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Computational complexity of tissue-like P systems

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Membrane systems, also called P systems, are biologically inspired theoretical models of distributed and parallel computing. This paper presents a new class of tissue-like P systems with cell separation, a feature which allows the generation of new workspace. We study the efficiency of the class of P systems and draw a conclusion that only tractable problems can be efficiently solved by using cell separation and communication rules with the length of at most 1. We further present an efficient (uniform) solution to SAT by using cell separation and communication rules with length at most 6. We conclude that a borderline between efficiency and non-efficiency exists in terms of the length of communication rules (assuming **P** $\neq$ **NP**). We discuss future research topics and open problems.

1. Introduction

Membrane computing is a young branch of natural computing initiated by Păun at the end of 1998 [17]. It has received great attention from the scientific community since then. Computer scientists, biologists, formal linguists, and complexity theoreticians have contributed greatly to this new field of research, enriching each others' with results, open problems and promising new research lines. Membrane computing was selected by the Institute for Scientific Information, USA, as a fast *Emerging Research Front* in computer science, and the paper of Păun and Păun [19] was ranked in [25] as a highly cited paper in October 2003.

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Membrane computing is inspired by the structure and function of living cells, as well as the organization of cells in tissues, organs, and other higher order structures. The devices investigated in this field, called *P systems*, are distributed parallel and non-deterministic computing models.

In general, the main components of P systems are a *membrane structure*, where *multisets* of *symbol-objects* are placed in its *compartments*. Multisets of symbol-objects evolve in a synchronous maximally parallel manner according to given *evolution rules*. Evolution rules are associated with the membranes. Please refer to [18] or [4] for an introduction and [26] for further references.

In recent years, many different models of P systems have been proposed. The most studied variants are characterized by a *cell-like* membrane structure, where communication takes place between a membrane and the surrounding membrane. These models have a set of nested membranes, chosen in such a way that the graph of neighborhood relations is a tree.

One of the topics in the field is the study of the computational power and efficiency of P systems. In particular, different models of these cell-like P systems have been successfully used for designing solutions to **NP**-complete problems in polynomial time (see [7] and the references therein). These solutions are obtained by generating an exponential workspace in polynomial time and simultaneously checking all the candidate solutions in parallel. With inspiration from the living cell, several ways to obtain exponential workspace in polynomial time have been proposed: membrane division (*mitosis*) [16], membrane creation (*autopoiesis*) [9], membrane separation (*membrane fission*) [15]. These three ways have given rise to the corresponding P system models: *P systems with active membranes, P systems with membrane creation*, and *P systems with membranes separation*. These three models are universal from a computational point of view, but technically, they are very different. To the best of our knowledge, there exists no theoretical result which proves that these models can simulate each other in polynomial time.

Under the hypothesis $\mathbf{P} \neq \mathbf{NP}$, it was shown that P systems without membrane division cannot solve **NP**-complete problems in polynomial time [24]. This result was generalized in [21]: an **NP**-complete problem cannot be solved in polynomial time by means of language accepting P systems (without using rules that allow an increase in the size of the structure of membranes).

Here, we focus on P systems of another type, called *tissue P systems* due to the structure of their membrane. Instead of considering a hierarchical structure, membranes are placed at the nodes of a graph. This variant takes inspiration from two biological phenomena (see [14]): intercellular communication and communication between neurons. The common mathematical model of these two mechanisms is a net of processors dealing with symbols and communicating these symbols along channels specified in advance. Communication among cells is based on symport/antiport rules, which were introduced to P systems in [19]. Symport rules move objects across a membrane together in one direction, whereas antiport rules move objects across a membrane in opposite directions.

From the seminal definitions of tissue P systems [13,14], several research lines have been developed and other variants have arisen (see, for example, [1–3,10,11,23]). One of the most interesting variants of tissue P systems was presented in [20]. In that paper, the definitions of tissue P systems and P systems with active membranes are combined. This yields *tissue P systems with cell division*, and a polynomial-time uniform solution to the **NP**-complete problem SAT is shown. In these kinds of tissue P systems [20], replication is used, that is, the two new cells generated by a division rule have exactly the same objects except for at most a pair of different objects. However, in the biological phenomenon of separation, the contents of the two new cells evolved from the original one can be significantly different, and membrane separation inspired by this biological phenomenon in the framework of cell-like P systems was proved to be an efficient way for obtaining exponential workspace in polynomial time [15]. In this paper, a new class of P systems, called *tissue P systems with cell separation*, is presented. We study the efficiency of the class of P systems and draw a conclusion that only tractable problems can be efficiently solved by using cell separation and communication rules with the length of at most 1. We further present an efficient (uniform) solution to SAT by using cell separation and communication rules with length at most 6. We conclude that a borderline between efficiency and non-efficiency exists in terms of the length of communication rules (assuming $\mathbf{P} \neq \mathbf{NP}$). We discuss future research topics and open problems.