a kind of peer pressure to bring them into line more quickly. As the researchers varied the strength of the magnetic field, they measured how quickly the atoms became aligned. They found that the atoms responded much faster than the strength of their mutual interactions would suggest. Evidently some additional effect was helping the atoms to act in unison, and the researchers argued that entanglement was the culprit. If so, the 10^{20} atoms of the salt formed a hugely entangled state.

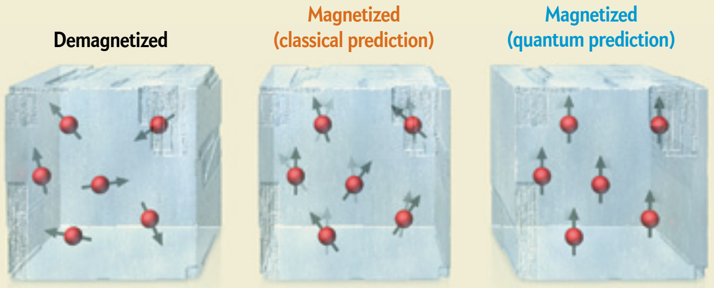
To avoid the confounding effects of the random motions asso-

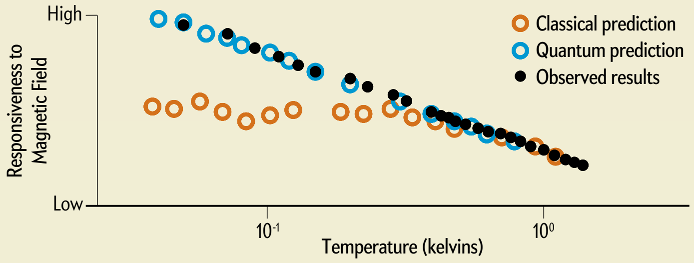
MACROSCOPIC ENTANGLEMENT

Quantum Salt

Physicists used to think that distinctive quantum phenomena would operate only at the level of individual particles; great big clusters of particles would behave classically. Recent experiments show otherwise. For example, the atoms in a salt crystal typically point every which way (*below left*) and line up when physicists apply a magnetic field. They line up faster than they would if only classical physics operated (*below center*). Evidently the quantum phenomenon of entanglement—the "spooky action" that coordinates the properties of far-flung particles—is helping bring them into line (*below right*). The role of entanglement is revealed by a measure of the crystal's magnetic properties (*graph*).

How Salt Defies Classical Expectations





SOURCE FOR GRAPH: "ENTANGLED QUANTUM STATE OF MAGNETIC DIPOLES," BY S. GHOSH ET AL., IN *NATURE*, VOL. 425; SEPTEMBER 4, 2003

Illustration by George Retseck, Graphic by Jen Christiansen

ciated with heat energy, Aeppli's team did its experiments at extremely low temperatures—a few millikelvins. Since then, however, Alexandre Martins de Souza of the Brazilian Center for Physics Research in Rio de Janeiro and his colleagues have discovered macroscopic entanglement in materials such as copper carboxylate at room temperature and higher. In these systems, the interaction among particle spins is strong enough to resist thermal chaos. In other cases, an external force wards off thermal effects [see "Easy Go, Easy Come," by George Musser; News Scan, Scientific American, November 2009]. Physicists have seen entanglement in systems of increasing size and temperature, from ions trapped by electromagnetic fields to ultracold atoms in lattices to superconducting quantum bits [*see table below*].

These systems are analogous to Schrödinger's cat. Consider an atom or ion. Its electrons can exist close to the nucleus or farther away—or both at the same time. Such an electron acts like the radioactive atom that has either decayed or not decayed in Schrödinger's thought experiment. Independently of what the electron is doing, the entire atom can be moving, say, left or right. This motion plays the role of the dead or alive cat. Using lasers to manipulate the atom, physicists can couple the two properties. If the electron is close to the nucleus, we can make the atom move to the left, whereas if the electron is farther away, the atom moves to the right. So the state of the electron is entangled with the movement of the atom, in the same way that the radioactive decay is entangled with the state of the cat. The feline that is both alive and dead is mimicked by an atom that is moving both to the left and to the right.

Other experiments scale up this basic idea, so that huge numbers of atoms become entangled and enter states that classical physics would deem impossible. And if solids can be entangled even when they are large and warm, it takes only a small leap of imagination to ask whether the same might be true of a very special kind of large, warm system: life.

