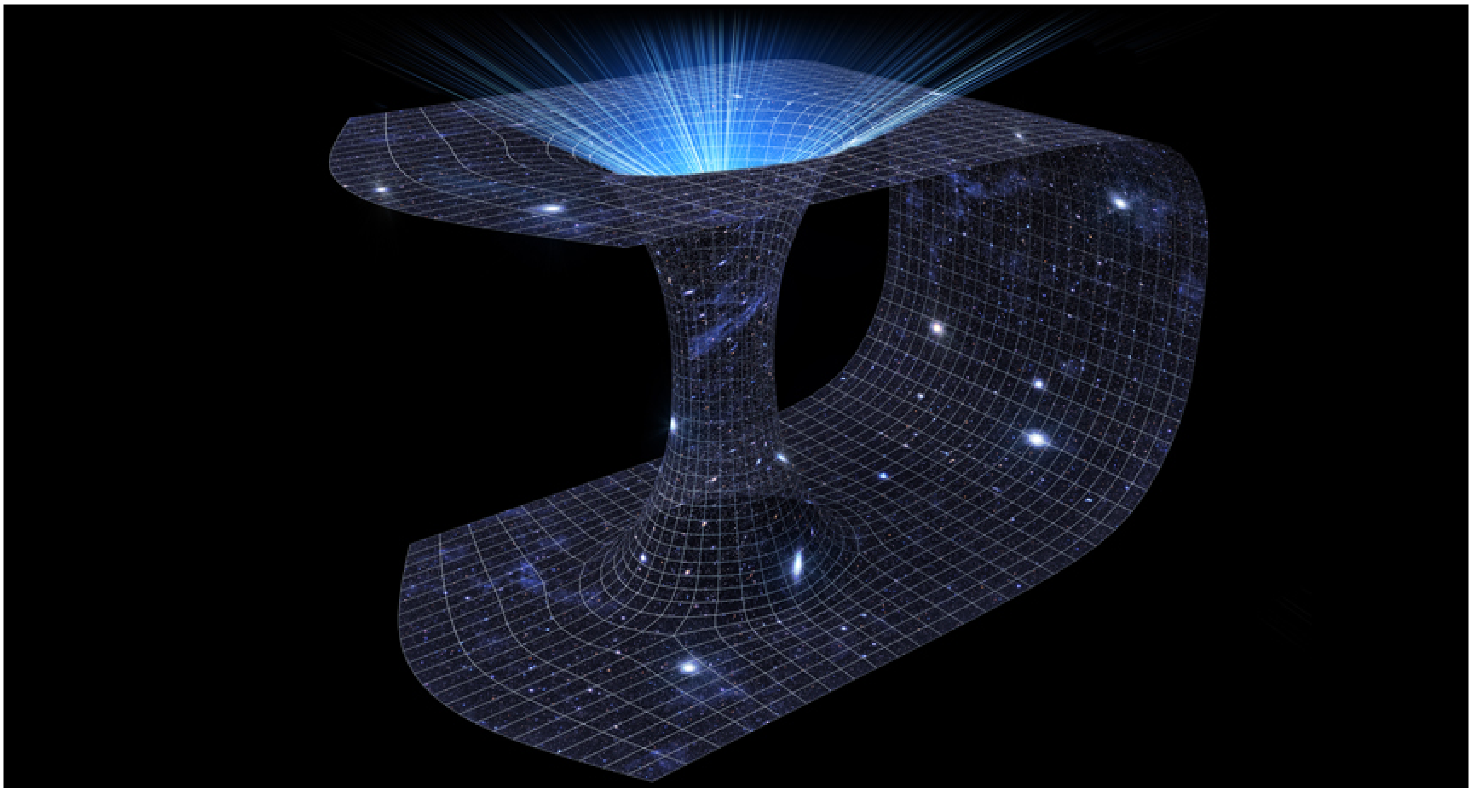
Quantum Physics

A new 'Einstein' equation suggests wormholes hold key to quantum gravity

ER=EPR summarizes new clues to understanding entanglement and spacetime

By Tom Siegfried 7:00am, August 17, 2016



Wormholes, tunnels through the fabric of spacetime that connect widely separated locations, are predicted by Einstein's general theory of relativity. Some physicists think that wormholes could connect black holes in space, possibly providing a clue to the mysteries of quantum entanglement and how to merge general relativity with quantum mechanics.
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There's a new equation floating around the world of physics these days that would make Einstein proud.

