Abstract

Quantum mechanics is fuelling the most significant technological advances of the twenty-first century. Underneath this remarkable feat is the phenomenon of *quantum advantage*, which refers to quantum resources and protocols outperforming their traditional counterparts in countless computational, communication, and information processing tasks. On the other hand, even after almost a century since its conception, there is no consensus about the structure of physical reality that quantum theory posits. Conceived specifically to address such questions, the realist framework featuring the *realist notions of classicality* such as Bell's local-causality, attempts to formalize what is meant by a "classical" description of reality. The operational quantum violation of these notions makes precise how quantum description of reality departs from classical worldviews. This dissertation bridges the gap between these seemingly disconnected aspects of quantum theory.

What does quantum communication advantage reveal about the structure of reality posited by quantum theory? The *first* article addresses this question and demonstrates that quantum advantage in a broad spectrum of communication tasks reveals the contextuality of quantum preparations.

Could there be a deeper realist notion whose violations directly fuel all of quantum communication advantage? The *second* article introduces such a realist notion of classicality, termed *bounded ontological distinctness* (BOD). BOD requires the operational distinguishability of physical entities to be explained exclusively by the distinctness of their realist counterparts. The quantum violation of the operational consequences of BOD implies that quantum physical entities must be more distinct in reality than they are operationally distinguishable. This excess ontological distinctness of quantum physical entities powers quantum advantage in communication tasks. BOD unifies the realist framework as it implies all other realist notions of classicality, and their quantum violations imply the quantum violation of BOD.

Apart from the foundational relevance of the fact, the maximal extent to which quantum theory violates the realist notions of classicality limits quantum advantage. The *third* article fulfills a long-standing desideratum by formulating *a theory-independent framework* and *a hierarchy of semidefinite programming relaxations* to characterize and bound the set of quantum behaviors that violate generalized noncontextuality. The theory-independent framework allows the recovery of several characteristic properties of the set of quantum behaviors in contextuality scenarios. The hierarchy retrieves tight bounds on the maximal quantum violation of several noncontextuality inequalities and enables the security proof of a novel semi-device independent quantum key distribution scheme powered by contextuality.

The *fourth* article introduces a generalization of the extensively studied, foundationally and cryptographically relevant class of communication tasks called *random access codes* and studies the performance of classical and quantum resources therein.