Physicists observe wormhole dynamics using a quantum computer

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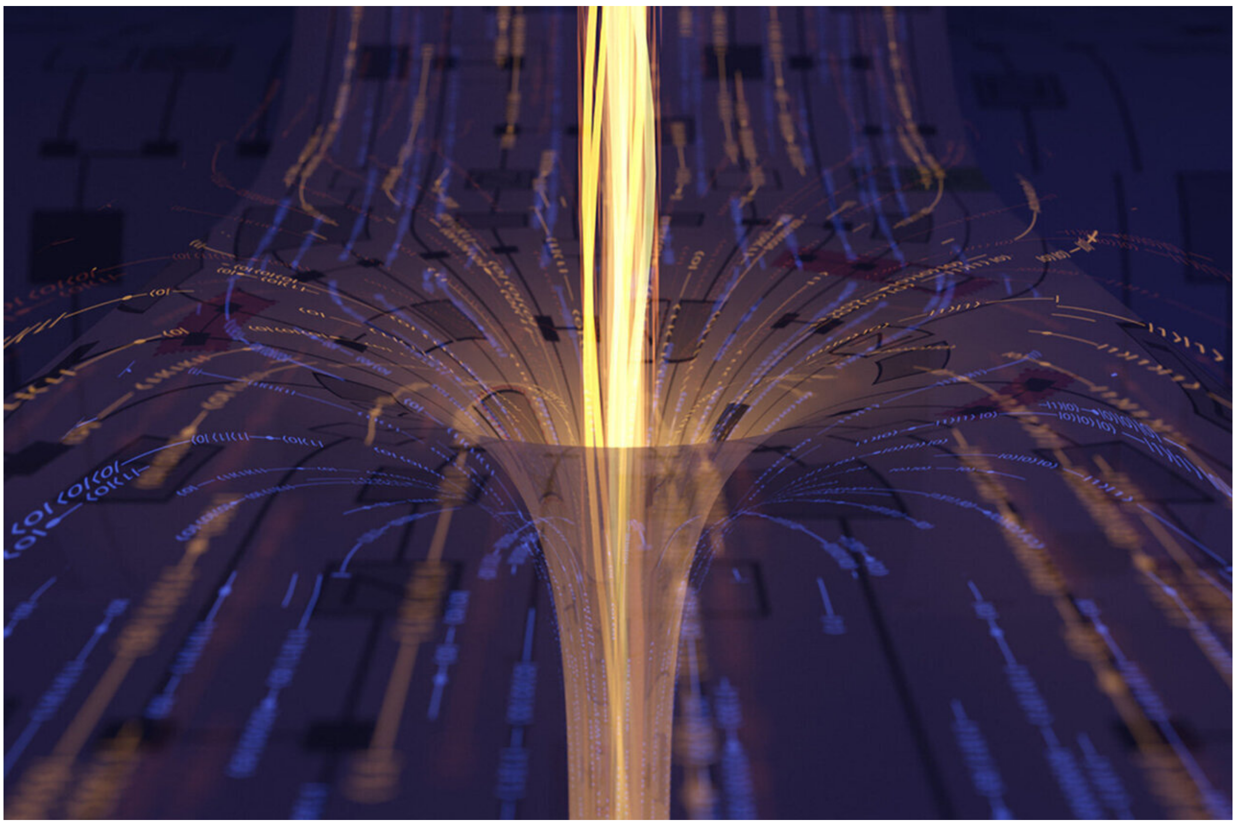

Artwork depicting a quantum experiment that studies traversable wormholes. Credit: inqnet/A. Mueller (Caltech)

Scientists have, for the first time, developed a quantum experiment that allows them to study the dynamics, or behavior, of a special kind of theoretical wormhole. The experiment has not created an actual wormhole (a rupture in space and time), rather it allows researchers to probe connections between theoretical wormholes and quantum physics, a prediction of so-called quantum gravity. Quantum gravity refers to a set of theories that seek to connect gravity with quantum physics, two fundamental and well-studied descriptions of nature that appear inherently incompatible with each other.

"We found a quantum system that exhibits key properties of a gravitational wormhole yet is sufficiently small to implement on today's quantum hardware," says Maria Spiropulu, the principal investigator of the U.S. Department of Energy Office of Science research program Quantum Communication Channels for Fundamental Physics (QCCFP) and the Shang-Yi Ch'en Professor of Physics at Caltech. "This work constitutes a step toward a larger program of testing quantum gravity physics using a quantum computer. It does not substitute for direct probes of quantum gravity in the same way as other planned experiments that might probe quantum gravity effects in the future using quantum sensing, but it does offer a powerful testbed to exercise ideas of quantum gravity."

The research will be published December 1 in the journal *Nature*. The study's first authors are Daniel Jafferis of Harvard University and Alexander Zlokapa (BS '21), a former undergraduate student at Caltech who started on this project for his bachelor's thesis with Spiropulu and has since moved on to graduate school at MIT.

Wormholes are bridges between two remote regions in spacetime. They have not been observed experimentally, but scientists have theorized about their existence and properties for close to 100 years. In 1935, Albert Einstein and Nathan Rosen described wormholes as tunnels through the fabric of spacetime in accordance with Einstein's general theory of relativity, which describes gravity as a curvature of spacetime.

Researchers call wormholes Einstein–Rosen bridges after the two physicists who invoked them, while the term "wormhole" itself was coined by physicist John Wheeler in the 1950s.

