MICHAEL MORGENSTERN

Everyday entanglement

Physicists take quantum weirdness out of the lab By Laura Sanders

If the Manning brothers were quantum physicists as well as NFL quarterbacks, one of them could win his game's opening coin toss every time. The night before they played, the brothers would take two coins from a special quantum box to use the next day. If Peyton's game came first, after learning the outcome of his coin toss, he would know without a doubt how his brother's coin would land. Say Peyton's came up heads; he could text "tails" to his little brother. Eli would correctly call tails in his later game and win the toss (not that it would do the Giants much good).

Such a creepy connection of the fates of far apart coins does not yet threaten the integrity of football. But in the microworld, where the players are atoms and photons, this long-distance connection — technically called quantum entanglement — is as real as instant replay. In fact, entanglement is at the very heart of reality. No mere quantum quirk of interest only to physicists, its peculiar possibilities have caught the attention of investment bankers and information entrepreneurs.

"We believe that there's a second quantum revolution going on right now," says physicist Chris Monroe of the Joint Quantum Institute at the University of Maryland in College Park.

The first revolution peaked when Austrian physicist Erwin Schrödinger introduced the term entanglement (a translation of the German *Verschränkung*) in a 1935 paper, inspired by a thought experiment proposed the same year by Albert Einstein and collaborators Boris Podolsky and Nathan Rosen. The thought experiment demonstrated that when two objects interact in a particular way, quantum physics requires them to become connected, or entangled, so that measuring a property of one instantly reveals the value of that property for the other, no matter how far away it is.

"No reasonable definition of reality" could permit two objects to be mysteriously entwined across great distances, Einstein and his collaborators complained in *Physical Review* (*SNL: 5/11/35, p. 300*). There must be more to reality, Einstein believed, than quantum theory described. But rather than undermining quantum physics, the EPR paper, as it became known, became fodder for other scientists who showed that this unreasonable connection was in fact real. If quantum rules applied in everyday life, as soon as Peyton saw his quantum coin land in Seattle, he would know the outcome of Eli's toss — even if Eli's game were across the country or on the moon.

For decades, though, few physicists worried about entanglement. It was regarded as a hypothetical concept with no real prospects for ever being tested. "Initially it was a pure theory — quasi-philosophy," says physicist Nicolas Gisin of the University of Geneva.

That's no longer the case. Now, laboratories around the world routinely create and study entanglement, pushing the limits on the types and sizes of objects that can be entangled. Some studies are attempting to clarify the mysterious boundary separating the strange realm of quantum weirdness from the macroscopic world of football. Others focus on entanglement itself, particularly how it changes over time. Much of the new work is building a base for powerful technologies that operate in the real world, from manipulating information in futuristic quantum computers to sending secret messages with unbreakable security.

Yet despite all the progress, there remains a deep mystery at the core of entanglement. "I want to be able to tell a story," Gisin says, "and I cannot tell you a story of how nature manages the trick."

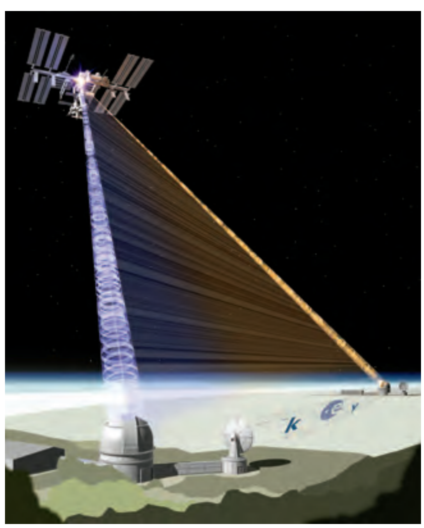
The Bell goes off

With no way to actually perform the EPR experiment, entanglement languished in philosophical obscurity for nearly 30 years. But that all changed in 1964, when Irish physicist John Bell devised an ingenious mathematical trick that allowed physicists to rule out mundane explanations for entanglement. One such physicist was Alain Aspect, now at the Institut d'Optique's campus in Palaiseau, France. When he saw Bell's paper, Aspect was immediately struck by its implications.

