

CONSTRAINT-BASED ATTRACTOR SEARCH IN BOOLEAN NETWORKS USING QUANTUM COMPUTING

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ABSTRACT: Quantum information offers a new computing paradigm which may yield further increases in computational resources beyond the limits of miniaturisation for Moore’s law. Various quantum algorithms such as Grover’s search algorithm also offer improvements in complexity when compared to their classical counterparts. In particular, quantum computing can be applied to the context of Boolean network analysis in systems biology. We demonstrate a new quantum algorithm which uses a modified Grover operator to identify attractor states in the dynamics of Boolean networks. This procedure is based on the iterated addition of constraints for previously identified attractors, thus restraining the size of the remaining state space that has to be searched.

KEYWORDS: quantum computing, quantum information, systems biology, network theory

1 Introduction

Boolean networks (BNs) are simple mathematical dynamic models describing gene regulatory interactions (Kauffman, 1969, Schwab *et al.*, 2020). Network components are represented as expressed (1) or not expressed (0). Logical rules combining network components via the operators AND, OR, and NOT describe the system’s interactions. Repeated evaluation of these update rules generates complex dynamics, leading to stable states called attractors. Knowledge of attractors is of interest in the biological context as these states correspond to cellular phenotypes (Huang *et al.*, 2005). The dynamic state space of BNs grows exponentially with the number of components, limiting analyses of larger systems. Motivated by the limits of traditional processors and the search for alternative hardware, we make use of gate-based, universal quantum computers which can perform calculations in an exponentially growing state

space using a linearly increasing number of qubits. Thus, quantum hardware can capture the complexity of the model’s dynamics. In our previous work we implemented BNs on quantum computers, highlighting how quantum algorithms can be used to obtain information about network dynamics (Weidner *et al.*, 2023a, Weidner *et al.*, 2023b).

2 Results

Building on this, we now propose a quantum circuit performing a search through the entire state space based on Grover’s algorithm (Grover, 1997, Liu & Ouyang, 2013), aiming to identify the entire set of attractors. Grover’s algorithm works by iteratively amplifying the weight associated with a specified subset of states, followed by a probabilistic readout of a single possible solution. In contrast, we invert the roles of solution and non-solution states, resulting in a suppression of previously identified attractors. After every readout leading to the detection of a new attractor, this state is then added as a constraint to the quantum circuit in all further runs. In this manner, the search space can be restricted to assign increased weight to states which lead to novel attractors without requiring previous knowledge of the distribution or number of attractors in the system. This also allows for the detection of small attractors which may be difficult to find using a classical random sampling of states. Such attractors may nevertheless be biologically interesting, e.g. in the early detection of rare but drug-resistant phenotypes in a network modeling cancer.

We demonstrate this algorithm on a small biologically motivated Boolean network with attractors of different sizes. We analyse its performance when accounting for the noise present in real quantum processors and quantify the improvement that can be gained from error mitigation techniques. Furthermore, we are investigating the possibility of implementing a constraint-based attractor search using quantum annealers rather than gate-based processors, due to the increased number of qubits available on such devices.

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