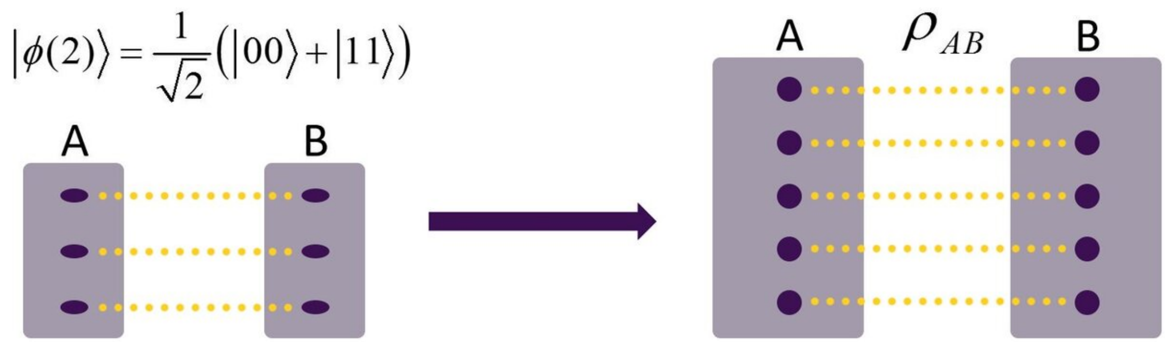
Healing an Achilles' heel of quantum entanglement

July 29 2020



Louisiana State University physicist Mark Wilde and Xin Wang of Baidu Research's mathematical formula, called κ entanglement or max-logarithmic negativity (upper left) makes it possible to effeciently calculate the cost of entanglement, which in itself is an entanglement measure, in the creation of a two-party quantum state. Credit: Mark Wilde, LSU

Louisiana State University Associate Professor of Physics Mark M. Wilde and his collaborator have solved a 20-year-old problem in quantum information theory on how to calculate entanglement cost—a way to measure entanglement—in a manner that's efficiently computable, useful, and broadly applicable in several quantum research areas.

In a new paper published in *Physical Review Letters*, Wilde and co-author

Dr. Xin Wang of Baidu Research describe how allowing a slightly wider range of physical operations than what's known as LOCC (local operations and classical communication)—which have boggled quantum scientists with difficult math for some time—makes it possible to characterize the exact entanglement cost of a given quantum state. Their work closes a longstanding investigation in entanglement theory that is known as the "PPT exact entanglement cost of a quantum state."

Quantum information science aims to understand and control the strange and sometimes spooky properties of quantum states (that is, entangled states) that enable information processing tasks that are impossible in the non-quantum world, such as teleportation, quantum computing, and absolutely secure communication.

The most basic unit of entanglement is known as a Bell state. You can think of it as the smallest possible molecule consisting of two entangled atoms (qubits, really) whose entanglement is absolute—implying, if you could peek at one of them, you would know beyond a doubt that the other one would be its twin, with the same characteristics. Like two people flipping a coin; if one person gets tails, which reasonably is a 50/50 chance, the other would be guaranteed to get tails (or they both get heads, same thing), a consequence of absolute entanglement or a Bell state. Additionally, no one else in the universe can know the exact outcome of the coin toss, and this is the main reason why secured communication based on quantum entanglement is possible as well as desirable.

"Quantum entanglement is a kind of super-correlation that two distant parties share," Wilde explained. "If the world were described by classical physics only, then it would not be possible to have the strong correlations available with quantum entanglement. However, our world is fundamentally quantum mechanical, and entanglement is an essential feature of it."

When quantum entanglement was first discovered in the 1930s, it was thought to be a nuisance because it was difficult to understand, and unclear what its benefits would be. But with the rise of quantum information science in the 1990s, it was understood in a theoretical sense as the key to remarkable quantum technologies. Recent examples of such technologies include the Chinese teleportation experiment from ground to satellite in 2017 as well as Google's quantum-computational supremacy achievement last year.

At LSU, quantum physicists like Omar Magaña-Loaiza and Thomas Corbitt routinely perform experiments that could benefit from Wilde and Wang's new and more precise measure. In their respective labs, Magaña-Loaiza recently generated entangled states via conditional measurements, which constitutes an important step in the development of entangled laser-like systems, while Corbitt performed a study of optomechanical entanglement, which has the potential to be a reliable source of multiphoton entanglement at short wavelengths. Wilde and Wang's new entanglement measure, called κ entanglement or max-logarithmic negativity, can be used to assess and quantify the entanglement produced in a wide range of quantum-physical experiments.

Basic entanglement units or Bell states are also known as e-bits. Entanglement can be looked at in two different ways: either how many e-bits it would take to prepare a quantum state, or how many e-bits one could extract or "distill" from a complex entangled state. The former is known as entanglement cost and is the problem Wilde and Wang considered.

"E-bits are a precious resource and you want to use as few of them as possible," Wilde said. "In physics, you often want to look at both the forwards process and the backwards process. Is it reversible? And if it is, do I lose something along the way? And the answer to that is yes."

Wilde admits the problem he and Wang have solved is somewhat esoteric—a mathematical trick. However, it will allow quantum information scientists to efficiently calculate entanglement costs given certain constraints.

"Not all entanglement measures are efficiently computable and have a meaning such as entanglement cost. That is a key distinction between all previous work and ours," Wilde added.

While the lack of this kind of measure has been an Achilles' heel in quantum information science for over 20 years, it was—ironically—Wilde becoming max-negatively "entangled" during a game of basketball in 2018 that led to him and Wang eventually solving the problem.

"I ruptured my Achilles' heel while going for the winning point of the game, then had surgery to repair it, and couldn't get out of bed for a month and a half," Wilde remembers. "So, I wrote a research paper about entanglement cost, and when Xin Wang learned about it, he asked me if I would be interested in developing this problem further. We then started working together, back and forth, and that became the paper we now have published in *Physical Review Letters*. We became good friends and collaborators after that—it is remarkable the surprises that can occur in life."

More information: Xin Wang et al, Cost of Quantum Entanglement Simplified, *Physical Review Letters* (2020). DOI: 10.1103/PhysRevLett.125.040502

Provided by Louisiana State University

Citation: Healing an Achilles' heel of quantum entanglement (2020, July 29) retrieved 22 September 2024 from https://phys.org/news/2020-07-achilles-heel-quantum-entanglement.html

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