"This is the most important experiment I've ever heard of," he recalls thinking. Undeterred by Bell's warning that such a pursuit might brand him a crackpot, Aspect figured out a way to perform Bell's test on twin photons emitted by calcium atoms. Aspect and his colleagues measured the light waves' orientation — a property called polarization (the feature of light exploited by sunglasses for reducing glare).

Aspect and his collaborators reported in 1982 that the two detectors, when aligned in the same way, gave results closely matching the scenario Bell had outlined if the bizarre quantum link were true. It was as if the photons were in cahoots, with each instantly deciding what to do as soon as its partner made a choice (see Page 24). Entanglement had been demonstrated (*SN: 1/11/86, p. 28*).

In the years since Aspect's experiment, physicists have been extending entanglement's reach in a number of ways. They've confirmed its existence over and over, and shown that it may one day be put to work. Researchers are creating entanglement that can be sent across the globe, entanglement that can link new kinds of objects and even entanglement that can connect gaggles of objects instead of just two. And physicists are upsizing objects that exhibit what Einstein dismissed as "spooky action at a distance."



A pair of entangled photons beamed from the International Space Station could allow for secret communication between faraway locales on Earth.

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■ In 2008, for instance, Gisin and colleagues measured entangled photons 18 kilometers apart at exactly the same time and calculated that any secret signal between the two would have to travel 10,000 times faster than the speed of light. The long-distance record is held by a team of physicists including Anton Zeilinger of the University of Vienna, who measured entangled photons 144 kilometers apart on two Canary Islands. A plan to break that record involves sending an entangled photon from Earth to the International Space Station. Quantum information beamed by satellites orbiting the planet might ultimately lead to new, powerful ways to communicate across the globe.

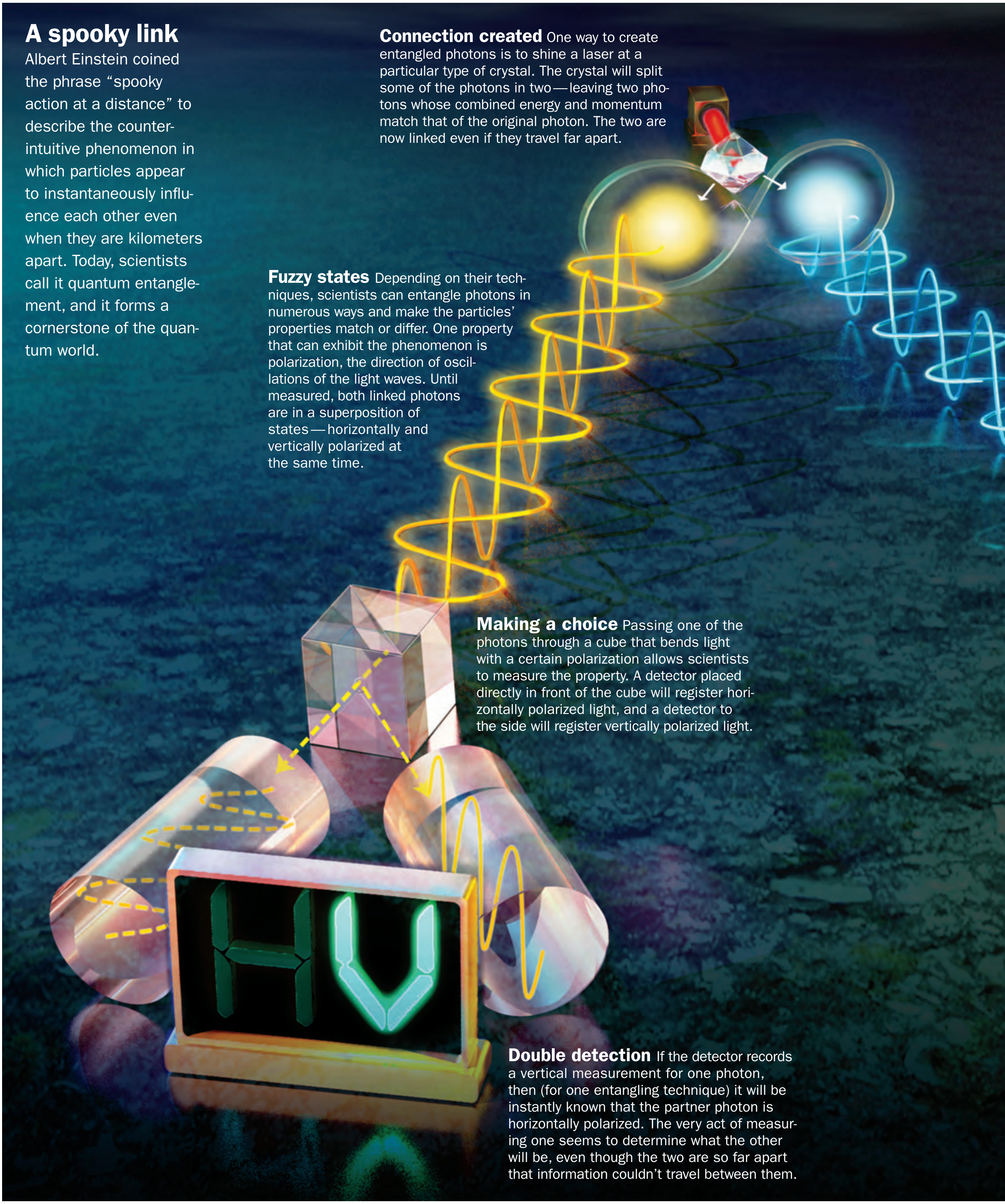
■ So far, photons are the only elementary particles that have been entangled, but Lucas Lamata of the Max Planck Institute of Quantum Optics in Garching, Germany, and his colleagues have devised a way to entangle electrons, which would be more stable. Other types of objects — including dissimilar ones — have been entangled as well, and these systems could offer more mix-and-match options for the design of new devices, such as quantum computers. "We're very interested in entangling new systems," Lamata says.

