Spacetime and Entanglement

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Abstract

This project seeks to investigate a proposed solution to the longstanding discontinuity between the well tested theories of the Standard Model of Quantum Physics and Albert Einstein's classical theory of General Relativity. Mark van Raamsdonk's entanglement/ connectedness hypothesis proposes that quantum entanglement is the geometric glue that holds spacetime together. To assess the claim we build a conceptual analysis of differing notions of entanglement (quantum entanglement, geometrical entanglement, topological entanglement), non-locality, and various measurements of entropy (entanglement entropy, black hole entropy, thermodynamic entropy). Finally we build a bridge between van Raamsdonk and Juan Maldecena and Leonard Susskind's ER=EPR hypothesis, which proposes that quantum entangled particles are linked by wormholes in spacetime.

Mark van Raamsdonk's Entanglement/Connectedness Hypothesis

Mark van Raamsdonk's hypothesis claims that entanglement on the boundary of a region corresponds to connectedness in the bulk of the region. [1] One of his main motivations behind this is the Ryu-Takayanagi formula. [2]

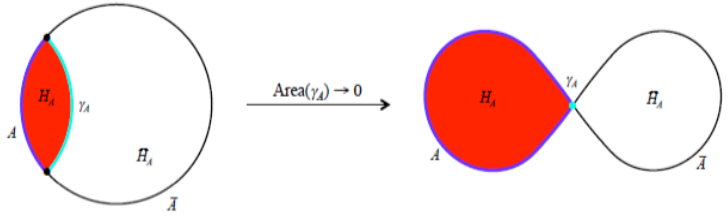
Quantum Entanglement on Boundary = **Local Bulk Geometry** + **Global Bulk Topology?**

Entanglement Correlations — Connectedness — Noncontractible nonlocality

Ryu-Takayanagi Formula

$$S_A = \frac{Area(\gamma_A)}{4G} + \Gamma^* \quad [2]$$

$$|\Psi\rangle = \sum_{i,j} p_{i,j} |\psi_i^A\rangle \otimes |\psi_i^{\bar{A}}\rangle \xrightarrow{S_A \to 0} |\Phi\rangle = \left(\sum_i c_i |\psi_i^A\rangle\right) \otimes \left(\sum_j d_j |\psi_i^{\bar{A}}\rangle\right)$$



$H_A \cup \bar{H}_A$ is a connected space.

$H_A \cup \bar{H}_A$ is a disconnected space.

Notions of Entropy

Boltzmann Entropy	Thermodynamic Entropy	Bekenstein-Hawking Entropy (black hole entropy)	Entanglement Entropy in AdS/ CFT [2]
A measure of the amount of microstates in a given macrostate	Ratio of the change in heat over temperature for a given reversible process	$S_{BH} \equiv (\text{area of horizon})/4G$	$S_A = (\text{area of } \gamma_A)/4G_N^{(d+2)}$
Interpreted as measuring uncertainty Under certain circumstances can be identified with thermodynamic entropy	Not interpreted as a measure of uncertainty Obeys 2nd Law of Thermodynamics	Motivated by potential violations with 2nd Law of Thermodynamics Related to thermodynamic entropy	Measurement of entanglement on the boundary derived from von Neumann entropy $S(\rho) \equiv -tr(\rho \log \rho)$

Notions of Entanglement [3]

Quantum Entanglement	Geometric Entanglement*	Topological Entanglement
Boundary	Bulk	Bulk
Spooky action at a distance	Emergent connectedness	Mechanism of entanglement
Entangled vector states of bipartite systems in tensor space		Entangling braid operator

*the notion of geometric entanglement is not as well understood as quantum or topological entanglement

Future Work

Now that we have created a conceptual framework of varying notions of entropy, entanglement, and non-locality, we can now use this, along with the van Raamsdonk hypothesis, to tackle the ER=EPR hypothesis. The ER=EPR hypothesis claims that wormholes and quantum entanglement are the same thing under differing viewpoints, much like electricity and magnetism. If the ER=EPR hypothesis holds up, this could have profound implications for all of physics, as the hypothesis unites a fundamental quantum mechanics concept with a fundamental general relativity concept.

Works Cited

[1] Van Raamsdonk (2010) 'Building Up Spacetime with Quantum Entanglement', *GRG 42*, 2323.
[2] Ryu, S. & T. Takayanagi (2006) "Holographic Derivation of Entanglement Entropy from the AdS/CFT Correspondence", *Phys Rev Let 96*, 181602.
[3] Kauffman, L. & S. Lomonaco (2002) 'Quantum entanglement and topological entanglement', *New Journal of Physics 4*, 73.

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