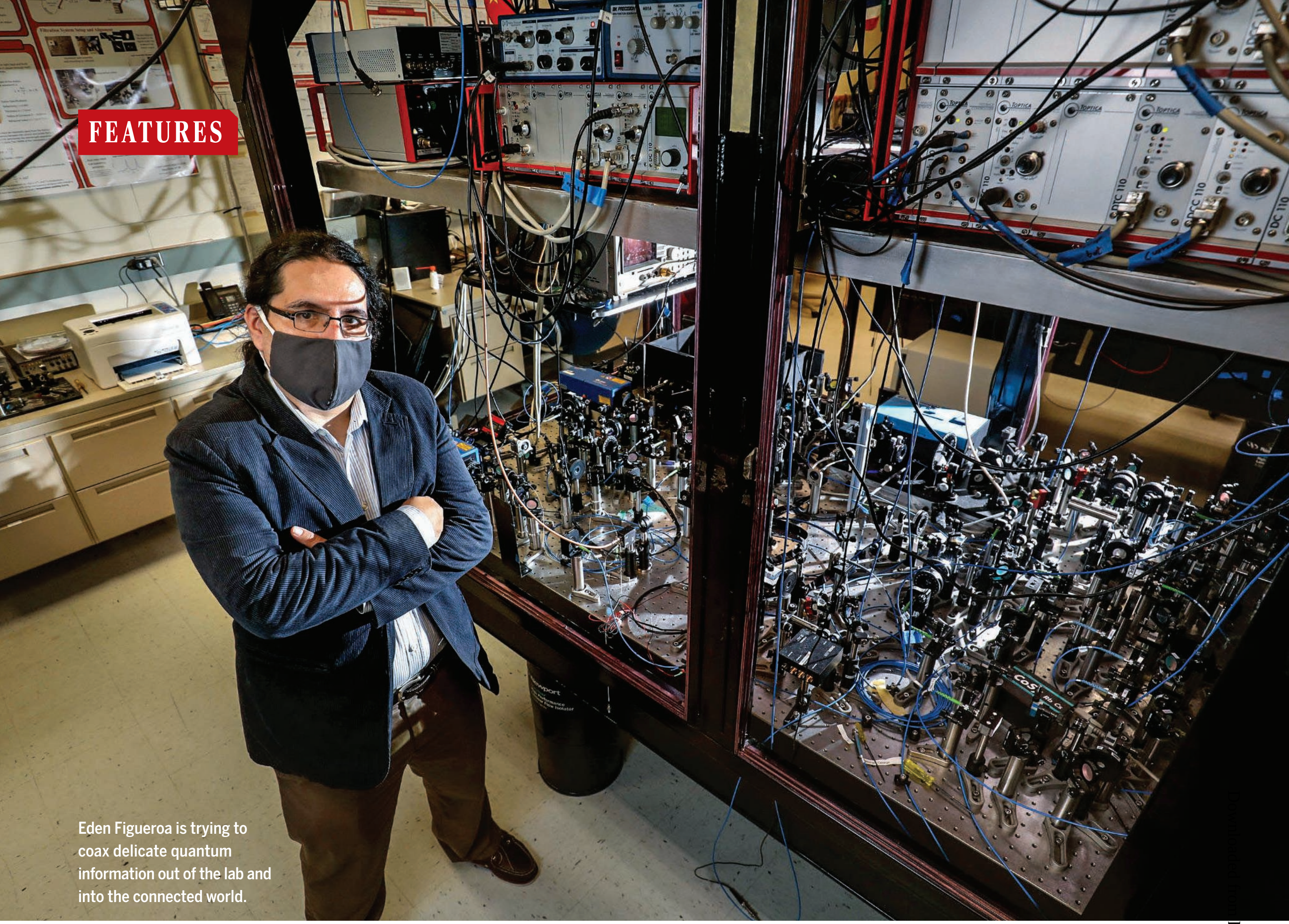


Eden Figueroa is trying to coax delicate quantum information out of the lab and into the connected world.