■ It's not all just about extending the kinds of things to be entangled — numbers matter too. "If you go to more than two parties, the number of ways the systems can be entangled becomes much more rich," Gisin says. Today, the formulas that describe two entangled particles are easy to understand. "Two particles is too simple," he says. "It took a long time for me to say that."

Researchers have succeeded in entangling three different-colored beams of light, entangling six photons and entangling eight calcium ions, revealing much more complex kinds of entanglement. "These experiments are confirming entanglement, but confirming it in more subtle ways than people had thought about," says

A spooky link

Albert Einstein coined the phrase “spooky action at a distance” to describe the counterintuitive phenomenon in which particles appear to instantaneously influence each other even when they are kilometers apart. Today, scientists call it quantum entanglement, and it forms a cornerstone of the quantum world.



Connection created One way to create entangled photons is to shine a laser at a particular type of crystal. The crystal will split some of the photons in two — leaving two photons whose combined energy and momentum match that of the original photon. The two are now linked even if they travel far apart.

Fuzzy states Depending on their techniques, scientists can entangle photons in numerous ways and make the particles’ properties match or differ. One property that can exhibit the phenomenon is polarization, the direction of oscillations of the light waves. Until measured, both linked photons are in a superposition of states — horizontally and vertically polarized at the same time.

Making a choice Passing one of the photons through a cube that bends light with a certain polarization allows scientists to measure the property. A detector placed directly in front of the cube will register horizontally polarized light, and a detector to the side will register vertically polarized light.

Double detection If the detector records a vertical measurement for one photon, then (for one entangling technique) it will be instantly known that the partner photon is horizontally polarized. The very act of measuring one seems to determine what the other will be, even though the two are so far apart that information couldn’t travel between them.

NICOLLE RAGER FULLER

Distant influence When passed through a similar cube, the partner photon does indeed register as having a horizontal polarization. The findings may make it look as if one measurement caused the other to come out a certain way, but that is not the case. Suppose the second photon was measured in a different reference frame, say speeding along on a rocket ship, it could look as if the second measurement came first. Scientists still can't fully explain this quantum link.

75 years of entanglement

Though it has been confirmed numerous times since 1935, entanglement is as spooky as ever.

1935: Physicists Albert Einstein, Boris Podolsky and Nathan Rosen publish a paper in *Physical Review* asking "Can quantum-mechanical description of physical reality be considered complete?" Their answer: no.

The same year, in the journal *Naturwissenschaften*, Erwin Schrödinger coins the term *Verschränkung*, meaning "entanglement," and develops his famous thought experiment of a cat that exists simultaneously in a state of being alive and dead.