SCHRÖDINGER'S BIRDS

EUROPEAN ROBINS ARE CRAFTY little birds. Every year they migrate from Scandinavia to the warm plains of equatorial Africa and return in the spring, when the weather up north becomes more tolerable. The robins navigate this round-trip of some 13,000 kilometers with natural ease.

People have long wondered whether birds and other animals might have some built-in compass. In the 1970s the husband-wife team of Wolfgang and Roswitha Wiltschko of the University of Frankfurt in Germany caught robins that had been migrating to Africa and put them in artificial magnetic fields. Oddly, the robins, they found, were oblivious to a reversal of the magnetic field direction, indicating that they could not tell north from south. The birds did, however, respond to the inclination of the earth's magnetic field—that is, the angle that the field lines make with the surface. That is all they need to navigate. Interestingly, blindfolded robins did not respond to a magnetic field at all, indicating that they somehow sense the field with their eyes.

In 2000 Thorsten Ritz, a physicist then at the University of Southern Florida who has a passion for migratory birds, and his colleagues proposed that entanglement is the key. In their scenario, which builds on the previous work of Klaus Schulten of the University of Illinois, a bird's eye has a type of molecule in which two electrons form an entangled pair with zero total spin. Such a situation simply cannot be mimicked with classical

LEADING EXPERIMENTS

Entanglement Heats Up

Quantum effects are not limited to subatomic particles. They also show up in experiments on larger and warmer systems.

WHAT	WHEN	HOW WARM	WHO
Observed interference pattern for buckyballs, showing for the first time that molecules, like elementary particles, behave like waves	1999	900–1,000 kelvins	Markus Arndt, Anton Zeilinger et al. (University of Vienna)
Deduced entanglement of trillions of atoms (or more) from the magnetic susceptibility of metal carboxylates	2009	630 K	Alexandre Martins de Souza et al. (Brazilian Center for Physics Research)
Found that quantum effects enhance photosynthetic efficiency in two species of marine algae	2010	294 K	Elisabetta Collini et al. (University of Toronto, University of New South Wales and University of Padua)
Set a new world record for observing quantum effects in giant molecules, including an octopus-shaped one with 430 atoms	2011	240–280 K	Stefan Gerlich, Sandra Eibenberger et al. (University of Vienna)
Entangled three quantum bits in a superconducting circuit. The procedure can create quantum systems of any size	2010	0.1 K	Leonardo DiCarlo, Robert J. Schoelkopf et al. (Yale University and University of Waterloo)
Coaxed a tiny springboard about 40 microns long (just visible to the unaided eye) to vibrate at two different frequencies at once	2010	25 millikelvins	Aaron O'Connell, Max Hofheinz et al. (University of California, Santa Barbara)
Entangled strings of eight calcium ions held in an ion trap. Today the researchers can manage 14	2005	0.1 mK	Hartmut Häffner, Rainer Blatt et al. (University of Innsbruck)
Entangled the vibrational motion—rather than internal properties such as spin—of beryllium and magnesium ions	2009	0.1 mK	John D. Jost, David J. Wineland et al. (National Institute of Standards and Technology)

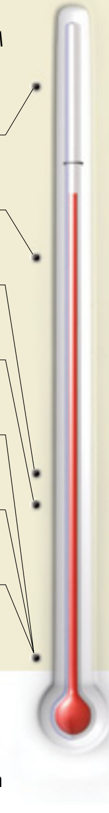


Illustration by George Retseck

physics. When this molecule absorbs visible light, the electrons get enough energy to separate and become susceptible to external influences, including the earth's magnetic field. If the magnetic field is inclined, it affects the two electrons differently, creating an imbalance that changes the chemical reaction that the molecule undergoes. Chemical pathways in the eye translate this difference into neurological impulses, ultimately creating an image of the magnetic field in the bird's brain.

> **Physicists thought the bustle of living cells would blot out quantum phenomena. Now they find that cells can nurture these phenomena—and exploit them.**

Although the evidence for Ritz's mechanism is circumstantial, Christopher T. Rogers and Kiminori Maeda of the University of Oxford have studied molecules similar to Ritz's in the laboratory (as opposed to inside living animals) and shown that these molecules are indeed sensitive to magnetic fields because of electron entanglement. According to calculations that my colleagues and I have done, quantum effects persist in a bird's eye for around 100 microseconds—which, in this context, is a long time. The record for an artificially engineered electron-spin system is about 50 microseconds. We do not yet know how a natural system could preserve quantum effects for so long, but the answer could give us ideas for how to protect quantum computers from decoherence.