THE INTERNET GOES QUANTUM

A global network that would use quantum "entanglement" to weave intimate ties between far-flung users is beginning to take shape

By **Gabriel Popkin**

A beam of ethereal blue laser light enters a specialized crystal. There it turns red, a sign that each photon has split into a pair with lower energies—and a mysterious connection. The particles are now quantum mechanically "entangled," linked like identical twins who know each other's thoughts despite living in distant cities. The photons zip through a tangle of fibers, then ever so gently deposit the information they encode into waiting clouds of atoms.

The transmogrifications are "a little bit like magic," exults Eden Figueroa, a physicist at Stony Brook University. He and colleagues have concocted the setup on a few laboratory benches cluttered with lenses and mirrors. But they have a much bigger canvas in mind.

By year's end, drivers in the largest U.S. metro areas—including, largely thanks to Figueroa, the suburbs of New York City—may unwittingly rumble over the tenuous strands of a new and potentially revolutionary network: a "quantum internet" stitched together by entangled photons like those in Figueroa's lab.

Billions of dollars have poured into research on quantum computers and sensors, but many experts say the devices will flourish only when they are yoked to each other over long distances. The vision parallels the way the web vaulted the personal computer from a glorified typewriter and game console to an indispensable telecommunications portal. Through entanglement, a strange quantum mechanical property once derided by Albert Einstein as a "spooky distant effect," researchers aim to create intimate, instantaneous links across long distances. A quantum internet could weld telescopes into arrays with ultrahigh resolution, precisely synchronize clocks, yield hypersecure communication networks for finance and elections, and make it possible to do quantum computing from anywhere. It could also lead to applications nobody's yet dreamed of.

Putting these fragile links into the warm, buzzing world will not be easy, however. Most strands that exist today can send entangled photons to receivers just tens of kilometers apart. And the quantum links are fleeting, destroyed as the photons are received and measured. Researchers dream of sustaining entanglement indefinitely, using streams of photons to weave lasting quantum connections across the globe.

For that, they will need the quantum equivalent of optical repeaters, the components of today's telecommunications networks that keep light signals strong across thousands of kilometers of optical fiber. Several teams have already demonstrated key elements of quantum repeaters and say they're well on their way to building extended networks. "We've solved all the scientific problems," says Mikhail Lukin, a physicist at Harvard University. "I'm extremely optimistic that on the scale of 5 to 10 years … we'll have continental-scale network prototypes."

ON THE NIGHT of 29 October 1969, 2 months after Woodstock and as the Vietnam War raged, Charley Kline, a student at the University of California, Los Angeles, fired off a message to a computer just over 500 kilometers away at the Stanford Research Institute in Menlo Park, California. It was the launch of the Advanced Research Projects Agency Network (ARPANET). From that precarious two-node beginning—Kline's intended message was "login" but only "lo" made it through before the system crashed—the internet has swelled into today's globe-encompassing network. About 2 decades ago, physicists began to wonder whether the same infrastructure could shuttle around something more exotic: quantum information.

It was a heady time: A mathematician named Peter Shor had, in 1994, devised a quantum code that could break a leading encryption algorithm, something classical computers could not do. Shor's algorithm suggested quantum computers, which exploit the ability of very small or cold objects to simultaneously exist in multiple, "superposed" states, might have a killer application—cracking codes—and ignited a decadeslong effort to build them. Some researchers wondered whether a quantum internet might vastly enhance the power of those machines.

But building a quantum computer was daunting enough. Like entanglement, the superposed states essential to its power are fragile, collapsing when measured or otherwise perturbed by the outside world. As the field focused on general-purpose quantum computers, thoughts about linking those computers were mostly banished to a distant future. The quantum internet, Figueroa quips, became "like the hipster version" of quantum computers.