1952: Building on earlier work by French physicist Louis de Broglie, theoretical physicist David Bohm suggests a deterministic interpretation of quantum theory that incorporates "hidden variables." He claims that the initial state of a system, like a particle's position, can determine its future evolution.

1964: Irish physicist John Bell proposes his inequality, which lays out math that would allow researchers to experimentally rule out any hidden variables operating locally to determine quantum entanglement outcomes. If the inequality holds, then entanglement could be explained through purely local effects. If violated, some amount of nonlocality must be occurring, as standard quantum mechanics would predict.

1972: Berkeley researchers Stuart Freedman and John Clauser experimentally test Bell's theorem by measuring the polarizations of a pair of photons. Though the team found that the inequality is indeed violated, some loopholes exist in the experiment.

1982: French physicist Alain Aspect performs an even stronger test of entanglement, confirming that nonlocal effects do exist.

1984: Charles Bennett and Gilles Brassard propose a theoretical system for quantum cryptography, which would use photons in a superposition of states to create a secure key.

1990: Bennett and colleagues report the first experimental quantum key distribution.

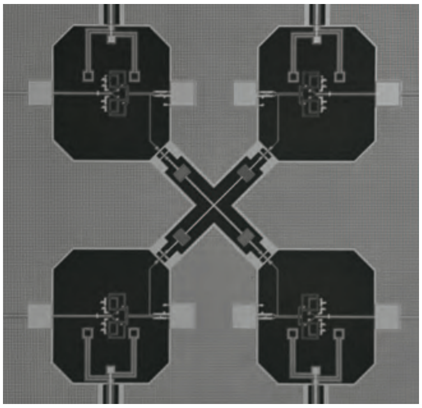
1993: Bennett and collaborators propose that entanglement can, in principle, be used to teleport a particle's quantum information from one place to another.

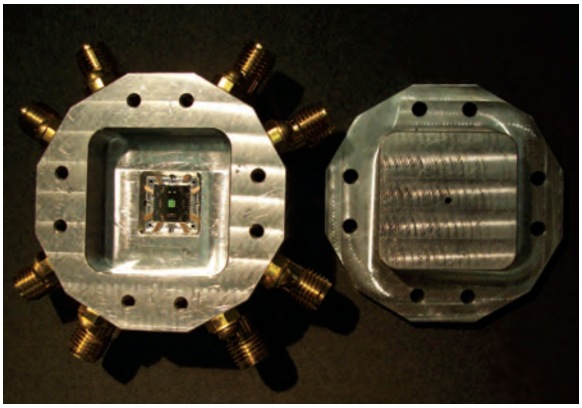
1997: Austrian quantum physicist Anton Zeilinger and colleagues report in *Nature* the first experimental verification of quantum teleportation.

2007: Zeilinger and colleagues set a distance record by sending entangled photons across 144 kilometers, between two of the Canary Islands. Chao-Yang Lu and colleagues also entangle six photons, a record number.

2010: Researchers observe new kinds of entanglement when linking multiple objects quantumly, quantum information is teleported a record 16 kilometers and teams find better ways to create and control entangled objects. —*Alexandra Witze*

Researchers recently entangled three superconducting chips big enough to be seen with the naked eye. Crisscrossed connections link the three chips (immediate right), along with a fourth chip that was not used. An aluminum box 4 centimeters wide (far right) enclosed the experiment.





John Martinis of the University of California, Santa Barbara. In a paper appearing September 30 in *Nature,* Martinis and colleagues show how entanglement between three superconducting chips might give quantum computers more oomph.

■ The fact that quantum mechanics is so good at describing diminutive particles implies that it should also be good at describing bigger "catlike" states, says Tony Leggett of the University of Illinois at Urbana-Champaign. (In a nod to Schrödinger's creepy cat that was simultaneously alive and dead — see Page 17 — physicists use "catlike" to describe large quantum objects.) "Most of us, at least in the year 2010, are prepared to live with the weird properties of quantum mechanics at the level of single atoms or electrons," Leggett says. "Most people are much less happy to live with it at the level of Schrödinger's cat."

Like the heft of NFL players, the size of entangled objects is steadily creeping upward. The superconductors entangled by Martinis' team are large enough to see with the naked eye. And a blob of thousands of photons and a centimeter-long crystal have, in separate experiments, been entangled with a single photon.

