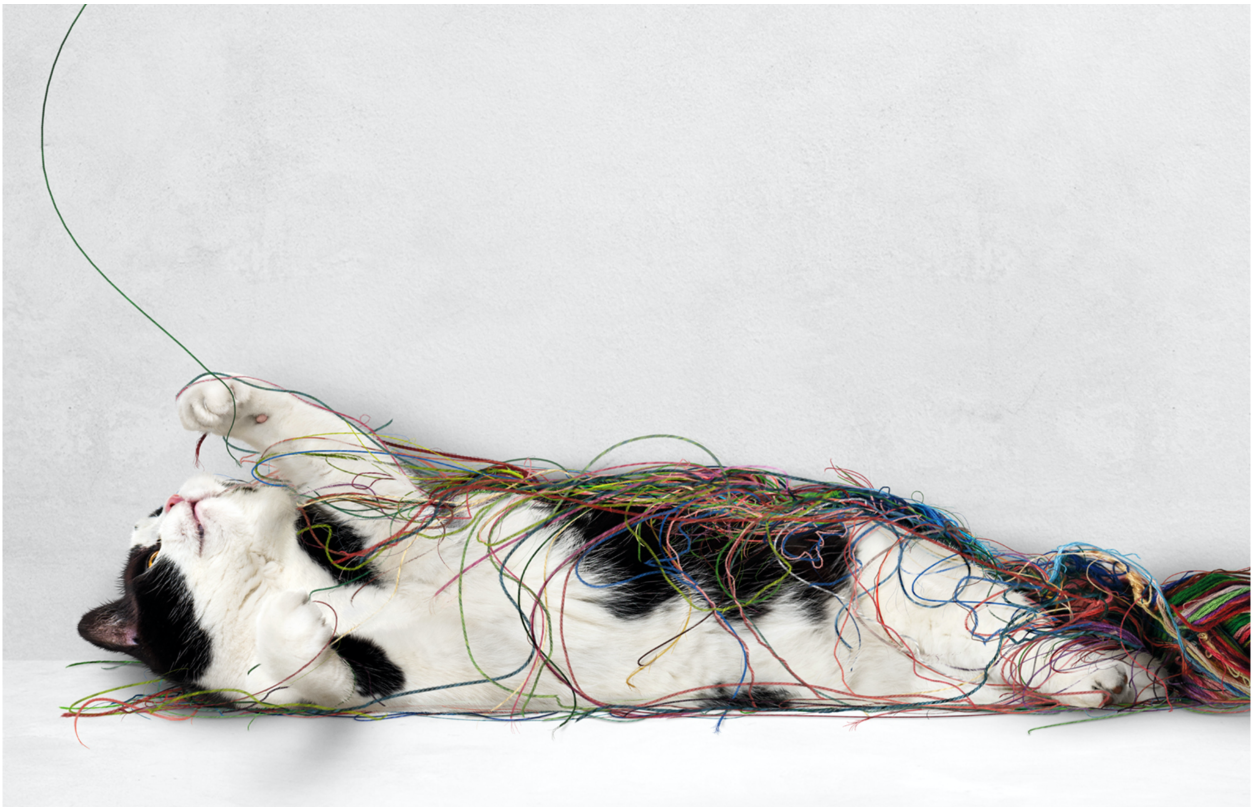
Untangling Quantum Entanglement



In Erwin Schrödinger's famous thought experiment, a cat is trapped in a box with a bit of poison the release of which is controlled by a quantum process. The cat therefore exists in a quantum state of being both dead and alive until somebody opens the box and finds the cat either dead or alive.

The perplexing phenomenon of quantum entanglement is central to quantum computing, quantum networking, and the fabric of space and time.

By Whitney Clavin

The famous "Jim twins," separated soon after birth in the 1940s, seemed to live parallel lives even though they grew up miles apart in completely different families. When they were reunited at the age of 39, they discovered many similarities between their life stories, including the names of their sons, wives, and childhood pets, as well as their preferences for Chevrolet cars, carpentry, and more.

