

# 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<sup>NP</sup>**-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

# The Complexity Of Boolean Networks

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