No one knows how to describe the separation between the bizarre quantum world where entanglement exists and the everyday world where nature appears to operate via easy-to-spot causes and effects. Creating entanglement on a larger scale may help clarify this mysterious division.

"Most of the experiments so far have been done with photons, which have no mass," Gisin says. "Some experiments have also been done with atoms or ions, and already there are some experiments going to ensembles of atoms. But a few atoms are still extremely light."

Entanglement evolves

Creating entanglement in multiple shapes and forms isn't that useful if the connection can't be preserved. Entanglement is notoriously finicky, fading away with even slight external disturbance. The motion of a quantum coin jangling in Peyton's pocket, for instance, could ruin the quantum connection long before the toss. A new area of research called entanglement dynamics aims to figure out how entanglement appears, disappears and morphs over time.

"We really want to go beyond static entanglement, which means you only care about a state without time evolution," says theoretical physicist Ting Yu of the Stevens Institute of Technology in Hoboken, N.J. "We know in nature, we really don't have that kind of thing."

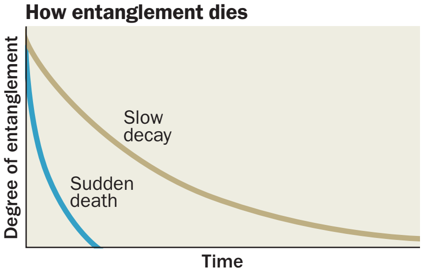
Yu and collaborator Joseph Eberly of the University of Rochester in New York reported that entanglement can disappear abruptly, a phenomenon called "entanglement sudden death," in a 2009 review paper in *Science*. This instant demise has been observed in other places since, including in experiments with the three entangled light beams conducted by Paulo Nussenzveig of the University of São Paulo and colleagues. The team is now trying to understand when and why this collapse happens, and whether particular starting states make it more probable.

Physicists aren't in agreement on what sudden death means. Some think it's nothing surprising, similar to well-studied phase transitions, such as the abrupt disappearance of liquid when water freezes into ice. But Yu thinks the phenomenon represents a previously unknown property of entanglement, one that is closely related to its environment.

A carefully tuned environment can also generate entanglement. Given just the right surroundings, energy leaving clouds of cesium atoms can actually cause atoms to become linked, a study posted June 22 on arXiv.org showed (*SN Online: 6/29/10*). This feat was accomplished at room temperature and lasted for the (relatively) long time of about 0.015 seconds.

Entanglement begone Scientists studying how entanglement changes over time have found that the effect can fade away or disappear suddenly, as shown below.

How entanglement dies



TOP, BOTH: MATTHEW NEELEY; T. YU AND J. EBERLY/*SCIENCE* 2009

Information encoded in the entanglement can leak out into a noisy environment and then leak back into the objects to reentangle them, Yu says, a process called "revival." In a paper posted online September 16 at arXiv.org, he and his colleagues mathematically describe how this ghostly effect works in different environments. And a group of physicists led by Chuan-Feng Li of the University of Science and Technology of China in Hefei recently witnessed such a revival, watching entanglement between two photons reemerge after it was completely gone. The findings appeared March 12 in *Physical Review Letters*.

Killer apps

Physicists have lots of ideas for what they would do with the power to create, demolish and resurrect entanglement on demand. Although some of the schemes are esoteric, entanglement has a few "killer apps," says Monroe. Chief among these are harnessing entanglement to shuttle information around in powerful quantum computers, across power lines and through the air, and distributing impenetrable coding keys to keep information secure.

Entanglement is at the heart of what physicists call teleportation — in which two entangled objects serve as a link that moves quantum information from one physical location to another. The setup is simple: One object (say a photon) holds the information to be teleported. When that photon interacts with one of a pair of entangled photons, new information is created, allowing the original photon to be reconstructed at a distant location with the help of the other member of the entangled photon pair. (The information needed to reconstruct the original photon must be sent over a normal communication network, though.) Teleportation was proposed in 1993 and was first experimentally demonstrated in 1997.

Such relocation could play a key role in quantum computers, which get their allure from the power of quantum information processing. One unit of quantum information, or qubit, can represent multiple possibilities simultaneously, a vast improvement over typical bits that are restricted to either a 0 or 1. This information abundance could prove to be extremely useful. If a football historian were looking for the most beneficial coin flip in the history of the NFL, a computer made of qubits could search all of the outcomes simultaneously instead of sifting through each toss one by one.