> **"On the scale of 5 to 10 years … we'll have continental-scale network prototypes."**
>
> **Mikhail Lukin**, Harvard University

More recently, with quantum computing starting to become a reality, quantum networking has begun to muscle its way back into the spotlight. To do something useful, a quantum computer will require hundreds of quantum bits, or qubits—still well beyond today's numbers. But quantum networks can prove their worth as soon as a few distant nodes are reliably entangled. "We don't need many qubits in order to do something interesting," says Stephanie Wehner, research lead for the quantum internet division at Delft University of Technology (TU Delft).

The first networks capable of transmitting individual entangled photons have begun to take shape. A 2017 report from China was one of the most spectacular: A quantum satellite named Micius sent entangled particle pairs to ground stations 1200 kilometers apart (*Science*, 16 June 2017, p. 1110). The achievement set off alarms in Washington, D.C., that eventually led to the passage of the 2018 National Quantum Initiative Act, signed into law by then-President Donald Trump and intended to spur U.S. quantum technology. The Department of Energy (DOE), which has led efforts to envision a U.S. quantum internet, added to the momentum in April, announcing $25 million for R&D on a quantum internet to link up national labs and universities. "Let's get our science facilities connected, show that this works, and provide a framework for the rest of the country to hop on and scale it up," says Chris Fall, who until recently led the DOE Office of Science.

The Chinese group, led by Jian-Wei Pan, a physicist at the University of Science and Technology of China, has continued to develop its network. According to a January *Nature* paper, it now spans more than 4600 kilometers, using fibers and non-quantum relays. Shorter quantum links have been demonstrated in other countries.

Industry and government are starting to use those first links for secure communication through a method called quantum key distribution, often abbreviated QKD. QKD enables two parties to share a secret key by making simultaneous measurements on pairs of entangled photons. The quantum connection keeps the key safe from tampering or eavesdropping, because any intervening measurement would destroy the entanglement; information encrypted with the key then travels through ordinary channels. QKD is used to secure some Swiss elections, and banks have tested it. But many experts question its importance, because simpler encryption techniques are also impervious to known attacks, including Shor's algorithm. Moreover, QKD does not guarantee security at sending and receiving nodes, which remain vulnerable.

A full-fledged quantum network aims higher. It wouldn't just transmit entangled particles; it "distributes entanglement as a resource," says Neil Zimmerman, a physicist at the National Institute of Standards and Technology, enabling devices to be entangled for long periods, sharing and exploiting quantum information (*Science*, 19 October 2018, 10.1126/science.aam9288).

Science might be the first to benefit. One possible use is very long baseline interferometry. The method has already linked radio telescopes around the globe, effectively creating a single, giant dish powerful enough to image a black hole at the center of a distant galaxy. Combining light from far-flung optical telescopes is far more challenging. But physicists have proposed schemes to capture light gathered by the telescopes in quantum memories and use entangled photons to extract and merge its phase information, the key to ultrahigh resolution. Entangling distributed quantum sensors could also lead to more sensitive detector networks for dark matter and gravitational waves.

More practical applications include ultrasecure elections and hack-proof communication in which the information itself—and not just a secret key for decoding it, as in QKD—is shared between entangled nodes. Entanglement could synchronize atomic clocks and prevent the delays and errors that accumulate as information is sent between them. And it could offer a way to link up quantum computers, increasing their power. Quantum computers of the near future will likely be limited to a few hundred qubits each, but if entangled together, they may be able to tackle more sophisticated computations.

Taking this idea further, some also envision an analog of cloud computing: so-called blind quantum computing. The thinking is that the most powerful quantum computers will one day be located at national labora-

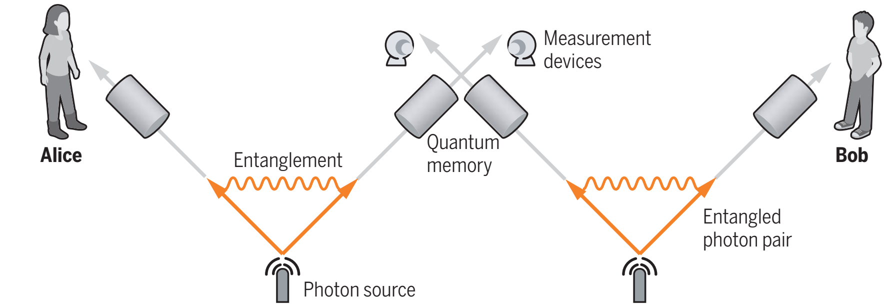
Making connections

A quantum internet would be woven together by photons that are entangled, meaning they share a quantum state. But quantum repeaters would be needed to relay the fragile photons between far flung users.

