Entanglement: Gravity's long-distance connection

Wormhole links between black holes could broker quantum-general relativity merger

By Andrew Grant 10:42am, October 7, 2015

Particles radiated from a black hole may sustain two kinds of links with the black hole’s interior: a quantum connection called entanglement and a tunnel through space called a wormhole.

When Albert Einstein scoffed at a “spooky” long-distance connection between particles, he wasn’t thinking about his general theory of relativity.

Einstein’s century-old theory describes how gravity emerges when massive objects warp the fabric of space and time. Quantum entanglement, the spooky source of Einstein’s dismay, typically concerns tiny particles that contribute insignificantly to gravity. A speck of dust depresses a mattress more than a subatomic particle distorts space.

Yet theoretical physicist Mark Van Raamsdonk suspects that entanglement and spacetime are actually linked. In 2009, he calculated that space without entanglement couldn’t hold itself
together. He wrote a paper asserting that quantum entanglement is the needle that stitches together the cosmic spacetime tapestry.

Multiple journals rejected his paper. But in the years since that initial skepticism, investigating the idea that entanglement shapes spacetime has become one of the hottest trends in physics. “Everything points in a really compelling way to space being emergent from deep underlying physics that has to do with entanglement,” says John Preskill, a theoretical physicist at Caltech.

In 2012, another provocative paper presented a paradox about entangled particles inside and outside a black hole. Less than a year later, two experts in the field proposed a radical resolution: Those entangled particles are connected by wormholes — spacetime tunnels imagined by Einstein that nowadays appear as often in sci-fi novels as in physics journals. If that proposal is correct, then entanglement isn’t the spooky long-distance link that Einstein thought it was — it’s an actual bridge linking distant points in space.

Story continues after video

Many researchers find these ideas irresistible. Within the last few years, physicists in seemingly unrelated specialties have converged on this confluence of entanglement, space and wormholes. Scientists who once focused on building error-resistant quantum computers are now pondering whether the universe itself is a vast quantum computer that safely encodes spacetime in an elaborate web of entanglement. “It’s amazing how things have been progressing,” says Van Raamsdonk, of the University of British Columbia in Vancouver.

Physicists have high hopes for where this entanglement-spacetime connection will lead them. General relativity brilliantly describes how spacetime works; this new research may reveal where spacetime comes from and what it looks like at the small scales governed by quantum mechanics. Entanglement could be the secret ingredient that unifies these supposedly incompatible views into a theory of quantum gravity, enabling physicists to understand conditions inside black holes and in the very first moments after the Big Bang.

Holograms and soup cans

Van Raamsdonk’s 2009 insight didn’t materialize out of thin air. It’s rooted in the math of the holographic principle, the idea that the boundary enclosing a volume of space can contain all the information about what’s inside. If the holographic principle applied to everyday life, then a nosy employee could perfectly reconstruct the inside of a coworker’s office cubicle — piles of papers,
family photos, dust bunnies in the corner, even files on the computer’s hard drive — just by looking at the cubicle’s outer walls. It’s a counterintuitive idea, considering walls have two dimensions and a cubicle’s interior has three. But in 1997, Juan Maldacena, a string theorist then at Harvard, perceived an intriguing example of what the holographic principle could reveal about the universe (SN: 11/17/07, p. 315).

He started with anti-de Sitter space, which resembles the universe’s gravity-dominated spacetime but also has some quirky attributes. It is curved in such a way that a flash of light emitted at any location eventually returns to where it started. And while the universe is expanding, anti-de Sitter space neither stretches nor contracts. Because of these features, a chunk of anti-de Sitter spacetime with four dimensions (three spatial, one time) can be surrounded by a three-dimensional boundary.

Maldacena considered a cylinder of anti-de Sitter spacetime. Each horizontal slice of the cylinder represented the state of its space at a given moment, while the cylinder’s vertical dimension represented time. Maldacena surrounded his cylinder with a boundary for the hologram; if the anti-de Sitter space were a can of soup and its contents, then the boundary was the label.

Just as nobody would mistake a Campbell’s label for the actual soup, the boundary seemingly shared nothing in common with the cylinder’s interior. The boundary “label,” for instance, observed the rules of quantum mechanics, with no gravity. Yet gravity described the space inside containing the “soup.” Maldacena showed, though, that the label and the soup were one and the same; the quantum interactions on the boundary perfectly described the anti-de Sitter space it enclosed. “They are two theories that seem completely different but describe exactly the same thing,” Preskill says.

