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Tissue-like P systems with evolutional symport/antiport rules

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ABSTRACT

Tissue P systems with symport/antiport rules are a class of distributed parallel computing models inspired by the cell intercommunication in tissues, where objects are never modified in the process of communication, just changing their place within the system. In this work, a variant of tissue P systems, called tissue P systems with evolutional symport/antiport rules is introduced, where objects are moved from one region to another region and may be evolved during this process. The computational power of such P systems is studied. Specifically, it is proved that such P systems with one cell and using evolutional symport rules of length at most 3 or using evolutional antiport rules of length at most 4 are Turing universal (only the family of all finite sets of positive integers can be generated by such P systems if standard symport/antiport rules are used). Moreover, cell division rules are considered in tissue P systems with evolutional symport/antiport rules, and a limit on the efficiency of such P systems is provided with evolutional communication rules of length at most 2. The computational efficiency of this kind of models is shown when using evolutional communication rules of length at most 4.

1. Introduction

Cells are the basic structural, functional and biological units of all known living organisms. A single cell is often considered a complete organism in itself, hence a cell may be viewed as an enclosed vessel composed of smaller subcell parts, each of which has specific functioning, and countless chemical reactions take place within the cell. On the other hand, a cell is not an independent functional unit; in order to acquire desired functions, each cell is in communication with other cells. With the inspiration of the structure and functioning of living cells as mentioned above, a computing paradigm, called *membrane computing*, has been proposed by Gh. Păun at the end of 1998, and has been an active research area since then [25], covering both theoretical results [12,15,39,43,47] and applications of solving real problems [30–33,44,45,48]. The models in this computational paradigm are usually called *P systems*, which are distributed and parallel computing devices. According to the membrane structure of P systems, there exist two main families: *cell-like P systems*, which have a hierarchical arrangement of membranes, as in a cell (hence described by a tree); and *tissue-like P systems* [19] or *neural-like P systems* [14], which have a net of processor units placed in the nodes of a directed graph [25]. An introduction and an overview

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of membrane computing can be found in [27,29]. One can refer to the P systems website http://ppage.psystems.eu for the most up-to-date references.

With mathematical, biological cells, theoretical computer science, or application motivations, several variants of P systems that recruited various ingredients (e.g., energy, catalysts, mitosis, etc.) have been proposed. A basic and interesting sub-class of cell-like P systems, called *P systems with active membranes*, was presented in [26], where each membrane is polarized, polarization being positive + , negative - or neutral 0. A further variant of such P systems, called *polarizationless P systems with active membranes*, is to avoid polarizations [2]. In these kinds of P systems with active membranes, several types of rules are used for evolving the systems, where two basic types of rules are as follows: (a) *in* or *out* communication rules: an object is sent inside or outside the membrane, maybe modified during this process; (b) division rules: two new membranes are created, the object specified in the rule is replaced in the two new membranes by possibly different new objects and the remaining objects are replicated and distributed in each of the newly created membranes. The present work will introduce the object evolution mechanism of the communication rules into tissue-like P systems.

Tissue-like P systems were considered in [18]. Briefly, in a tissue P system, cells are placed in the nodes of a graph and the environment is considered as a distinguished node; an arc between two nodes corresponds to a communication channel between two regions (two cells or a cell and the environment). If a communication channel between two regions exists, then they can communicate by communication (symport/antiport) rules [23]. Symport rules move objects across a membrane together in one direction, whereas antiport rules move objects across a membrane in opposite directions. It is worth noting that objects in the process of communication are never modified: they just change their place within the system.

From the seminal definition of tissue P systems, several variants of such P systems have been arisen [9,10,16,24]. In [1], an integer that represents energy is associated with each cell in tissue P systems, and it was proved that computational completeness is reached when maximally parallel mode or sequential mode enforced with priorities are used. Tissue P systems as control language generators were considered in [49], where each rule is assigned with a label chosen from an alphabet with the empty label λ, and the sequence of labels of rules applied during a halting computation is defined as the result of the computation. It is shown that any recursively enumerable language can be generated by tissue P systems as language generating devices [49].

Cell division (mitosis) is a process of nuclear division in which replicated DNA molecules of each chromosome are faithfully partitioned into two nucleus. Two daughter cells resulting mitosis possess a genetic content identical to each other and to the mother cell from which they arose. Cell division, which provides a way to obtain an exponential workspace, has been used to solve computationally hard problems in membrane computing. The first attempt in tissue P systems was done in [28], which was successfully used for designing solutions to the SAT problem. Since then, tissue P systems with cell division were also considered to solve other **NP**-complete problems: 3-coloring [7], vertex cover [8], and so on.

Computational complexity of tissue P systems has also been studied, considering the length of symport/antiport rules (number of objects involved in the rules) as an essential parameter for the computational power. In the framework of tissue P systems with cell division, communication rules of length at most one can only solve tractable problems [13]. Later, it was proved in [36] that tissue P systems with cell division and communication rules of length at most two can solve the HAM-CYCLE problem. Hence, in the framework of tissue P systems with cell division, the length of communication rules provides an optimal tractability frontier: passing from 1 to 2 amounts to passing from non-efficiency to efficiency, assuming that $\mathbf{P} \neq \mathbf{NP}$.

Note that, under the hypothesis $\mathbf{P} \neq \mathbf{NP}$, it was shown that **NP**-complete problems cannot be solved by P systems without membrane division in polynomial time [35,46].

In the original tissue P systems [18] and the variants mentioned above, objects between cells or between a cell and the environment are communicated by means of standard symport/antiport rules, that is, objects in the process of communication are never modified, but they just change their place within the system. Actually, this is not exactly the case in cell biology. Chemical substances that enter or exit cells can be evolved, which is also reflected in P systems with active membranes, objects can be modified during the process of communication. Thus, it is a rather natural idea to consider objects evolution during the process of communication in tissue P systems.

In this work, a variant of communication rules, called *evolutional communication rules*, is introduced into tissue P systems. Such P systems are called *tissue P systems with evolutional symport/antiport rules*, where objects are moved between cells or between a cell and the environment, and may be evolved during this process. More specifically, when an evolutional symport rule is applied, objects are moved in one direction, and maybe evolved to other multiset of objects (can be empty) during this process. When an evolutional antiport rule is applied, two multisets of objects are moved in opposite directions, both of these multisets of objects may be evolved to other multiset of objects (can be empty) during this process.

The computational power of tissue P systems with evolutional symport/an-tiport rules is studied. By using evolutional symport/antiport rules instead of standard symport/antiport rules, as expected, the computational power of such P systems is increased. Specifically, it is proved that such P systems with one cell and using evolutional symport rules of length at most 3 or using evolutional antiport rules of length at most 4 are Turing universal. Note that only the family of all finite sets of positive integers can be generated by such P systems if standard symport/antiport rules are used.

A computational complexity perspective of tissue P systems with evolutional symport/antiport rules is also investigated, and a limit on the efficiency of such P systems is presented which use evolutional communication rules of length at most 2. Moreover, the computational efficiency of this kind of models is shown when using evolutional communication rules of