A similar kind of parallelism happens at a quantum level, too. The electrons, photons, and other particles that make up our universe can become inextricably linked, such that the state observed in one particle will be identical for the other. That connection, known as entanglement, remains strong even across vast distances.

"When particles are entangled, it's as if they are born that way, like twins," says Xie Chen, associate professor of theoretical physics at Caltech. "Even though they might be separated right after birth, [they'll] still look the same. And they grow up having a lot of personality traits that are similar to each other."

The phenomenon of entanglement was first proposed by Albert Einstein and colleagues in the 1930s. At that time, many questioned the validity of entanglement, including Einstein himself. Over the years and in various experiments, however, researchers have generated entangled particles that have supported the theory. In these experiments, researchers first entangle two particles and then send them to different locations miles apart. The researchers then measure the state of one particle: for instance, the polarization (or direction of vibration) of a photon. If that entangled photon displays a horizontal polarization, then so too will its faithful partner.

John Preskill wrote a song about entanglement, and performed it with singer Gia Mora at One Entangled Evening, a 2016 IQIM event. Watch the video.

"It may be tempting to think that the particles are somehow communicating with each other across these great distances, but that is not the case," says Thomas Vidick, a professor of computing and mathematical sciences at Caltech. "There can be correlation without communication." Instead, he explains, entangled particles are so closely connected that there is no need for communication; they "can be thought of as one object."

As baffling as the concept of two entangled particles may be, the situation becomes even more complex when more particles are involved. In natural settings such as the human body, for example, not two but hundreds of molecules or even more become entangled, as they also do in various metals and magnets, making up an interwoven community. In these many-body entangled systems, the whole is greater than the sum of its parts.

"The particles act together like a single object whose identity lies not with the individual components but in a higher plane. It becomes something larger than itself," says Spyridon (Spiros) Michalakis, outreach manager of Caltech's Institute for Quantum Information and Matter (IQIM) and a staff researcher. "Entanglement is like a thread that goes through every single one of the individual particles, telling them how to be connected to one another."

At Caltech, researchers are focusing their studies on many-body entangled systems, which they believe are critical to the development of future technologies and perhaps to cracking fundamental physics mysteries. Scientists around the world have made significant progress applying the principles of many-body entanglement to fields such as quantum computing, quantum cryptography, and quantum networks (collectively known as quantum information); condensed-matter physics; chemistry; and fundamental physics. Although the most practical applications, such as quantum computers, may still be decades off, according to John Preskill, the Richard P. Feynman Professor of Theoretical Physics at Caltech and the Allen V.C. Davis and Lenabelle Davis Leadership Chair of the Institute of Quantum Science and Technology (IQST), “entanglement is a very important part of Caltech’s future.”

Entanglement Passes Tests with Flying Colors

In 1935, Albert Einstein, Boris Podolsky, and Nathan Rosen published a paper on the theoretical concept of quantum entanglement, which Einstein called “spooky action at a distance.” The physicists described the idea, then argued that it posed a problem for quantum mechanics, rendering the theory incomplete. Einstein did not believe two particles could remain connected to each other over great distances; doing so, he said, would require them to communicate faster than the speed of light, something he had previously shown to be impossible.

Today, experimental work leaves no doubt that entanglement is real. Physicists have demonstrated its peculiar effects across hundreds of kilometers; in fact, in 2017, a Chinese satellite named Micius sent entangled photons to three different ground stations, each separated by more than 1,200 kilometers, and broke the distance record for entangled particles.

Entanglement goes hand in hand with another quantum phenomenon known as superposition, in which particles exist in two different states simultaneously. Photons, for example, can display simultaneously both horizontal and vertical states of polarization.

Go Wider

Quantum Code-Cracking: An Interview with Thomas Vidick

Quantum Entanglement and Quantum Computing

Intrinsically Quantum

Glitz & Qubits

Go Deeper

Quantum Computing in the NISQ Era and Beyond

Or, to simplify, consider two “entangled” quarters, each hidden under a cup. If two people, Bob and Alice, were each to take one of those quarters to a different room, the quarters would remain both heads and tails until one person lifted the cup and observed his or her quarter; at that point, it would randomly become either heads or tails. If Alice were to lift her cup first and her quarter was tails, then when Bob observed his quarter, it would also be tails. If you repeated the experiment and the coins are covered once more, they would go back to being in a state of superposition. Alice would lift her cup again and might find her quarter as heads this time. Bob would then also find his quarter as heads. Whether the first quarter is found to be heads or tails is entirely random.

