

Quantum superchannels are a fundamental concept in quantum information theory, extending the idea of quantum channels to encompass higher-order transformations. Quantum information theory, a relatively new field at the intersection of quantum mechanics and information theory, explores how information is stored in quantum systems, processed, and transmitted using the principles of quantum mechanics. While quantum channels represent physical processes that map quantum states (represented by density matrices) to other quantum states, superchannels describe transformations that act on quantum channels themselves — mapping one quantum channel to another. For instance, a quantum process like quantum decoherence can be modeled by a quantum channel that captures the loss of coherence in a quantum system due to interactions with its environment. Such a channel transforms a quantum state into a classical state, typically represented by a diagonal density matrix. Analogously, superdecoherence refers to a process modeled by a quantum superchannel, where a quantum channel is transformed into a classical channel, represented by a diagonal Choi matrix.

From a mathematical perspective, quantum channels are described by completely positive trace-preserving maps. Quantum superchannels, on the other hand, are represented by completely positive bipartite maps with additional properties ensuring that when they act on a trace-preserving input map, the output remains trace-preserving. Notably, this additional property is connected to a critical concept in quantum information: non-signaling, which ensures that information cannot be transmitted instantaneously between distant parties.

This project proposes an in-depth exploration of quantum superchannels. Specifically, we aim to investigate how the quantum evolution of open quantum systems — systems interacting with their environments—can be modeled in terms of specific superchannels. These superchannels map an initial quantum channel (such as the identity map) to a channel at a later time, thereby generalizing the concept of a quantum dynamical map to the level of supermaps.

Part of the project focuses on constructing superchannels to define higher-order transformations with specific properties. A key property of interest is covariance under symmetry groups. We intend to examine symmetry groups that are significant in quantum information theory and extend symmetry requirements to the supermap level.

Additionally, we will explore potential applications of supermap techniques. One such avenue involves analyzing the nonlocal properties of bipartite quantum channels — channels that act on correlated quantum states shared between two parties, often referred to as Alice and Bob. There is an intricate relationship between nonlocality in composite quantum states and nonlocality in quantum channels. We aim to uncover new insights into this relationship, advancing our understanding of quantum superchannels and opening new pathways for their application in quantum information theory.