Analogue quantum black hole models and the Hayden-Preskill protocol

Tanay Kibe,[a] **Ayan Mukhopadhyay,**[a] **Alexander Soloviev,**[b] **and Hareram Swain**[a]

[a] *Department of Physics, Indian Institute of Technology Madras, Chennai 600036, India*

[b] *Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794, USA*

Abstract: Black holes past their Page time have intriguing information processing properties such as the rapid encoding of infalling qubits into the Hawking radiation. Taking inspiration from the fragmentation of the near horizon geometry of a near-extremal black hole, we have constructed a model that can reproduce some of the information processing properties of a black hole. Our model is a lattice of two dimensional nearly AdS spacetimes. We show that our model reproduces the Hayden-Preskill protocol of information mirroring. We also construct generalizations of our model that are analogous to tensor networks of SYK spin-states

Keywords: Quantum black holes, holographic principle, quantum information theory, tensor networks

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Extended Abstract

Ideas from quantum information theory have provided deep insights into the many puzzles surrounding information processing properties of quantum black holes. Treating the black hole interior and the Hawking radiation [1, 2] as a bipartite system we can compute the entanglement entropy of the radiation subsystem. Assuming the process of black hole evaporation is unitary, we are then led to the hypothesised Page curve for the entanglement entropy of the radiation [3, 4], which needs to be reconciled with Hawking's original computation [1]. After the Page time, the entanglement entropy of the Hawking radiation should decrease. This implies that the information about the formation of the black hole is gradually revealed after the Page time. One easy way to avoid other information paradoxes discussed by Mathur [5], Braunstein, Pirandola and Zyczkowski [6] and Almheiri, Marolf, Polchinski and Sully [7], is to argue that the Hawking radiation post Page time has sufficient complexity [8]. This implies that the time it takes to decode the Hawking radiation scales exponentially with the black hole entropy (at the Page time). Since the black hole evaporation time scales polynomially with its entropy, it follows that the thought experiments involved in the information paradoxes mentioned before are not realizable even in principle. Modelling black holes as quantum circuits, Hayden and Preskill have argued that black holes act as quantum information mirrors [9]. If Alice throws some quantum information inside the black hole after the Page time, it eventually leaks out after the Hayden-Preskill time. Bob can obtain this information by performing a decoding operation on the Hawking radiation. The act of the black hole revealing what falls in later first is called information mirroring.

Thus we see that quantum black holes have very interesting information processing properties. In this work, we are motivated to understand some of the underlying mechanisms of the information processing properties of quantum black holes, particularly fast scrambling and information mirroring. In order to do this we have constructed a concrete phenomenological model and have studied its dynamics. We take inspiration from the fragmentation of the near horizon geometry of near extremal black holes into multiple AdS_2 throats [10, 11]. A large number of low energy states arise at the boundary of the instanton moduli space when any two of the AdS_2 throats come within sub-Planckian distances of each other. We refer to these low energy gapless excitations as *hair*. Our model black hole consists of two main ingredients: (i) a lattice of nearly AdS_2 throat geometries each described by Jackiw-Teitelboim (JT) gravity [12, 13], (ii) quantum hair carrying $SL(2,R)$ charges that propagate over the lattice. We find that our model is phenomenologically viable for a particular coupling between the AdS_2 throats and the hair. We show that our model captures the semi-classical features of a black hole and also demonstrate an explicit realization of the Hayden-Preskill protocol for information mirroring. We also construct generalizations of our model involving a network of AdS_2 geometries connected via wormholes. These networks are analogous to tensor networks of SYK spin-states [14]

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