# The Quantum Internet Is Emerging, One Experiment at a Time

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Today's internet is a playground for hackers. From insecure communication links to inadequately guarded data in the cloud, vulnerabilities are everywhere. But if quantum physicists have their way, such weaknesses will soon go the way of the dodo.

They want to build quantum networks sporting full-blown quantumness, where information is created, stored and moved around in ways that mirror the bizarre behavior of the quantum world—think of the metaphorical cats that can be both dead and alive or particles that can exert "spooky action at a distance." Freed from many limitations of "classical" networks, these systems could provide a level of privacy, security and computational clout that is impossible to achieve with today's internet.

Although a fully realized quantum network is still a far-off vision, recent breakthroughs in transmitting, storing and manipulating quantum information have convinced some physicists that a simple proof-of-principle is imminent.

From defects in diamonds and crystals that help photons change color, to drones that serve as spooky network nodes, researchers are using a smorgasbord of exotic materials and techniques in this quantum quest. The first stage, many say, would be a quantum network using standard optical fiber to connect at least three small quantum devices about 50 to 100 kilometers apart.

Such a network may be built in the next five years, according to Ben Lanyon of the Institute for Quantum Optics and Quantum Information in Innsbruck, Austria. Lanyon's team is part of Europe's Quantum Internet Alliance, coordinated by Stephanie Wehner at the Delft University of Technology in the Netherlands, which is tasked with creating a quantum network. Europe is competing with similar national efforts in China—which in 2016 launched Micius, a quantum communications satellite—as well as in the United States. Last December, the U.S. government enacted the National Quantum Initiative Act, which will lavishly fund a number of research hubs dedicated to quantum technologies, including quantum computers and networks. "The main feature of a quantum network is that you are sending quantum information instead of classical information," says Delft University's Ronald Hanson. Classical information deals in bits that have values of either 0 or 1. Quantum information, however, uses quantum bits, or qubits, which can be in a superposition of both 0 and 1 at the same time. Qubits can be encoded, for example, in the polarization states of a photon or in the spin states of electrons and atomic nuclei.

## Quantum Networking

In what Hanson calls the "low hanging fruit of quantum networks," qubits are already being used for creating secret keys—random strings of 0s and 1s—that can then be used to encode classical information, an application called quantum key distribution (QKD).

QKD involves one party, say Alice, sending qubits to Bob, who measures the qubits (Alice and Bob first appeared in a 1978 paper on public key cryptography, and have now become placeholders for nodes in a quantum network). Only for certain types of measurements will Bob get the same value that Alice encoded in the qubits. Alice and Bob can compare notes over a public channel to figure out what those measurements are, without actually sharing the qubit values. They can then use those private values to create a secret shared key to encrypt classical messages. Crucially, if an intruder were to intercept the qubits, Alice and Bob could detect the intrusion, discard the qubits and start over—theoretically continuing until no one is eavesdropping on the quantum channel.

In July last year, Alberto Boaron of the University of Geneva, Switzerland, and colleagues reported distributing secret keys using QKD over a record distance of more than 400 kilometers of optical fiber, at 6.5 kilobits per second. In contrast, commercially available systems, such as the one sold by the Geneva-based company ID Quantique, provide QKD over 50 kilometers of fiber.

## Alice and Bob Get Spooky

Ideally, quantum networks will do more than QKD. The next step would be to transfer quantum states directly between nodes. Whereas qubits encoded using a photon’s polarization can be sent over optical fibers (as is done with QKD), using such qubits to transfer large amounts of quantum information is problematic. Photons can get scattered or absorbed along the way, or may simply fail to register in a detector, making for an unreliable transmission channel. Fortunately, there is a more robust way to exchange quantum information—via the use of another property of quantum systems, called entanglement.

When two particles or quantum systems interact, they can get entangled. Once entangled, both systems are described by a single quantum state, so measuring the state of one system instantly influences the state of the other, even if they are kilometers apart. Einstein called entanglement “spooky action at a distance,” and it is an invaluable resource for quantum networks. Imagine two network nodes, Alice and Bob, each made of some isolated bit of matter (the most obvious and reliable substrate for encoding and storing quantum states). Such “matter nodes” can become entangled with each other via a process that involves the exchange of entangled photons.

Using entangled matter nodes, Alice can exploit her share of the entanglement to send an entire qubit to Bob, without actually transmitting a physical qubit, making the transfer foolproof and secure. The key here is that once entanglement is established between the nodes, the protocol to transfer qubits from Alice to Bob is robust and deterministic.

But to do this across long distances, one first needs to distribute the entanglement—usually via standard fiber optic networks. In January, Lanyon's team in Innsbruck reported setting the record for creating entanglement between matter and light over 50 kilometers of optical fiber.

For matter, Lanyon's team used a so-called trapped ion—a single calcium ion confined to an optical cavity using electromagnetic fields. When manipulated with lasers, the ion ends up encoding a qubit as a superposition of two energy states, while also emitting a photon, with a qubit encoded in its polarization states. The qubits in the ion and the photon are entangled. The task: to send this photon through an optical fiber while preserving the entanglement.

Unfortunately, the trapped ion emits a photon at a wavelength of 854 nanometers (nm), which does not last long inside an optical fiber. So, Lanyon's team sent the emitted photon into something called a nonlinear crystal being pumped with a powerful laser. The entire interaction converts the incoming photon into another of "telecom" wavelength, one well-suited for optical fibers.

The Innsbruck team then injected this photon into a 50-kilometer-long section of optical fiber. Once it reached the other end, they tested the ion and the photon to see if they were still entangled. They were.