It's pretty easy to remember: ER=EPR.

You might suspect that to make this equation work, P must be equal to 1. But the symbols in this equation stand not for numbers, but for names. E, you probably guessed, stands for Einstein. R and P are initials — for collaborators on two of Einstein's most intriguing papers. Combined in this equation, these letters express a possible path to reconciling Einstein's general relativity with quantum mechanics.

Quantum mechanics and general relativity are both spectacularly successful theories. Both predict bizarre phenomena that defy traditional conceptions of reality. Yet when put to the test, nature always complies with each theory's requirements. Since both theories describe nature so well, it's hard to explain why they've resisted all efforts to mathematically merge them. Somehow, everybody believes, they must fit together in the end. But so far nature has kept the form of their connection a secret.

ER=EPR, however, suggests that the key to their connection can be found in the spacetime tunnels known as wormholes. These tunnels, implied by Einstein's general relativity, would be like subspace shortcuts physically linking distant locations. It seems that such tunnels may be the alter ego of the mysterious link between subatomic particles known as quantum entanglement.

For the last 90 years or so, physicists have pursued two main quantum issues separately: one, how to interpret the quantum math to make sense of its weirdness (such as entanglement), and two, how to marry quantum mechanics to gravity. It turns out, if ER=EPR is right, that both questions have the same answer: Quantum weirdness can be understood only if you understand its connection to gravity. Wormholes may forge that link.

Wormholes are technically known as Einstein-Rosen bridges (the "ER" part of the equation). Nathan Rosen collaborated with Einstein on a paper describing them in 1935. EPR refers to another paper Einstein published with Rosen in 1935, along with Boris Podolsky. That one articulated quantum entanglement's paradoxical puzzles about the nature of reality. For decades nobody seriously considered the possibility that the two papers had anything to do with one another. But in 2013, physicists Juan Maldacena and Leonard Susskind proposed that in some sense, wormholes and entanglement describe the same thing.

In a recent paper, Susskind has spelled out some of the implications of this realization. Among them: understanding the wormhole-entanglement equality could be the key to merging quantum mechanics and general relativity, that details of the merger would explain the mystery of entanglement, that spacetime itself could emerge from quantum entanglement, and that the controversies over how to interpret quantum mechanics could be resolved in the process.

"ER=EPR tells us that the immensely complicated network of entangled subsystems that comprises the universe is also an immensely complicated (and technically complex) network of Einstein-Rosen bridges," Susskind writes. "To me it seems obvious that if ER=EPR is true it is a very big deal, and it must affect the foundations and interpretation of quantum mechanics."

Entanglement poses one of the biggest impediments to understanding quantum physics. It happens, for instance, when two particles are emitted from a common source. A quantum description of such a particle pair tells you the odds that a measurement of one of the particles (say, its spin) will give a particular result (say, counterclockwise). But once one member of the pair has been measured, you instantly know what the result will be when you make the same measurement on the other, no matter how far away it is. Einstein balked at this realization, insisting that a measurement at one place could not affect a distant experiment (invoking his famous condemnation of "spooky action at a distance"). But many actual experiments have confirmed entanglement's power to defy Einstein's preference. Even though (as Einstein insisted) no information can be sent instantaneously from one particle to another, one of them nevertheless seems to "know" what happened to its entangled partner.

Ordinarily, physicists speak of entanglement between two particles. But that's just the simplest example. Susskind points out that quantum fields — the stuff that particles are made from — can also be entangled. "In the vacuum of a quantum field theory the quantum fields in disjoint regions of space are entangled," he writes. It has to do with the well-known (if bizarre) appearance of "virtual" particles that constantly pop in and out of existence in the vacuum. These particles appear in pairs literally out of nowhere; their common origin ensures that they are entangled. In their brief lifetimes they sometimes collide with real particles, which then become entangled themselves.