Similarly, when a researcher entangles two photons and then sends each one in different directions under carefully controlled conditions, they will continue to be in a state of superposition, both horizontally and vertically polarized. Only when one of the photons is measured do both randomly adopt just one of the two possible polarization states.

"Quantum correlations are deeply different than ordinary correlations," says Preskill. "And randomness is the key. This spooky intrinsic randomness is actually what bothered Einstein. But it is essential to how the quantum world works."

"Scientists often use the word correlation to explain what is happening between these particles," adds Oskar Painter, the John G Braun Professor of Applied Physics and Physics at Caltech. "But, actually, entanglement is the perfect word."

Entanglement to the Nth Degree

Untangling the relationship between two entangled particles may be difficult, but the real challenge is to understand how hundreds of particles, if not more, can be similarly interconnected.

According to Manuel Endres, an assistant professor of physics at Caltech, one of the first steps toward understanding many-body entanglement is to create and control it in the lab. To do this, Endres and his team use a brute force approach: they design and build laboratory experiments with the goal of creating a system of 100 entangled atoms.

"This is fundamentally extremely difficult to do," says Endres. In fact, he notes, it would be difficult even at a much smaller scale. "If I create a system where I generate, for instance, 20 entangled particles, and I send 10 one way and 10 another way, then I have to measure whether each one of those first 10 particles is entangled with each of the other set of 10. There are many different ways of looking at the correlations."

While the task of describing those correlations is difficult, describing a system of 100 entangled atoms with classical computer bits would be unimaginably hard. For instance, a complete classical description of all the quantum correlations among as many as 300 entangled particles would require more bits than the number of atoms in the visible universe. "But that's the whole point and the reason we are doing this," Endres says. "Things get so entangled that you need a huge amount of space to describe the information. It's a complicated beast, but it's useful."

"Generally, the number of parameters you need to describe the system is going to scale up exponentially," says Vidick, who is working on mathematical and computational tools to describe entanglement. "It blows up very quickly, which, in general, is why it's hard to make predictions or simulations, because you can't even represent these systems in your laptop's memory."

To solve that problem, Vidick and his group are working on coming up with computational representations of entangled materials that are simpler and more succinct than models that currently exist.

"Quantum mechanics and the ideas behind quantum computing are forcing us to think outside the box," he says.

A Fragile Ecosystem

Another factor in creating and controlling quantum systems has to do with their delicate nature. Like *Mimosa pudica* ,a member of the pea family also known as the "sensitive plant," which droops when its leaves are touched, entangled states can easily disappear, or collapse, when the environment changes even slightly. For example, the act of observing a quantum state destroys it. "You don't want to even look at your experiment, or breathe on it," jokes Painter. Adds Preskill, "Don't turn on the light, and don't even dare walk into the room."

The problem is that entangled particles become entangled with the environment around them quickly, in a matter of microseconds or faster. This then destroys the original entangled state a researcher might attempt to study or use. Even one stray photon flying through an experiment can render the whole thing useless.

"You need to be able to create a system that is entangled only with itself, not with your apparatus," says Endres. "We want the particles to talk to one another in a controlled fashion. But we don't want them to talk to anything in the outside world."

In the field of quantum computing, this fragility is problematic because it can lead to computational errors. Quantum computers hold the promise of solving problems that classical computers cannot, including those in cryptography, chemistry, financial modeling, and more. Where classical computers use binary bits (either a "1" or a "0") to carry information, quantum computers use "qubits," which exist in states of "1" and "0" at the same time. As Preskill explains, the qubits in this mixed state, or superposition, would be both dead and alive, a reference to the famous thought experiment proposed by Erwin Schrödinger in 1935, in which a cat in a box is both dead and alive until the box is opened, and the cat is observed to be one or the other. What's more, those qubits are all entangled. If the qubits somehow become disentangled from one another, the quantum computer would be unable to execute its computations.