## Swapping Entanglements

Lanyon's team now wants to entangle two trapped ion nodes that are 100 kilometers apart. Each node would transmit an entangled photon through 50 kilometers of optical fiber to a station in the middle. There, the photons would be measured in such a way that they lose entanglement with their respective ions, causing the ions themselves to get entangled with each other. As a consequence, the two nodes, 100 kilometers apart, will each form a quantum link via a pair of entangled qubits. The entire process is called entanglement swapping. Although relatively inefficient for now, Lanyon calls the setup "a good start" for developing better, faster swapping systems.

Meanwhile, Hanson's team at Delft has demonstrated how to entangle a different type of matter node with a telecom-wavelength photon. They used a defect in diamond called a nitrogen-vacancy (NV) center. The defect arises when a nitrogen atom replaces a carbon atom in the gem's crystalline structure, leaving a vacancy in the crystal lattice adjacent to the nitrogen atom. The team used lasers to manipulate the spin of one "free" electron in the diamond NV center, placing the electron in a superposition of spin states, thus encoding one qubit. The process also results in the emission of a photon. The photon is in a superposition of being emitted in one of two consecutive time slots. "The photon is always there, but in a superposition of being emitted early or late," says Hanson. The qubit stored in the electron's spin and the qubit stored in the photon's presence or absence in the time slots are now entangled.

In 2015, the Delft team placed two spatially separated matter nodes made of diamond NV centers about 1.3 kilometers apart, linked by optical fiber. The team then transmitted an entangled photon from each node to a point roughly midway on the path between these two nodes. There, the team swapped the entanglement, causing the two NV centers to become entangled. But, just as with Lanyon's experiment, the photons emitted by the Delft team's apparatus have a wavelength of 637 nm. Such photons are terrible travelers when injected into optical fibers, diminishing in intensity by an order of magnitude for every kilometer they travel. “It makes it impossible to go beyond a few kilometers,” says Hanson.

So, in May, the Delft team reported a remedy similar to that developed by the Innsbruck team, also using nonlinear crystals and lasers to convert the photon to telecom wavelengths. In this approach, the qubits encoded by the NV center and telecom-wavelength photon remained entangled, setting the stage for entanglement swapping between two diamond NV center nodes.

Although they have not yet transmitted a diamond-entangled telecom-wavelength photon through any significant length of optical fiber, Hanson is confident that they can do so and then entangle diamond NV centers 30 kilometers apart using entanglement swapping. “We are now building two of these nodes,” he says. “We’ll use glass fiber that’s already in the ground to entangle these two NV centers.” Their next goal is to entangle nodes using the preexisting fiber infrastructure between three cities in the Netherlands, where distances are amenable to such state-of-the-art experiments.

## Mix and Match: The Challenge Ahead

The Innsbruck and Delft teams each worked with only one type of matter for storing and entangling qubits. But real-life quantum networks may use different types of materials in each node, depending on the exact task at hand—for example quantum computation or quantum sensing. And quantum nodes, besides manipulating qubits, may also have to store them for brief periods, in so-called quantum memories.

“It’s still not clear what’s going to be the right platform and the right protocol,” says Marcelli Grimau Puigibert, of the University of Basel in Switzerland. “It’s always good to be able to connect different hybrid systems.”

To this end, Puigibert, working with Wolfgang Tittel’s team at the University of Calgary, recently showed how to entangle qubits stored in two different types of materials. They started with a source that emits a pair of entangled photons, one at a wavelength of 794 nm and the other at 1,535 nm. The 794 nm photon interacts with a lithium-niobate crystal doped with thulium, so that the photon’s state becomes stored in the crystal. The 1,535 nm photon goes into an erbium-doped fiber, which also stores the quantum state.

Both memories were designed to reemit photons at a particular time. The team analyzed those reemitted photons and showed that they remained entangled. This, in turn, implies that the quantum memories were also entangled just prior to emitting those photons, thus preserving entanglement over time.

The photon wavelengths were also designed to cross-connect different transmission systems: optical fibers on one end (1,535 nm) and satellite communications on the other (794 nm). The latter is important because if quantum networks are to go intercontinental, entanglement will need to be distributed via satellites. In 2017, a team led by Jian-Wei Pan of the University of Science and Technology of China in Hefei used Micius, China’s quantum satellite, to distribute entanglement between ground stations on the Tibetan Plateau and southwest China.

Satellites, however, seem destined to remain an expensive, niche option of last resort for quantum networks. The next best choice may be relatively inexpensive drones. In May, Shi-Ning Zhu of Nanjing University and colleagues reported that they had used a 35-kilogram drone to send entangled photons to two quantum nodes 200 meters apart on the ground. The experiment used a classical communication link between the nodes to confirm that the photons they received were indeed entangled. The experiment succeeded in significantly varying conditions, working in sunlight and in darkness, and even on rainy nights. If such drones can be scaled up and installed on high-altitude UAVs, the distance between the nodes on the ground can extend to about 300 kilometers, the authors write.

Challenges remain in the march towards a fully functioning quantum network. Reliable quantum memories are one. Another important missing piece is the ability to extend the reach of a quantum link to arbitrarily long distances, using so-called quantum repeaters. Quantum states cannot be simply copied and regurgitated, as is done with classical information. Quantum nodes will need sophisticated quantum logic gates to ensure that entanglement is preserved in face of losses due to interaction with the environment. “It’s definitely one of the next big challenges,” says Lanyon.

Nonetheless, the basic elements are falling into place for building a quantum network that connects at least three cities—and, perhaps, eventually the world. “We now have platforms with which we can start to explore true quantum networks for the first time,” says Hanson. More sophisticated networks beckon. “There’s no guarantee. There’s only promise there [of] the cool stuff we’ll be able to do if we succeed.”