ER = EPR? Topology and Quantum Entanglement

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Abstract

Maldacena & Susskind's "ER=EPR" hypothesis claims that two physical systems in a quantum entangled ("EPR", or Einstein-Podolsky-Rosen) state are connected by an Einstein-Rosen ("ER") wormhole. More generally, it claims that spacetime topology is the "dual" of quantum entanglement: physical systems in a quantum entangled state can be described as systems connected by a wormhole, and *vice-versa*. Our project's goals are to assess the motivations for "ER=EPR", including AdS /CFT theory and the Black Hole Firewall Problem, and to construct a conceptual map that relates characteristics of wormholes to characteristics of entanglement.

Motivations for ER=EPR [1]

1. Correspondence between extended AdS-Schwarzschild spacetime and entangled vacuum state of a CFT.
2. Resolves Firewall Problem.
3. No superluminal signals, and no creation and/or increase by LOCC.

Firewall Paradox

(i) *B* is maximally entangled with *A*.

(ii) *B* is maximally entangled with R_B.

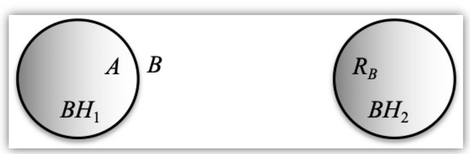
(iii) *B* cannot be maximally entangled with two systems.

ER=EPR Resolution

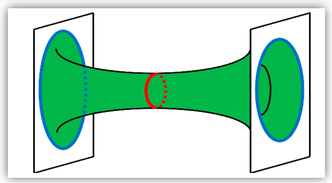
Deny (i): When R_B is distilled, it "disrupts" *A* via a wormhole connection.

Conceptual Map

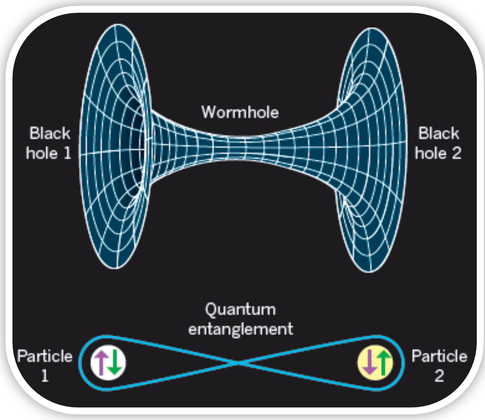
Quantum Entanglement	Wormhole
Entanglement Entropy $S_A = -Tr(\rho_A \log \rho_A)$ Used to describe the extent to which a bipartite system AB is entangled.	Maximin Cross-Sectional Area of Throat *Under ER=EPR, a wormhole's maximin cross-sectional area is considered the dual of entanglement entropy.
No Superluminal Signaling Quantum entanglement cannot be used to send superluminal signals.	Non-traversability Any future-directed curve that passes through a wormhole must become space-like along some of its extent.
Quantum Cloning [2] If a multipartite entangled state is the result of cloning one of the substates B of a bipartite entangled state AB, and: (1) all B-clones remain entangled with A; (2) entanglements of different subsystems do not influence each other; then it facilitates superluminal signaling.	Topology Change If a wormhole has formed as a result of topology change, and if it violates the null energy condition, then it is traversable, which indicates superluminal signaling.
Entanglement Non-detectability There is no observable that represents entanglement in terms of a linear operator.	Wormhole Non-detectability There is no local curvature measurement that can distinguish between a one-sided black hole spacetime and a two-sided black hole (i.e., wormhole) spacetime.
Entanglement Conservation For a bipartite system AB, the entanglement entropy S_A of subsystem A is invariant under local operations.	Area Conservation The maximin cross-sectional area of a wormhole is invariant under local operations performed near its mouths.
Entanglement Monogamy [3] If A and B are maximally entangled, then neither A nor B is entangled with any other system C.	Wormhole Monogamy If a "maximal" wormhole connects regions A and B, then neither A nor B can be connected by a wormhole to any other region C.



P1. An Illustration of Firewall Paradox



P2. Maximin Cross Sectional Area of Throat



Future Work

We have now created a conceptual map between entanglement and wormholes. While this map exposes intriguing relations that support ER=EPR, additional questions remain. First, we need to further specify the meaning of non-detectability, since it risks making ER=EPR unverifiable. Second, entanglement monogamy is potentially contradictory to ER=EPR's resolution to the Firewall Paradox: RB cannot be wormhole-connected with A since it is maximally entangled with B. Finally, more conceptual work could be done on the relation between ER=EPR and recent derivations of the Einstein equations from entanglement first principles.

Select Works Cited

[1] Maldacena, J. & L. Susskind (2013) "Cool Horizons for Entangled Black Holes", *Fortschritte der Physik 61*, 781.

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[3] Gharibyan, H. & R. Penna (2014) "Are entangled particles connected by wormholes? Evidence forthe ER ¼ EPR conjecture from entropy inequalities", *Physical Review D 89*, 066001-1.

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