Characterizing nonclassicality in quantum networks

Bell's theorem can be understood as a conflict between correlations one sees in a Bell experiment and the causal relations one believes hold between the separate labs when the correlations are analyzed in terms of classical causal models. This motivates the study of causality in the quantum realm, specifically how it differs from classical causality in a distributed setting. This project will deploy quantum causal models for analyzing quantum networks.

Firstly, we will develop applications of the framework of (split-node) quantum causal models by considering natural generalizations of the classical and quantum causal compatibility problems to scenarios where the parties are allowed to implement arbitrary quantum instruments and send out quantum systems to other parties.

Secondly, it has been recently demonstrated that classical examples of indefinite causality can simulate quantum nonlocality without entanglement. This has opened a causality-inspired path to characterizing the gap between local operations and classical communication vs. separable operations. We will follow up on this insight to isolate the sources of nonclassicality that can drive quantum advantage in distributed settings where SEP provides an advantage over LOCC. We will also investigate the possibility of local implementation of operations beyond SEP using indefinite causal order.

Finally, we will conduct an in depth investigation of a recently proposed notion of nonclassicality for correlations without causal order order, termed antinomicity. In particular, we will investigate whether unitary processes can witness antinomicity and, if not, whether antinomicity is then a device independent witness of the impossibility of a causal account within the quantum causal models framework. We will also investigate if antinomicity admits a mapping to an operational task in quantum information, thereby acquiring an operational meaning. Overall, this project will address fundamental questions about quantum networks and open new pathways to their deployment in quantum technologies.