

Complexity of limit-cycle problems in Boolean networks

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Abstract

Boolean networks are a general model of interacting entities, with applications to biological phenomena such as gene regulation. Attractors play a central role, and the schedule of entities update is *a priori* unknown. This article presents results on the computational complexity of problems related to the existence of update schedules such that some limit-cycle lengths are possible or not. We first prove that given a Boolean network updated in parallel, knowing whether it has at least one limit-cycle of length k is **NP**-complete. Adding an existential quantification on the block-sequential update schedule does not change the complexity class of the problem, but the following alternation brings us one level above in the polynomial hierarchy: given a Boolean network, knowing whether there exists a block-sequential update schedule such that it has no limit-cycle of length k is **NP^{NP}**-complete.

1 Introduction

Boolean networks (BNs) were introduced by McCulloch and Pitts in the 1940s through the well known formal neural networks [17] that are specific BNs governed by a multi-dimensional threshold function. Informally, BNs are finite dynamical systems in which entities having Boolean states may interact with each other over discrete time. After their introduction, neural networks were studied in depth from the mathematical standpoint. Among the main works on them are the introduction by Kleene of finite automata and regular expression [16], first results on the dynamical behaviors of linear feedback shift register [13] and linear networks [8]. These researches led Kauffman and Thomas (independently) from the end of the 1960s to develop the use of BNs in the context of biological networks modeling [15, 27], which has paved the way to numerous applied works at the interface between molecular biology, computer science and discrete mathematics. In parallel, theoretical developments were done in the framework of linear algebra and numerical analysis by Robert [24], and in that of dynamical system theory and computational models, which constitutes the lens through which we look at BNs in this paper.

In this context, numerous studies have already been led and have brought very important results. Considering that a BN can be defined as a collection of local Boolean

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The Complexity of Boolean Networks Paul E. Dunne, 1988

Complex Networks & Their Applications IX Rosa M. Benito, Chantal Cherifi, Hocine Cherifi, Esteban Moro, Luis Mateus Rocha, Marta Sales-Pardo, 2021-01-04 This book highlights cutting edge research in the field of network science offering scientists researchers students and practitioners a unique update on the latest advances in theory and a multitude of applications It presents the peer reviewed proceedings of the IX International Conference on Complex Networks and their Applications COMPLEX NETWORKS 2020 The carefully selected papers cover a wide range of theoretical topics such as network models and measures community structure network dynamics diffusion epidemics and spreading processes resilience and control as well as all the main network applications including social and political networks networks in finance and economics biological and neuroscience networks and technological networks

Systems Biology Modelling and Analysis Elisabetta De Maria, 2022-12-08 Systems Biology Modelling and Analysis Describes important modelling and computational methods for systems biology research to enable practitioners to select and use the most suitable technique Systems Biology Modelling and Analysis provides an overview of state of the art techniques and introduces related tools and practices to formalize models and automate reasoning for systems biology The authors present and compare the main formal methods used in systems biology for modelling biological networks including discussion of their advantages drawbacks and main applications Each chapter includes an intuitive presentation of the specific formalism a brief history of the formalism and of its applications in systems biology a formal description of the formalism and its variants at least one realistic case study some applications of formal techniques to validate and make deep analysis of models encoded with the formalism and a discussion on the kind of biological systems for which the formalism is suited along with concrete ideas on its possible evolution Edited by a highly qualified expert with significant experience in the field some of the methods and techniques covered in Systems Biology Modelling and Analysis include Petri nets an important tool for studying different aspects of biological systems ranging from simple signaling pathways to metabolic networks and beyond Pathway Logic a formal rule based system and interactive viewer for developing executable models of cellular processes Boolean networks a mathematical model which has been widely used for decades in the context of biological regulation networks Answer Set Programming ASP which has proven to be a strong logic programming paradigm to deal with the inherent complexity of biological models For systems biologists biochemists bioinformaticians molecular biologists pharmacologists and computer scientists Systems Biology Modelling and Analysis is a comprehensive all in one resource to understand and harness the field s current models and techniques while also preparing for their potential developments in coming years with the help of the author s expert insight

Symbolic Approaches to Modeling and Analysis of Biological Systems Cedric Lhoussaine, Elisabeth Remy, 2023-08-29 Systems Biology is an approach to biology that involves understanding the complexity of interactions among biological entities within a systemic whole The

goal is to understand the emergence of physiological or functional properties

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Handbook of Research on Computational Methodologies in Gene Regulatory Networks Das, Sanjoy, Caragea, Doina, Welch, Stephen, Hsu, William H., 2009-10-31 This book focuses on methods widely used in modeling gene networks including structure discovery learning and optimization Provided by publisher

Thinking About Biology Wilfred Stein, Francisco J. Varela, 2018-03-08 This book discusses the emergence of life the development of the individual and the study of the interaction between individuals and species It gives the student of theoretical biology some idea of the flavor of current research in the field

SOFSEM 2021: Theory and Practice of Computer Science Tomáš Bureš, Riccardo Dondi, Johann Gamper, Giovanna Guerrini, Tomasz Jurdziński, Claus Pahl, Florian Sikora, Prudence W.H. Wong, 2021-01-20 This book contains the invited and contributed papers selected for presentation at SOFSEM 2021 the 47th International Conference on Current Trends in Theory and Practice of Computer Science which was held online during January 25-28 2021 hosted by the Free University of Bozen Bolzano Italy The 33 full and 7 short papers included in the volume were carefully reviewed and selected from 100 submissions They were organized in topical sections on foundations of computer science foundations of software engineering foundations of data science and engineering and foundations of algorithmic computational biology The book also contains 5 invited papers

Proceedings of the Twenty-seventh Annual ACM Symposium on Theory of Computing, 1995

Logical Modeling of Cellular Processes: From Software Development to Network Dynamics Matteo Barberis, Tomáš Helikar, 2019-08-16 Mathematical models have become invaluable tools for understanding the intricate dynamic behavior of complex biochemical and biological systems Among computational strategies logical modeling has been recently gaining interest as an alternative approach to address network dynamics Due to its advantages including scalability and independence of kinetic parameters the logical modeling framework is becoming increasingly popular to study the dynamics of highly interconnected systems such as cell cycle progression T cell differentiation and gene regulation Novel tools and standards have been developed to increase the interoperability of logical models which can now be employed to respond a variety of biological questions This Research Topic brings together the most recent and cutting edge approaches in the area of logical modeling including among others novel biological applications software development and model analysis techniques

Efficient Algorithms Susanne Albers, Helmut Alt, Stefan Näher, 2009-09-01 This Festschrift volume published in honor of Kurt Mehlhorn on the occasion of his 60th birthday contains

28 papers that demonstrate how the field of algorithmics has developed and matured in the decades since Mehlhorn's first book on the subject in 1977

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Size-time Complexity of Boolean Networks for Prefix Computation Cornell University. Department of Computer Science, G. Bilardi, F. P. Preparata, 1987 The prefix problem consists of computing all the products $x_0 x_1 \dots x_j$ $0 \leq j \leq N-1$ given a sequence $X = x_0 x_1 \dots x_{N-1}$ of elements in a semigroup In this paper we completely characterize the size time complexity of computing prefixes with boolean networks which are synchronized interconnections of boolean gates and one bit storage devices This complexity crucially depends upon a property of the underlying semigroup which we call cycle freedom no cycle of length greater than one in the Cayley graph of the semigroup Denoting by S and T size and computation time respectively we have $S = \Theta(N T \log N)$ for non cycle free semigroups and $S = \Theta(N T)$ for cycle free semigroups In both cases $T = \Omega(\log N)$

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