Nearby qubits, such as those in a working quantum computer, often become entangled, says physicist David Hanneke of the National Institute of Standards and Technology's Boulder, Colo., campus. This fortuitous entanglement is a naturally occurring resource that can be used to shuffle information from one location to another in a quantum processor. "You can use entanglement to move the information without physically moving the qubit that stores the information," Hanneke says.

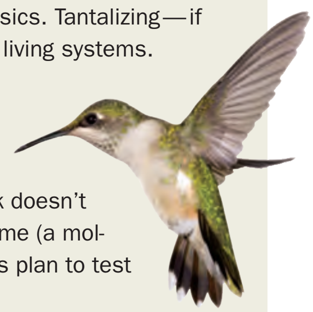
Martinis says his group has come up with a new (unpublished) version of a quantum computer with entangled superconductors as the qubits. Though the research is still under way, he thinks the team has hit upon a "good hardware architecture" that seems to work well.

Teleportation can be used to move information much farther than within the confines of a computer processor. Chinese researchers report in the June *Nature Photonics* a record-setting teleportation distance. For the experiment, the team went wireless, sending entangled photons through the air, whizzing over 16 kilometers of roads, factories and even Guanting Lake. Using the entangled photons, the researchers teleported a piece of information. Performing the feat at such great distances could one day enable satellites to communicate with ground stations quantumly.

Other researchers are figuring out ways to send entangled photons through existing wires. Thomas Jennewein of the University of Waterloo in Canada and his colleagues sent entangled photons

Colliding with biology

Quantum effects may not be limited to the realm of physics. Tantalizing — if unconfirmed — hints of entanglement have appeared in living systems.



MIKE TRUCHON/SHUTTERSTOCK

Avian navigation

Some studies suggest that migrating birds may exploit quantum effects in their visual systems to boost sensitivity to Earth's magnetic field. Though theoretical work doesn't show a benefit to entangling the electrons of cryptochrome (a molecule thought to be important in navigation), researchers plan to test the idea in other molecules (*SN Online: 4/30/10*).

DNA's double helix

Entanglement, another study suggests, may help hold the genetic building blocks of life together. In DNA, two complementary nucleotides meet up to form a base pair, creating the core of the double helix structure. After constructing a simplified model of the pairing, Elisabeth Rieper of the National University of Singapore and her colleagues conclude that entangling the electron clouds of two nucleotides would give DNA more stability.

Photosynthesis

During photosynthesis, light hits a pigment molecule and boosts one of the molecule's electrons into an excited state, kicking off a series of electron transfers. Some scientists have turned to quantum physics to explain the unexpected efficiency of this process (*SN: 5/9/09, p. 26*). A study earlier this year also found evidence of entanglement at work in the light-harvesting protein of a type of bacteria. — *Laura Sanders*

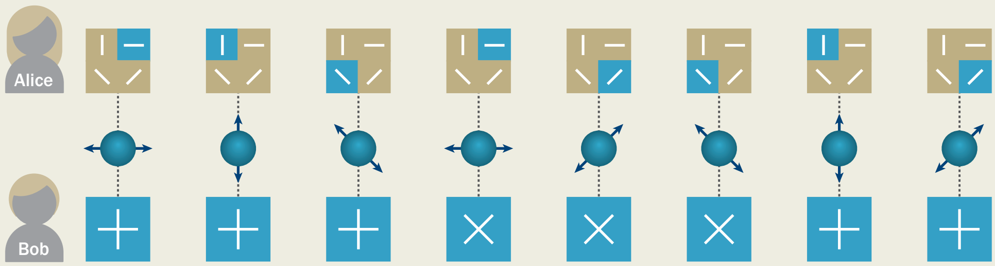
Quantum weirdness in action

Physicists can't explain what lies behind weird quantum effects, such as the ability of particles to exist in two states at once and the mysterious connection between a pair of far apart particles. But that doesn't stop researchers from taking advantage of the bizarre quantum properties.