A quantum repeater

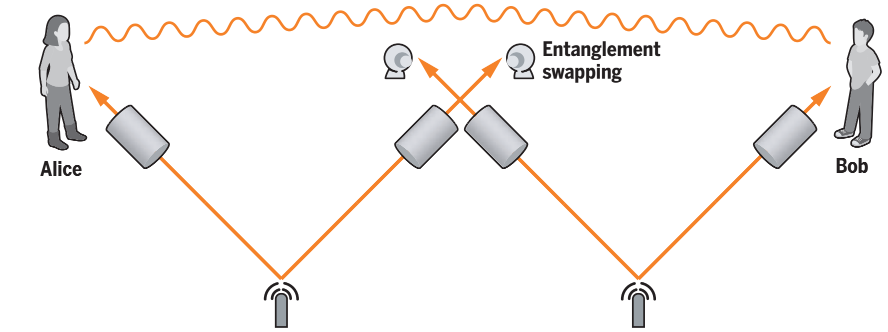
1 Generating photon pairs

One popular protocol begins by creating pairs of entangled photons and sending one member of each pair toward measurement devices while the others fly toward end users, conventionally called Alice and Bob.



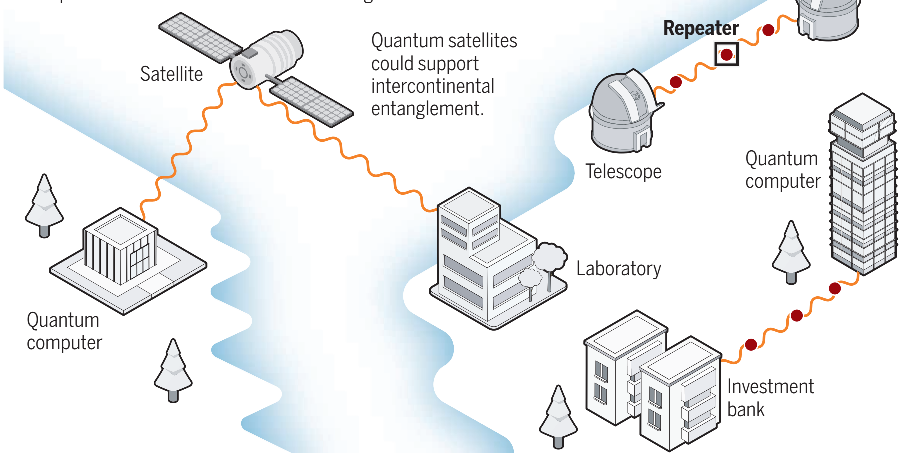
2 Long-range link

The photons are captured in quantum memories that store their quantum states. Processors correct and prepare the states while preserving the entanglements. A specialized measurement on the middle two quantum memories then "swaps" the entanglement to link Alice and Bob.



Versatile network

A quantum internet could establish intimate and secure connections among widely separated users and facilities. It could allow powerful quantum computers to run complicated algorithms for remote users while protecting sensitive information, or merge telescopes and other instruments into ultra–high-resolution networks.



GRPHIC: N. DESAI/SCIENCE

tories, universities, and companies, much as supercomputers are today. Designers of drugs and materials or stock traders might want to run quantum algorithms from distant locations without divulging their programs' contents. In theory, users could encode the problem on a local device that's entangled with a remote quantum computer—exploiting the distant computer's power while leaving it blind to the problem being solved.