The notion that wormholes and quantum physics, specifically entanglement (a phenomenon in which two particles can remain connected across vast distances), may have a connection was first proposed in theoretical research by Juan Maldacena and Leonard Susskind in 2013. The physicists speculated that wormholes (or "ER") were equivalent to entanglement (also known as "EPR" after Albert Einstein, Boris Podolsky [Ph.D. '28], and Nathan Rosen, who first proposed the concept). In essence, this work established a new kind of theoretical link between the worlds of gravity and quantum physics. "It was a very daring and poetic idea," says Spiropulu of the ER = EPR work.

Later, in 2017, Jafferis, along with his colleagues Ping Gao and Aron Wall, extended the ER = EPR idea to not just wormholes but traversable wormholes. The scientists concocted a scenario in which negative repulsive energy holds a wormhole open long enough for something to pass through from one end to the other. The researchers showed that this gravitational description of a traversable wormhole is equivalent to a process known as quantum teleportation. In quantum teleportation, a protocol that has been experimentally demonstrated over long distances via optical fiber and over the air, information is transported across space using the principles of quantum entanglement.

The present work explores the equivalence of wormholes with quantum teleportation. The Caltech-led team performed the first experiments that probe the idea that information traveling from one point in space to another can be described in either the language of gravity (the wormholes) or the language of quantum physics (quantum entanglement).

A key finding that inspired possible experiments occurred in 2015, when Caltech's Alexei Kitaev, the Ronald and Maxine Linde Professor of Theoretical Physics and Mathematics, showed that a simple quantum system could exhibit the same duality later described by Gao, Jafferis, and Wall, such that the model's quantum dynamics are equivalent to quantum gravity effects. This Sachdev–Ye–Kitaev, or SYK model (named after Kitaev, and Subir Sachdev and Jinwu Ye, two other researchers who worked on its development previously) led researchers to suggest that some theoretical wormhole ideas could be studied more deeply by doing experiments on quantum processors.

Furthering these ideas, in 2019, Jafferis and Gao showed that by entangling two SYK models, researchers should be able to perform wormhole teleportation and thus produce and measure the dynamical properties expected of traversable wormholes.

In the new study, the team of physicists performed this type of experiment for the first time. They used a "baby" SYK-like model prepared to preserve gravitational properties, and they observed the wormhole dynamics on a quantum device at Google, namely the Sycamore quantum processor. To accomplish this, the team had to first reduce the SYK model to a simplified form, a feat they achieved using machine learning tools on conventional computers.

"We employed learning techniques to find and prepare a simple SYK-like quantum system that could be encoded in the current quantum architectures and that would preserve the gravitational properties," says Spiropulu. "In other words, we simplified the microscopic description of the SYK quantum system and studied the resulting effective model that we found on the quantum processor. It is curious and surprising how the optimization on one characteristic of the model preserved the other metrics! We have plans for more tests to get better insights on the model itself."

In the experiment, the researchers inserted a qubit—the quantum equivalent of a bit in conventional silicon-based computers—into one of their SYK-like systems and observed the information emerge from the other system. The information traveled from one quantum system to the other via quantum teleportation—or, speaking in the complementary language of gravity, the quantum information passed through the traversable wormhole.

"We performed a kind of quantum teleportation equivalent to a traversable wormhole in the gravity picture. To do this, we had to simplify the quantum system to the smallest example that preserves gravitational characteristics so we could implement it on the Sycamore quantum processor at Google," says Zlokapa.

Co-author Samantha Davis, a graduate student at Caltech, adds, "It took a really long time to arrive at the results, and we surprised ourselves with the outcome."

"The near-term significance of this type of experiment is that the gravitational perspective provides a simple way to understand an otherwise mysterious many-particle quantum phenomenon," says John Preskill, the Richard P. Feynman Professor of Theoretical Physics at Caltech and director of the Institute for Quantum Information and Matter (IQIM). "What I found interesting about this new Google experiment is that, via machine learning, they were able to make the system simple enough to simulate on an existing quantum machine while retaining a reasonable caricature of what the gravitation picture predicts."

In the study, the physicists report wormhole behavior expected both from the perspectives of gravity and from quantum physics. For example, while quantum information can be transmitted across the device, or teleported, in a variety of ways, the experimental process was shown to be equivalent, at least in some ways, to what might happen if information traveled through a wormhole. To do this, the team attempted to "prop open the wormhole" using pulses of either negative repulsive energy pulse or the opposite, positive energy. They observed key signatures of a traversable wormhole only when the equivalent of negative energy was applied, which is consistent with how wormholes are expected to behave.

"The high fidelity of the quantum processor we used was essential," says Spiropulu. "If the error rates were higher by 50 percent, the signal would have been entirely obscured. If they were half we would have 10 times the signal!"

In the future, the researchers hope to extend this work to more complex quantum circuits. Though bona fide quantum computers may still be years away, the team plans to continue to perform experiments of this nature on existing quantum computing platforms.

"The relationship between quantum entanglement, spacetime, and quantum gravity is one of the most important questions in fundamental physics and an active area of theoretical research," says Spiropulu. "We are excited to take this small step toward testing these ideas on quantum hardware and will keep going."

The study is titled "Traversable wormhole dynamics on a quantum processer." Other authors include: Joseph Lykken of Fermilab; David Kolchmeyer, formerly at Harvard and now a postdoc at MIT; Nikolai Lauk, formerly a postdoc at Caltech; and Hartmut Neven of Google.

More information: Maria Spiropulu, Traversable wormhole dynamics on a quantum processor, *Nature* (2022). DOI: 10.1038/s41586-022-05424-3.
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Adam R. Brown et al, A holographic wormhole traversed in a quantum computer, *Nature* (2022). DOI: 10.1038/d41586-022-03832-z , www.nature.com/articles/d41586-022-03832-z

More information can be found at the Alliance for Quantum Technologies website: https://inqnet.caltech.edu/wormhole2022.