Now suppose Alice and Bob, universally acknowledged to be the most capable quantum experimenters ever imagined, start collecting these real entangled particles in the vacuum. Alice takes one member of each pair and Bob takes the other. They fly away separately to distant realms of space and then each smushes their particles so densely that they become a black hole. Because of the entanglement these particles started with, Alice and Bob have now created two entangled black holes. If ER=EPR is right, a wormhole will link those black holes; entanglement, therefore, can be described using the geometry of wormholes. "This is a remarkable claim whose impact has yet to be appreciated," Susskind writes.

Even more remarkable, he suggests, is the possibility that two entangled subatomic particles alone are themselves somehow connected by a sort of quantum wormhole. Since wormholes are contortions of spacetime geometry — described by Einstein's gravitational equations — identifying them with quantum entanglement would forge a link between gravity and quantum mechanics.

In any event, these developments certainly emphasize the importance of entanglement for understanding reality. In particular, ER=EPR illuminates the contentious debates about how quantum mechanics should be interpreted. Standard quantum wisdom (the Copenhagen interpretation) emphasizes the role of an observer, who when making a measurement "collapses" multiple quantum possibilities into one definite result. But the competing Everett (or "many worlds") interpretation says that the multiple possibilities all occur — any observer just happens to experience only one consistent branching chain of the multiple possible events.

In the Everett picture, collapse of the cloud of possibilities (the wave function) never happens. Interactions (that is, measurements) just cause the interacting entities to become entangled. Reality, then, becomes "a complicated network of entanglements." In principle, all those entangling events could be reversed, so nothing ever actually collapses — or at least it would be misleading to say that the collapse is irreversible. Still, the standard view of irreversible collapse works pretty well in practice. It's never feasible to undo the multitude of complex interactions that occur in real life. In other words, Susskind says, ER=EPR suggests that the two views of quantum reality are "complementary."

Susskind goes on to explore in technical detail how entanglement functions with multiple participants and describes the implications for considering entanglement to be equivalent to a wormhole. It remains certain, for instance, that wormholes cannot be used to send a signal through space faster than light. Alice and Bob cannot, for instance, send messages to each other through the wormhole connecting their black holes. If they really want to talk, though, they could each jump into their black hole and meet in the middle of the wormhole. Such a meeting would provide strong confirmation for the ER=EPR idea, although Alice and Bob would have trouble getting their paper about it published.

In the meantime, a great many papers are appearing about ER=EPR and other work relating gravity — the geometry of spacetime — to quantum entanglement. In one recent paper, Caltech physicists ChunJun Cao, Sean M. Carroll and Spyridon Michalakis attempt to show how spacetime can be “built” from the vast network of quantum entanglement in the vacuum. “In this paper we take steps toward deriving the existence and properties of space itself from an intrinsically quantum description using entanglement,” they write. They show how changes in “quantum states” — the purely quantum descriptions of reality — can be linked to changes in spacetime geometry. “In this sense,” they say, “gravity appears to arise from quantum mechanics in a natural way.”

Cao, Carroll and Michalakis acknowledge that their approach remains incomplete, containing assumptions that will need to be verified later. “What we’ve done here is extremely preliminary and conjectural,” Carroll writes in a recent blog post. “We don’t have a full theory of anything, and even what we do have involves a great deal of speculating and not yet enough rigorous calculating.”

Nevertheless there is a clear sense among many physicists that a path to unifying quantum mechanics and gravity has apparently opened. If it’s the right path, Carroll notes, then it turns out not at all to be hard to get gravity from quantum mechanics — it’s “automatic.” And Susskind believes that the path to quantum gravity — through the wormhole — demonstrates that the unity of the two theories is deeper than scientists suspected. The implication of ER=EPR, he says, is that “quantum mechanics and gravity are far more tightly related than we (or at least I) had ever imagined.”

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