Quantum-Enhanced Causal Inference for High-Dimensional Astronomical Data – Extended Abstract

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Abstract

We propose an approach based on the Fixed-Point Grover search in combinatorial spaces to efficiently identify acyclic causal structures compatible with the PC and FCI causal discovery algorithm's output, paving the way for scalable statistical studies of causal structures in large astrophysical datasets.

Keywords

Causal Discovery, Constraint-based methods, PC algorithm, Boolean Satisfiability (SAT), Quantum search, Fixed-Point Grover algorithm, Astronomical applications

Summary

Causal Discovery provides a principled framework for uncovering causal relationships from observational data – an especially valuable feature in domains like astrophysics, where direct interventions are often impossible. Although its applications in astronomy remain limited, initial results – such as studies of supermassive black hole and host galaxy coevolution – highlight its promise. Existing algorithms, such as the Peter-Clark (PC) and Fast Causal Inference (FCI) methods, along with their emerging quantum counterparts, can infer partial causal structures from data but frequently return graphs with undirected edges due to ambiguities inherent in the underlying statistical dependencies. Among the many graphs compatible with these partial structures, only those that are acyclic (i.e. Directed Causal Graphs, DAGs) are valid causal candidates, making the selection of a suitable graph a non-trivial task. This challenge escalates with dataset dimensionality, as the number of DAGs consistent with observed conditional independencies can grow superexponentially. So far, the application of causal discovery in astrophysics has been made possible only by severely constraining the dimensionality of the problem. However, as the field moves toward higher-dimensional latent representations – such as those extracted from images or spectra – classical approaches may become computationally infeasible. In this context, quantum algorithms offer a promising alternative. We propose a quantum-accelerated approach to structure learning that addresses this problem. Specifically, we explore a variant of Grover's algorithm – the fixed-point Grover search – to efficiently explore the constrained space of acyclic directed graphs compatible with the output of the PC algorithm. To this purpose, we map the PC and FCI constraints into a Boolean satisfiability (SAT) problem and construct a SAT oracle, followed by an acyclicity oracle that either exploits Kahn's algorithm (which relies on the existence of a topological ordering in DAGs) or a frontier-propagation method (that tracks the return to a source node). The two methods offer different trade-offs between circuit width and depth. Within this large combinatorial space, the proposed framework can be used to sample from the set of DAGs consistent with the PC/FCI results, thus enabling the statistical characterization of multiple causal solutions compatible with the observational data.

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The design of this quantum-enhanced causal discovery scheme is intended for future applicability to large-scale astrophysical datasets, contingent on the availability of suitable quantum hardware.

Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

References