Maldacena added entanglement to the holographic equation in 2001. He considered the space within two soup cans, each containing a black hole. Then he created the equivalent of a tin can telephone by connecting the black holes with a wormhole — a tunnel through spacetime first proposed by Einstein and Nathan Rosen in 1935. Maldacena looked for a way to create the equivalent of that spacetime connection on the cans’ labels. The trick, he realized, was entanglement.

Like a wormhole, quantum entanglement links entities that share no obvious relationship. The quantum world is a fuzzy place: An electron can seemingly be spinning up and down simultaneously, a state called superposition, until a measurement provides a definitive answer. But if two electrons are entangled, then measuring the spin of one enables an experimenter to know what the spin of the other will be — even though the partner electron is still in a superposition state. This quantum link remains if the electrons are separated by meters, kilometers or light-years.

Maldacena demonstrated that by entangling particles on one can’s label with particles on the other, he could perfectly describe the wormhole connection between the cans in the language of quantum mechanics. In the context of the holographic principle, entanglement is equivalent to physically tying chunks of spacetime together.

Inspired by this entanglement-spacetime link, Van Raamsdonk wondered just how large a role entanglement might play in shaping spacetime. He considered the blandest quantum soup-can label he could think of: a blank one, which corresponded to an empty disk of anti-de Sitter space. But he knew that because of quantum mechanics, empty space is never truly empty. It is filled with pairs of particles that blink in and out of existence. And those fleeting particles are
entangled.

So Van Raamsdonk drew an imaginary line bisecting his holographic label and then mathematically severed the quantum entanglement between particles on one half of the label and those on the other. He discovered that the corresponding disk of anti-de Sitter space started to split in half. It was as if the entangled particles were hooks that kept the canvas of space and time in place; without them, spacetime pulled itself apart. As Van Raamsdonk decreased the degree of entanglement, the portion connecting the diverging regions of space got thinner, like the rubbery thread that narrows as a chewed wad of gum is pulled apart. “It led me to suggest that the origin of having space at all is having this entanglement,” he says.

That was a bold claim, and it took a while for Van Raamsdonk’s paper, published in *General Relativity and Gravitation* in 2010, to garner serious attention. The spark came in 2012, when four physicists at the University of California, Santa Barbara wrote a paper challenging conventional wisdom about the event horizon, a black hole’s point of no return.

**Insight behind a firewall**

In the 1970s, theoretical physicist Stephen Hawking showed that pairs of entangled particles — the same kinds Van Raamsdonk later analyzed on his quantum boundary — can get split up at the event horizon. One falls into the black hole, and the other escapes as what’s known as Hawking radiation. The process gradually saps the mass of a black hole, ultimately leading to its demise. But if black holes disappear, then so would the record of everything that ever fell inside. Quantum theory maintains that information cannot be destroyed.

By the 1990s several theoretical physicists, including Stanford’s Leonard Susskind, had proposed resolutions of the issue. Sure, they said, matter and energy fall into a black hole. But from the perspective of an outside observer, that stuff never quite makes it past the event horizon; it seemingly teeters on the edge. As a result, the event horizon becomes a holographic boundary containing all the information about the space inside the black hole. Eventually, as the black hole shrivels away, that information will leak out as Hawking radiation. In principle, the observer could collect the radiation and piece together information about the black hole’s interior.

In their 2012 paper, Santa Barbara physicists Ahmed Almheiri, Donald Marolf, James Sully and Joseph Polchinski claimed something was wrong with that picture. For an observer to assemble the puzzle of what’s inside a black hole, they noted, all the individual puzzle pieces — the particles of Hawking radiation — would have to be entangled with each other. But each Hawking
It led me to suggest that the origin of having space at all is having this entanglement.

— Mark Van Raamsdonk

Unfortunately, there is not enough entanglement to go around. Quantum theory dictates that the entanglement required to link all the particles outside the black hole precludes those particles from also linking up with particles inside the black hole. Compounding the problem, the physicists found that severing one of those entanglements would create an impenetrable wall of energy, called a firewall, at the event horizon (SN: 5/31/14, p. 16).

Many physicists doubted that black holes actually vaporize everything trying to enter. But the mere possibility that firewalls exist had disturbing implications. Previously, physicists had wondered what the space inside a black hole looked like. Now they weren’t sure whether black holes even had an inside. “It was kind of humbling,” Preskill says.