Another biological process where entanglement may operate is photosynthesis, the process whereby plants convert sunlight into chemical energy. Incident light ejects electrons inside plant cells, and these electrons all need to find their way to the same place: the chemical reaction center where they can deposit their energy and set off the reactions that fuel plant cells. Classical physics fails to explain the near-perfect efficiency with which they do so.

Experiments by several groups, such as Graham R. Fleming, Mohan Sarovar and their colleagues at the University of California, Berkeley, and Gregory D. Scholes of the University of Toronto, suggest that quantum mechanics accounts for the high efficiency of the process. In a quantum world, a particle does not just have to take one path at a time; it can take all of them simultaneously. The electromagnetic fields within plant cells can cause some of these paths to cancel one another and others to reinforce mutually, thereby reducing the chance the electron will take a wasteful detour and increasing the chance it will be steered straight to the reaction center.

The entanglement would last only a fraction of a second and would involve molecules that have no more than about 100,000 atoms. Do any instances of larger and more persistent entanglement exist in nature? We do not know, but the question is exciting enough to stimulate an emerging discipline: quantum biology.

THE MEANING OF IT ALL

To Schrödinger, the prospect of cats that were both alive and dead was an absurdity; any theory that made such a prediction must surely be flawed. Generations of physicists shared this discomfort and thought that quantum mechanics would cease to apply at a still larger scale. In the 1980s Roger Penrose of Oxford suggested that gravity might cause quantum mechanics to give way to classical physics for objects more massive than 20 micrograms, and a trio of Italian physicists—GianCarlo Ghirardi and Tomaso Weber of the University of Trieste and Alberto Rimini of the University of Pavia—proposed that large numbers of particles spontaneously behave classically. But experiments now leave very little room for such processes to operate. The division between the quantum and classical worlds appears not to be fundamental. It is just a question of experimental ingenuity, and few physicists now think that classical physics will ever really make a comeback at any scale. If anything, the general belief is that if a deeper theory ever supersedes quantum physics, it will show the world to be even more counterintuitive than anything we have seen so far.

Thus, the fact that quantum mechanics applies on all scales forces us to confront the theory's deepest mysteries. We cannot simply write them off as mere details that matter only on the very smallest scales. For instance, space and time are two of the most fundamental classical concepts, but according to quantum mechanics they are secondary. The entanglements are primary. They interconnect quantum systems without reference to space and time. If there were a dividing line between the quantum and the classical worlds, we could use the space and time of the classical world to provide a framework for describing quantum processes. But without such a dividing line—and, indeed, without a truly classical world—we lose this framework. We must explain space and time as somehow emerging from fundamentally spaceless and timeless physics.

That insight, in turn, may help us reconcile quantum physics with that other great pillar of physics, Einstein's general theory of relativity, which describes the force of gravity in terms of the geometry of spacetime. General relativity assumes that objects have well-defined positions and never reside in more than one place at the same time—in direct contradiction with quantum physics. Many physicists, such as Stephen Hawking of the University of Cambridge, think that relativity theory must give way to a deeper theory in which space and time do not exist. Classical spacetime emerges out of quantum entanglements through the process of decoherence.

An even more interesting possibility is that gravity is not a force in its own right but the residual noise emerging from the quantum fuzziness of the other forces in the universe. This idea of "induced gravity" goes back to the nuclear physicist and Soviet dissident Andrei Sakharov in the 1960s. If true, it would not only demote gravity from the status of a fundamental force but also suggest that efforts to "quantize" gravity are misguided. Gravity may not even exist at the quantum level.

The implications of macroscopic objects such as us being in quantum limbo is mind-blowing enough that we physicists are still in an entangled state of confusion and wonderment.

MORE TO EXPLORE

Entangled Quantum State of Magnetic Dipoles. S. Ghosh et al. in *Nature,* Vol. 425, pages 48–51; September 4, 2003. Preprint available at **arxiv.org/abs/cond-mat/0402456**

Entanglement in Many-Body Systems. Luigi Amico, Rosario Fazio, Andreas Osterloh and Vlatko Vedral in *Reviews of Modern Physics,* Vol. 80, No. 2, pages 517–576; May 6, 2008. **arxiv.org/abs/quant-ph/0703044**

Decoding Reality: The Universe as Quantum Information. Vlatko Vedral. Oxford University Press, 2010.

SCIENTIFIC AMERICAN ONLINE

"I think I can safely say that nobody understands quantum mechanics," Richard Feynman once wrote. But have fun trying at **ScientificAmerican.com/jun2011/quantum**