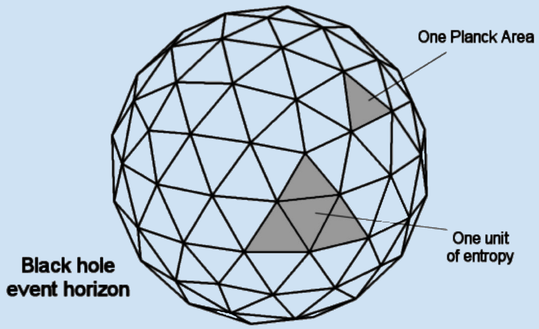
A Survey of Theories of Quantum Gravity and Their Respective Approaches to the Information Paradox

Logan Fisher & Dr. Timm Wrase
Department of Physics, Lehigh University, Bethlehem, PA 18015

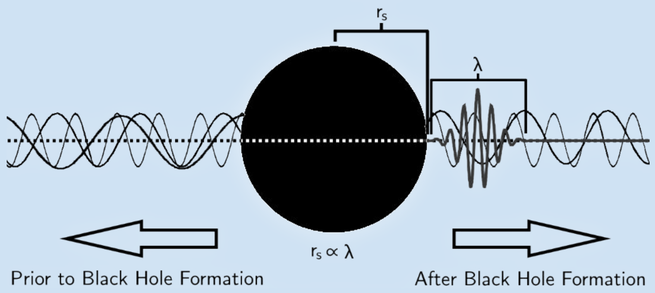
Foundations

Information: Structured and implicitly meaningful data inherent to the description of a physical system. On the quantum scale, this is measured in terms of the Von Neumann entropy of a system, given by $S=-Tr(\rho \cdot ln(\rho))$ [1]. Quantum information is necessarily conserved as a consequence of the unitarity of the S-matrix [2].

The Bekenstein Bound: Relates information with the curvature of space-time via a limit on information densities at which a black hole is formed. In terms of Von Neumann entropy, this is given by $S(\rho_V)-S(\rho_{V^0})\leq Tr(K\rho_V)-Tr(K\rho_{V^0})$ [3]. The information in question is proportional to the surface area of the black hole, not its volume [4].



Hawking Radiation: The process by which black holes decay over time. This phenomena is best described in terms of the scattering of the vibrational modes of a quantum field in a vacuum state tracing a null geodesic, resulting in fluctuations that to a distant observer appear as particles leaving the region of the black hole [5].

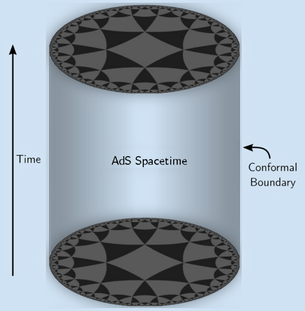


The Information Paradox: The black hole itself must lose mass and thereby shrink, implying a loss of information, but there is no known mechanism by which Hawking radiation could remove information from the black hole. In accordance with the Bekenstein bound, this implies a loss information, creating a violation of the unitarity of the S-matrix [6].

String Theory

The Holographic Principle: Derived from the black hole complementarity conjecture that copies of information are space-like separated by event horizons, we find that the 3D structure can be entirely described by the 2D surface [2]. This is then exemplified by the Bekenstein bound.

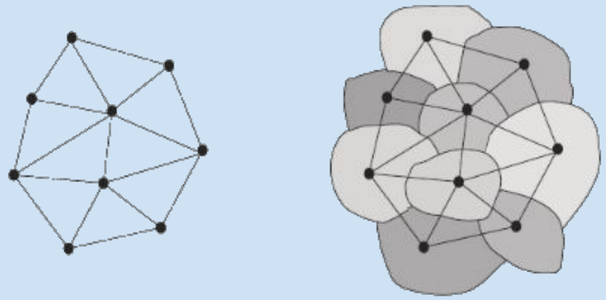
AdS/CFT Correspondence: A realization of the holographic principle - AdS/CFT is a relationship between perturbative gravity in D dimensions with constant negative curvature and a non-perturbative Weyl-invariant unitary QFT of D-1 dimensions. As such a field theory must be unitary, information is therefore conserved for an AdS spacetime [7]. While not necessarily unique to string theory, all examples have been found in the context of string theory or later found to be embeddable into string constructions.



Loop Quantum Gravity

LQG: A theory in which the universe is comprised of Planck-scale loops together forming a “spin network” creating a granular space with gravity as an embedded feature. As a spin network evolves over time, it forms a “spin foam” [8].

Planck Stars: Under the assumption of a quantized space, infalling matter in a black hole is limited to the Planck energy density in the form of some exotic matter - further compression would require the violation of the uncertainty principle. This negates the information paradox by creating an internal structure to the black hole into which information may be encoded [9].



A spin network and the discretized space regions created by it

Citations

[1] Ingemar Bengtsson and Karol Zyczkowski. Geometry of quantum states: An introduction to quantum entanglement. Cambridge University Press, 1st edition, 2017.
[2] Leonard Susskind and James Lindesay. An Introduction to Black Holes, Information and the String Theory Revolution - The Holographic Universe. World Scientific, 2010.
[3] Casini. Relative entropy and the Bekenstein bound. Classical and Quantum Gravity, 25(20), 2008.
[4] Jacob D. Bekenstein. How does the Entropy/Information Bound Work? Foundations of Physics, 35(11):1805–1823, 11 2005.
[5] S. W. Hawking. Particle Creation by Black Holes. Communications in Mathematical Physics, 43(3), 1975.
[6] Xavier Calmet and Stephen D. H. Hsu. A Brief History of Hawking’s Information Paradox. 7 2022.
[7] Barton Zwiebach. A First Course in String Theory - B.Zwiebach.pdf, 2004.
[8] Seth A. Major. A Spin Network Primer. arXiv, 5 1999.
[9] Carlo Rovelli and Francesca Vidotto. Planck stars. arXiv, 1 2014.