To address these issues, Preskill and Alexei Kitaev (Caltech's Ronald and Maxine Linde Professor of Theoretical Physics and Mathematics and recipient of a 2012 Breakthrough Prize in Fundamental Physics), along with other theorists at Caltech, have devised a concept to hide the quantum information within a global entangled state, such that none of the individual bits have the answer. This approach is akin to distributing a code among hundreds of people living in different cities. No one person would have the whole code, so the code would be much less vulnerable to discovery.

“The key to correcting errors in entangled systems is, in fact, entanglement,” says Preskill. “If you want to protect information from damage due to the extreme instability of superpositions, you have to hide the information in a form that’s very hard to get at,” he says. “And the way you do that is by encoding it in a highly entangled state.”

Spreading the Entanglement

At Caltech, this work on the development of quantum-computing systems is conducted alongside with research into quantum networks in which each quantum computer acts as a separate node, or connection point, for the whole system. Painter refers to this as “breaking a quantum computer into little chunks” and then connecting them together to create a distributed network. In this approach, the chunks would behave as if they were not separated. “The network would be an example of many-body entanglement, in which the bodies are the different nodes in the network,” says Painter.

Quantum networks would enhance the power of quantum computers, notes Preskill.

“We’d like to build bigger and bigger quantum computers to solve harder and harder problems. And it’s hard to build one piece of hardware that can handle a million qubits,” he says. “It’s easier to make modular components with 100 qubits each or something like that. But then, if you want to solve harder problems, you’ve got to get these different little quantum computers to communicate with one another. And that would be done through a quantum network.”

Quantum networks could also be used for cryptography purposes, to make it safer to send sensitive information; they would also be a means by which to distribute and share quantum information in the same way that the World Wide Web works for conventional computers. Another future use might be in astronomy. Today’s telescopes are limited. They cannot yet see any detail on, for instance, the surface of distant exoplanets, where astronomers might want to look for signs of life or civilization. If scientists could combine telescopes into a quantum network, it “would allow us to use the whole Earth as one big telescope with a much-improved resolution,” says Preskill.

“Up until about 20 years ago, the best way to explore entanglement was to look at what nature gave us and try to study the exotic states that emerged,” notes Painter. “Now our goal is to try to synthesize these systems and go beyond what nature has given us.”

At the Root of Everything

While entanglement is the key to advances in quantum-information sciences, it is also a concept of interest to theoretical physicists, some of whom believe that space and time itself are the result of an underlying network of quantum connections.

“It is quite incredible that any two points in space-time, no matter how far apart, are actually entangled. Points in space-time that we consider closer to each other are just more entangled than those further apart,” says Michalkis.

The link between entanglement and space-time may even help solve one of the biggest challenges in physics: establishing a unifying theory to connect the macroscopic laws of general relativity (which describe gravity) with the microscopic laws of quantum physics (which describe how subatomic particles behave).

The quantum error-correcting schemes that Preskill and others study may play a role in this quest. With quantum computers, error correction ensures that the computers are sufficiently robust and stable. Something similar may occur with space-time. “The robustness of space may come from a geometry where you can perturb the system, but it isn’t affected much by the noise, which is the same thing that happens in stable quantum-computing schemes,” says Preskill.

“Essentially, entanglement holds space together. It’s the glue that makes the different pieces of space hook up with one another,” he adds.

At Caltech, the concept of entanglement connects various labs and buildings across campus. Theorists and experimentalists in computer science, quantum-information science, condensed-matter physics, and other fields regularly work across disciplines and weave together their ideas.

“We bring our ideas from condensed-matter physics to quantum-information folks, and we say, ‘Hey, I have a material you can use for quantum computation,’” says Chen. “Sometimes we borrow ideas from them. Many of us from different fields have realized that we have to deal with entanglement head-on.”

Preskill echoes this sentiment and is convinced entanglement is an essential part of Caltech’s future: “We are making investments and betting on entanglement as being one of the most important themes of 21st-century science.”