Quantum cryptography

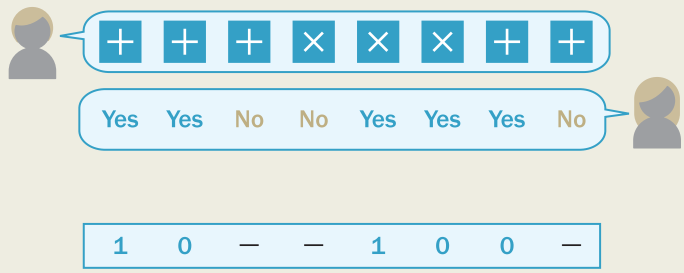
Quantum weirdness allows for the creation of eavesdropper-proof coded messages. In the most widely used setup, two partners (referred to as Alice and Bob) can create a secret coding key that they can later use to send secret messages. Though the concept works with just a stream of photons (shown below), quantumly linked photons, or entangled photons, can lend extra security.

Alice sends Bob a stream of photons that she has randomly put through one of four filters so the photons take on a particular orientation.



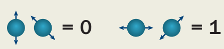
Bob chooses one of two filters to look at the photons, and he writes down the states he measures.

Alice then tells Bob which filters were "correct," meaning they lined up with the filters she used.



Each state corresponds to a bit value, either 0 or 1, allowing Alice and Bob to create their key.

Pre-established bit value:

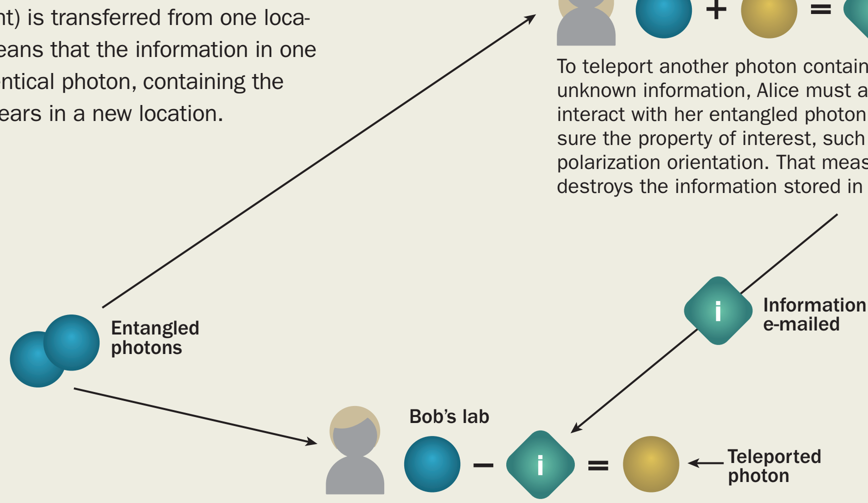


Quantum teleportation

In quantum teleportation, the information stored in a quantum particle (typically a photon of light) is transferred from one location to another. In effect, that means that the information in one photon is destroyed while an identical photon, containing the same quantum information, appears in a new location.

To teleport another photon containing unknown information, Alice must allow it to interact with her entangled photon, then measure the property of interest, such as spin or polarization orientation. That measurement destroys the information stored in the photon.

To accomplish this task, a sender and receiver must each obtain one photon of an entangled pair. Such photons have the peculiar property that measuring one reveals the state of the other. If Alice, the sender, sneaks a peek at her photon and finds its spin axis points up, for example, Bob will know that his has a spin pointing down without even looking at it.



But when Alice sends the result of that measurement to Bob via ordinary communications channels, he can use that result to transform his entangled photon into a replica of the photon that Alice destroyed.

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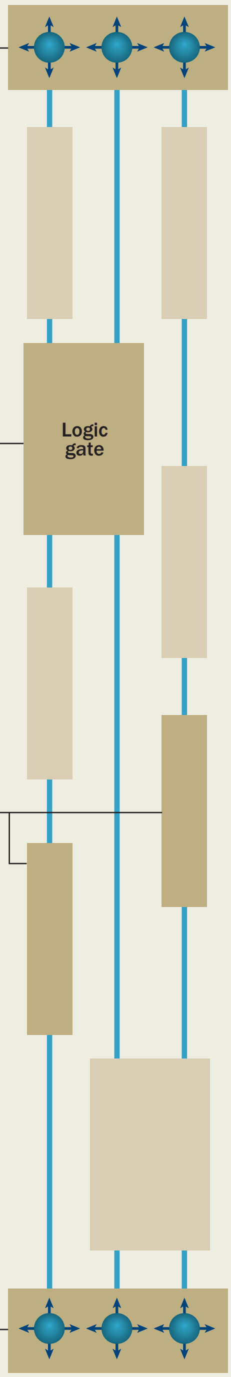
Quantum computing

Like traditional computers, a quantum computer is made up of a network of logic gates (brown) that operate on information. Though current versions can perform only rudimentary operations, scientists hope future devices will be powerful alternatives for solving some types of problems.



