

Chapter 15

Cellular Automata Communication Models: Comparative Analysis of Parallel, Sequential and Asynchronous CA with Simple Threshold Update Rules

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ABSTRACT

In this paper, cellular automata (CA) are viewed as an abstract model for distributed computing. The author argues that the classical CA model must be modified in several important respects to become a relevant model for large-scale MAS. The paper first proposes sequential cellular automata (SCA) and formalizes deterministic and nondeterministic versions of SCA. The author then analyzes differences in possible dynamics between classical parallel CA and various SCA models. The analysis in this paper focuses on one-dimensional parallel and sequential CA with node update rules restricted to simple threshold functions, as arguably the simplest totalistic, yet non-linear (and non-affine) update rules. The author identifies properties of asymptotic dynamics that can be proven to be entirely due to the assumption of perfect synchrony in classical, parallel CA. Finally, the paper discusses what an appropriate CA-based abstraction would be for large-scale distributed computing, insofar as the inter-agent communication models. In that context, the author proposes genuinely asynchronous CA and discusses main differences between genuinely asynchronous CA and various weakly asynchronous sequential CA models found in the literature.

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1. INTRODUCTION AND MOTIVATION

Cellular automata (CA) are one of the most popular and most researched models of discrete dynamical systems. Originally introduced as a mathematical model that captures high-level dynamic behavior of biological systems capable of self-reproduction, CA have been extensively studied in a great variety of application domains – primarily in modeling and simulation of complex physical, biological, social and/or socio-technical systems. However, CA have also been viewed as an abstraction of massively parallel computers. While most of the previous computer science research on CA and similar models has used those models as an abstraction for parallel hardware architectures, our agenda is to use these complex system models as an abstraction for open distributed environments at the software level.

More specifically, we would like to apply CA as an abstraction for autonomously executing local processes that are coupled to and interacting with one another and possibly also with other aspects of their environment. Even when these individual processes are rather simple, their mutual interaction and synergy may potentially yield a highly complex and difficult to predict long-term global behavior. This property, namely, that the behavior of the “whole” (the entire system) cannot be easily deduced from the simple and well-understood behaviors of the “pieces” (individual components), is a hallmark property of both nonlinear dynamical systems in physical sciences and distributed systems in computer science.

It has been observed that large-scale computational and communication infrastructures in general, and multi-agent systems (MAS) of software, robotic and other varieties in particular, are getting increasingly physically and logically distributed, heterogeneous, and complex. We are particularly interested in modeling and simulation of large-scale MAS made of relatively simple autonomous software or other types of agents, with the focus on collective dynamics and emerging

behavior of such systems (Tosic, 2005). Research on MAS heavily draws on the existing theories, tools and methodologies from AI, software engineering and distributed computing. We would like to contribute to the more thorough understanding and better design of large-scale MAS some ideas, paradigms and tools from another scientific discipline, namely, discrete dynamical systems – especially those models of dynamical systems that are based on communicating automata.

To formally analyze, predict and verify properties of complex distributed systems, various formal models based on different types of communicating automata have been proposed (see, e.g., Lynch, 1996). Among a broad variety of such formal automata based models, we particularly like the idea of using models based on classical cellular automata for modeling and analysis of large-scale distributed infrastructures and multi-agent systems; reasons behind this preference include CA’s descriptive simplicity, mathematical elegance, ease of computer simulations and wealth of “prior art” insofar as rich history multi-faceted research on various properties of CA dynamics spanning nearly half a century.

What are, then, the important properties of large-scale distributed computational and communication systems in general, and MAS in particular, that can be adequately captured by the classical CA and CA-like models? Let’s consider a cellular automaton from a MAS perspective. Studying the global dynamics of a CA then translates into an exploration of the global behavior of a multi-agent system when (i) the individual agent behaviors are fixed, (ii) the pattern of multi-agent interaction (“network topology”) is fixed, and (iii) both the individual agent behaviors and the interaction patterns among the agents are highly regular and uniform (i.e., homogeneous) across the entire system. In particular, CA and other related models capture the critically important MAS features of the locality of interaction among the agents, and the bounded speed of information and impact propagation.

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