"As a physicist, I think [blind quantum computing] is very beautiful," says Tracy Northup of the University of Innsbruck.

RESEARCHERS HAVE TAKEN early steps toward fully entangled networks. In 2015, Wehner and colleagues entangled photons with electron spins in nitrogen atoms, encased within two tiny diamonds 1.3 kilometers apart on the TU Delft campus. The photons were then sent to an intermediate station, where they interacted with each other to entangle the diamond nodes. The experiment set a record for the distance of "heralded" entanglement—meaning researchers could confirm and use it—and the link lasted for up to several microseconds.

More expansive networks, however, will likely require quantum repeaters to copy, correct, amplify, and rebroadcast virtually every signal. And although repeaters are a relatively straightforward technology for the classical internet, a quantum repeater has to elude the "no-cloning" theorem—which holds, essentially, that a quantum state cannot be copied.

One popular repeater design starts with two identical, entangled photon pairs at separate sources. One photon from each pair flies toward distant end points, which could be quantum computers, sensors, or other repeaters. Let's call them Alice and Bob, as quantum physicists are wont to do.

The other halves of each pair zip inward, toward the heart of the repeater. That device must trap the photon that arrives first, coax its information into a quantum memory—perhaps a diamond or atom cloud—correct any errors that have accumulated in transit, and coddle it until the other photon arrives. The repeater then needs to mate the two in a way that entangles their far-flung twins. This process, known as entanglement swapping, creates a link between the distant end points, Alice and Bob. Additional repeaters could daisy-chain Alice to a Carol and Bob to a Dave, ultimately spanning big distances.

Figueroa traces his drive to build such a device to his 2008 Ph.D. thesis defense at the University of Calgary. After the young Mexican-born physicist described how he entangled atoms with light, a theorist asked what he was going to do with the setup. "At the time—shame on me—I didn't have an answer. To me, it was a toy I could play with," Figueroa recalls. "He told me: 'A quantum repeater is what you're going to do with it.'"

Inspired, Figueroa pursued the system at the Max Planck Institute of Quantum Optics before landing at Stony Brook. He decided early on that commercial quantum repeaters should operate at room temperature—a break from most quantum lab experiments, which are conducted at very cold temperatures to minimize thermal vibrations that could upset fragile quantum states.

Figueroa is counting on rubidium vapor for one component of a repeater, the quantum memory. Atoms of rubidium, a heavy cousin of the more familiar lithium and sodium, are appealing because their internal quantum states can be set and controlled by light. In Figueroa's lab, entangled photons from the frequency-splitting crystal enter plastic cells containing 1 trillion or so rubidium atoms each. There, each photon's information is encoded as a superposition among the atoms, where it lasts for a fraction of a millisecond—pretty good for a quantum experiment.

Figueroa is still developing the second stage of the repeater: using computer-controlled bursts of laser light to correct errors and sustain the clouds' quantum states. Additional laser pulses will then send photons carrying entanglement from the memories to measurement devices to entangle the end users.

Lukin builds quantum repeaters using a different medium: silicon atoms encased in diamonds. Incoming photons can tweak the quantum spin of a silicon electron, creating a potentially stable memory; in a 2020 *Nature* paper, his team reported catching and storing quantum states for more than one-fifth of a second, far longer than in the rubidium memory. Although the diamonds must be chilled to within a fraction of a degree above absolute zero, Lukin says the fridges needed are fast becoming compact and efficient. "Right now it's the least of my worries."

At TU Delft, Wehner and her colleagues are pushing the diamond approach as well, but with nitrogen atoms instead of silicon. Last month in *Science*, the team reported entangling three diamonds in the lab, creating a miniature quantum network. First, the researchers used photons to entangle two different diamonds, Alice and Bob. At Bob, the entanglement was transferred from nitrogen to a spin in a carbon nucleus: a long-lived quantum memory. The entanglement process was then repeated between Bob's nitrogen atom and one in a third diamond, Charlie. A joint measurement on Bob's nitrogen atom and carbon nucleus then transferred the entanglement to the third leg, Alice to Charlie.

