Algorithms for quantum causal discovery

Christina Giarmatzi[a] and Alexei Gilchrist[b]

[a]*Centre for Engineered Quantum Systems, University of Technology Sydney, Australia*

[b]*Centre for Engineered Quantum Systems, Macquarie University, Sydney, Australia*

Correlation does not imply causation—but then what does, especially in the quantum world? The discovery of causal relations is the basis of every scientific discipline, yet, a formal framework has been developed only recently. While it is now clear that to discover the causal relation between two classical events, one has to intervene on one and observe changes in the other, quantum causal relations are not that straightforward. As quantum devices increase in size and complexity, causal discovery tasks will be increasingly necessary, either as part of the algorithm or for the device's characterisation protocol to know all the causes and effects and the presence of noise. We use a recently proposed framework for quantum causal models [1, 2] to develop computational and statistical tools for quantum causal discovery. We provide a suite of methods to discover the causal model of a quantum process. First, we improve an existing quantum causal discovery algorithm [3] for better performance and write it as an open-source Python module. The algorithm inputs data from full process tomography and outputs a quantum causal model and the precise mechanisms behind the causal relations. Then, we develop witnesses of quantum causal orders [4] that require far fewer measurements and output the underlying causal order. Lastly, we build Machine Learning techniques for causal discovery requiring even fewer measurements for a more experimentally-friendly method or to be used when the previous methods have reached their computational limit. This is the first complete toolkit for quantum causal discovery, taking into account experimental and computational limitations. It aims to provide the basis for our future quantum causal discovery needs as part of the quantum software and testing of future quantum devices.

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[4] M. Araújo, C. Branciard, F. Costa, A. Feix, C. Giarmatzi, and Č. Brukner, "Witnessing causal non-separability," *New J. Phys.*, vol. 17, no. 10, p. 102001, 2015.