While the pieces of information, or bits, inputted into an ordinary computer can exist in only two states—0 or 1—the qubits of a quantum computer can exist in both states simultaneously. Photons carrying the information (blue) are in a "superposition" of states.

Because of a qubit's ability to occupy multiple states, it is possible to perform an operation on two qubits that evaluates multiple scenarios simultaneously, allowing for improved processing power.

With the help of entanglement, two qubits at distant places in a quantum computer can be linked and operated on together.

Reading out the information in a qubit returns it to a definite state, a process known as "decoherence," making the extra analyses inaccessible to researchers. But scientists have found ways to avoid this limitation for certain types of problems.

through standard telecom lines designed to carry a particular wavelength of light. One of the entangled photons traveled six kilometers between two labs in Waterloo, using lines that normally carry information such as cable television programming.

The researchers thought that this entanglement would be so fragile that the photons would be lost to the noisy telecom environment in the wires. But the entangled photons survived the trip, the team reported online July 22 in *Applied Physics Letters*. "It's very easy to put the quantum signal on top of the telecom signal, and pick it off again," Jennewein says.

To be truly useful, quantum information must also be stored. Photons fly through the air at quite a clip, so holding the information they carry is a challenge. Gisin's group at the University of Geneva has developed a device capable of storing the information carried by an entangled photon. The method, reported online September 6 at arXiv.org, hinges on a crystal that can catch one of a pair of entangled photons and hold its quantum information, while the other photon "idles" by traveling through a 50-meter-long fiber. The crystal can store the information for up to 200 nanoseconds before it emits another photon carrying the exact same information.

Another way to store quantum information was detailed in a paper published online September 26 in *Nature Physics*. Researchers from Georgia Tech in Atlanta managed to hold information from an entangled photon in a gas of cold rubidium atoms.

Manageable entanglement has caught the interest of security firms as a new way to encrypt data. For several years now, researchers have been using quantum properties to generate unbreakable keys that can disguise and then decode messages. The original technique relied on sending a stream of single photons between two parties. But some people see entangled photons as a better way.

In the entanglement scheme, one photon flies off to a destination and its partner flies somewhere else. Measurements made on the distant photons can be used to generate a key, known only to the measurers. Unlike the single photon plan, where the sender knows the state of a particle before sending it, the entanglement-based code is secret to everyone initially. "The beauty is, due to entanglement, this random key reaching the two receivers is not preexisting," says Jennewein, reducing the chances that someone can eavesdrop on the signal.

With all the grand promise that entanglement has for changing the way information is handled, the biggest question around it — why it happens — remains unanswered. It's easy to explain why an egg changes as it fries and why a car runs, Gisin says. Even though scientists can measure it, at its heart, the disconcerting quantum effect remains a mystery. "There is simply no story in spacetime that can tell us how this happens," he says.

But not having the complete story isn't stopping anyone from using entanglement. "It's in real use, every day," Gisin says. The quantum process is proving its worth outside of thought experiments that require quarterbacks to have quantum coins and advanced physics degrees.

A consortium of research institutes and technology companies has set up a quantum network in Tokyo and, on October 18, demonstrated a leak-proof security system. Entangled photons were distributed across a one-kilometer portion of the network and generated a key used to encrypt audio and video data.

Though such schemes are in their infancy, "entanglement has a more important role to play in the future," says Momtchil Peev of the Austrian Institute of Technology in Vienna, who worked on the project.

Since entanglement was first described, it has morphed from a philosophical debate to an experimental oddity to a potentially powerful way to communicate, showing itself to be even weirder than Einstein didn't want it to be. ■

Explore more

- For more on the Tokyo demonstration: www.uqcc2010.org