Although the distances were much shorter and the efficiency lower than real-world quantum networks will require, the controllable swapping of entanglement demonstrated "the working principle of a quantum repeater," says TU Delft physicist Ronald Hanson, who led the experiment. It is "something that has never been done."

Pan's team has also demonstrated a partial repeater, with atom clouds serving as the quantum memories. But in a study published in 2019 in *Nature Photonics*, his team demonstrated an early prototype of a radically different scheme: sending such large numbers of entangled photons through parallel fibers that at least one might survive the journey. Although potentially avoiding the need for repeaters, the network would require the ability to entangle at least several hundred photons, Pan says; his current record is 12. Using satellites to generate entanglement, another technology Pan is developing, could also reduce the need for repeaters because photons can survive much longer journeys through space than through fibers.

A true quantum repeater, most experts agree, remains years away, and may ultimately use technologies common in today's quantum computers, such as superconductors or trapped ions, rather than diamonds or atom clouds. Such a device will need to capture nearly every photon that hits it and will probably require quantum computers of at least a few hundred qubits to correct and process signals. In a yin-yang sort of way, better quantum computers could boost the quantum internet—which in turn could supercharge quantum computing.

Impurity atoms in minuscule diamonds like the one at the heart of this chip can store and relay quantum information.

PHOTO: QUTECH

While physicists labor to perfect repeaters, they are racing to link sites within single metropolitan areas, for which repeaters are not needed. In a study posted to arXiv in February, Figueroa sent photons from two atom-cloud memories in his lab through 79 kilometers of commercial fibers to Brookhaven National Laboratory, where the photons were merged—a step toward end-to-end entanglement of the type demonstrated by the TU Delft group. By next year, he plans to deploy two of his quantum memories—compacted to the size of a minirefrigerator—midway between his university and the New York City office of his startup company, Qunnect, to see if they boost the odds of photons surviving the journey.

Embryonic quantum networks are also being built in the Boston, Los Angeles, and Washington, D.C., regions, and two networks will link Argonne National Laboratory and Fermi National Accelerator Laboratory in Illinois to several Chicago-area universities. TU Delft researchers hope to soon extend their record-long entanglement to a commercial telecommunications facility in The Hague, Netherlands, and other fledgling networks are growing in Europe and Asia.

The ultimate goal is to use repeaters to link these small networks into an intercontinental internet. But first, researchers face more mundane challenges, including building better photon sources and detectors, minimizing losses at fiber connections, and efficiently converting photons between the native frequency of a particular quantum system—say, an atom cloud or diamond—and the infrared wavelengths that telecom fibers conduct. "Those real-world problems," Zimmerman says, "may actually be bigger than fiber attenuation."

Some doubt the technology will live up to the hype. Entanglement "is a very odd, very special kind of property," says Kurt Jacobs, a physicist at the Army Research Laboratory. "It doesn't necessarily lend itself to all kinds of applications." For clock synchronization, for example, the advantage over classical methods scales only as the square root of the number of entangled devices. A threefold gain requires linking nine clocks—which may be more trouble than it's worth. "It's always going to be harder to have a functional quantum network than a classical one," Jacobs says.

To such doubts, David Awschalom, a physicist at the University of Chicago who is spearheading one of the Midwest networks, counters, "We're at the transistor level of quantum technology." It took a few years after the transistor was invented in 1947 before companies found uses for it in radios, hearing aids, and other devices. Transistors are now etched by the billions into chips in every new computer, smartphone, and car.

Future generations may look back on this moment the way we look nostalgically at ARPANET, a pure infant version of the internet, its vast potential yet to be recognized and commercialized. "You can be sure that we haven't yet thought of some of the most important things this technology will do," Awschalom says. "It would take extraordinary arrogance to believe you've done that." ■

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Science

The internet goes quantum

Gabriel Popkin

Science, 372 (6546),

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