Susskind was not so much humbled as restless. He had spent years trying to show that information wasn’t lost inside a black hole; now he was just as convinced that the firewall idea was wrong, but he couldn’t prove it. Then one day he received a cryptic email from Maldacena: “It had very little in it,” Susskind says, “except for ER = EPR.” Maldacena, now at the Institute for Advanced Study in Princeton, N.J., had thought back to his 2001 paper on interconnected soup cans and wondered whether wormholes could resolve the entanglement mess raised by the firewall problem. Susskind quickly jumped on the idea.

In a paper in the German journal *Fortschritte der Physik* in 2013, Maldacena and Susskind argued that a wormhole — technically, an Einstein-Rosen bridge, or ER — is the spacetime equivalent of quantum entanglement. (EPR stands for Einstein, Boris Podolsky and Rosen, authors of the 1935 paper that belittled entanglement.) That means that every particle of Hawking radiation, no matter how far away it is from where it started, is directly connected to a black hole’s interior via a shortcut through spacetime. “Through the wormhole, the distant stuff is not so distant,” Susskind says.

Susskind and Maldacena envisioned gathering up all the Hawking particles and smushing them together until they collapse into a black hole. That black hole would be entangled, and thus connected via wormhole, with the original black hole. That trick transformed a confusing mess of Hawking particles — paradoxically entangled with both a black hole and each other — into two black holes connected by a wormhole. Entanglement overload is averted, and the firewall problem goes away.

Not everyone has jumped aboard the ER = EPR bandwagon. Susskind and Maldacena admit they have more work to do to prove the equivalence of wormholes and entanglement. But after pondering the implications of the firewall paradox, many physicists agree that the spacetime inside a black hole owes its existence to entanglement with radiation outside. That’s a major insight, Preskill says, because it also implies that the entire universe’s spacetime fabric, including the patch on which we reside, is a product of quantum spookiness.
Cosmic computer

It’s one thing to say the universe constructs spacetime through entanglement; it’s another to show how the universe does it. The trickier of those assignments has fallen on Preskill and colleagues, who have come to view the cosmos as a colossal quantum computer. For two decades scientists have worked on building quantum computers that use information encoded in entangled entities, such as photons or tiny circuits, to solve problems intractable on traditional computers, such as factoring large numbers. Preskill’s team is using knowledge gained in that effort to predict how particular features inside a soup can would be depicted on the entanglement-filled label.

Quantum computers work by exploiting components that are in superposition states as data carriers — they can essentially be 0s and 1s at the same time. But superposition states are very fragile. Too much heat, for example, can destroy the state and all the quantum information it carries. These information losses, which Preskill compares to having pages torn out of a book, seem inevitable.

But physicists responded by creating a protocol called quantum error correction. Instead of relying on one particle to store a quantum bit, scientists spread the data among multiple entangled particles. A book written in the language of quantum error correction would be full of gibberish, Preskill says, but its entire contents could be reconstructed even if half the pages were missing.

Spooky entanglement

The polarizations of entangled photons (top row) are initially uncertain — in essence they are horizontal and vertical simultaneously. But once the light blue person measures her photon and sees it is vertically polarized, the fate of the dark blue person’s photon is set: When measured, it will be horizontally polarized.

*Credit: J. Hirshfeld*
Quantum error correction has attracted a lot of attention in recent years, but now Preskill and his colleagues suspect that nature came up with it first. In the June *Journal of High Energy Physics*, Preskill’s team showed how the entanglement of multiple particles on a holographic boundary perfectly describes a single particle being pulled by gravity within a chunk of anti-de Sitter space. Maldacena says this insight could lead to a better understanding of how a hologram encodes all the details about the spacetime it surrounds.

Physicists admit that their approximations have a long way to go to match reality. While anti-de Sitter space offers physicists the advantage of working with a well-defined boundary, the universe doesn’t have a straightforward soup-can label. The spacetime fabric of the cosmos has been expanding since the Big Bang and continues to do so at an increasing clip. If you shoot a pulse of light into space, it won’t turn around and come back; it will just keep going. “It is not clear how to define a holographic theory for our universe,” Maldacena wrote in 2005. “There is no convenient place to put the hologram.”

Yet as crazy as holograms, soup cans and wormholes sound, they seem to be promising lenses in the search for a way to meld quantum spookiness with spacetime geometry. In their paper on wormholes, Einstein and Rosen discussed possible quantum implications but didn’t make a connection to their earlier entanglement paper. Today that link may help reconcile quantum mechanics and general relativity in a theory of quantum gravity. Armed with such a theory, physicists could dig into mysteries such as the state of the infant universe, when matter and
energy were packed into an infinitesimally small space. “We don’t really know the answers yet by any means,” Preskill says. “But we’re excited to find a new way of looking at things.”

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