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The computational power of tissue-like P systems with promoters

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ABSTRACT

Tissue P systems are distributed parallel computing models inspired by the structure of tissue and the way of communicating substances between two cells or between a cell and the environment. In this work, we consider a variant of tissue P systems, called tissue P systems with promoters, where the application of rules is regulated by promoters. The computational power of such P systems is investigated. Specifically, it is proved that such P systems using only antiport rules of length 2 or using only symport rules of length 1 are able to compute only finite sets of non-negative integers. However, such P systems with one cell and using antiport rules of length 2 and symport rules of length 1 or only using symport rules of length 2 are Turing universal. Moreover, a uniform solution to the SAT problem is provided by tissue P systems with promoters and cell division using only antiport rules of length 2.

1. Introduction

Membrane computing is an unconventional computing area that aims to abstract computing ideas (e.g., computing models, data structures, data operations) from the structure and functioning of living cells, as well as from more complex biological entities, like tissues, organs and populations of cells [25]. The area of membrane computing has developed rapidly on both theoretical results [1,19,38,41] and application of solving real problems [29,30,42,44]. The computational models that are part of this paradigm are generically called *P systems*, which are distributed and parallel computing devices. One of the essential ingredients of a P system is its membrane structure, which can be a hierarchical arrangement of membranes as in a cell (hence described by a tree) [25], or a net of membranes (placed in the nodes of a graph) as in a tissue [17] or a neural net [14]. For a comprehensive presentation of this research area, *The Oxford Handbook of Membrane Computing* is recommended [28], and for an almost exhaustive list of publications in this area, one can consult the P systems web page http://ppage.psystems.eu. The present work focuses on *tissue P systems*.

Tissue P systems are inspired by the structure of tissue and the way of communicating substances between two cells or between a cell and the environment. 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

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communicate by means of communication (symport/antiport) rules [22]. Symport rules move objects across a membrane together in one direction, whereas antiport rules move objects across a membrane in opposite directions.

Tissue P systems have been studied widely. Various types of tissue-like P systems inspired by biological phenomena have been proposed, and many of them are proved to be computationally complete (see, e.g., [2,3,10,12,16,24]). Tissue P systems are also proved to be computationally efficient. In particular, by introducing cell division rules or cell separation rules into tissue P systems, an exponential workspace can be generated in polynomial time, which is successfully used for designing solutions to **NP**-complete problems [7–9,21,27,39,43].

Recently, a variant of tissue P systems, called *tissue P systems with promoters*, was proposed in [4,33]. In these papers, tissue P systems with promoters are studied on the algorithmic level. Specifically, in [4], a set of techniques for the problem of counting cells inspired in the treatment of digital images via tissue P systems with promoters was presented; while in [33], tissue P systems with promoters were used to implement a cell complex based algorithm for thinning images.

In this work, we investigate the computational power of tissue P systems with promoters. Specifically, it is proved that such P systems using only antiport rules of length 2 or using only symport rules of length 1 are able to compute only finite sets of non-negative integers. We also show that such P systems with one cell and using antiport rules of length 2 and symport rules of length 1, or only using symport rules of length 2 are Turing universal (tissue P systems without promoters the same cases are not universal). Furthermore, we present a new variant of tissue P systems, called *tissue P systems with promoters and cell division*, where cell division is introduced into tissue P systems with promoters, and a uniform solution to the SAT problem is provided by such P systems using only antiport rules of length 2 (it is open whether tissue P systems with cell division without promoters using only antiport rules of length 2 can solve **NP**-complete problems).

2. Preliminaries

It is helpful for the reader to have some familiarity with language theory [34], as well as basic elements of membrane computing [28]. Here we only recall some of notions used in this work.

An *alphabet* Γ is a non-empty set and their elements are called *symbols*. A *multiset* m over an alphabet Γ is a pair (Γ, f), where f is a mapping from Γ onto the set of natural numbers $\mathbb{N}$. We denote by $M_f(\Gamma)$ the set of all finite non-empty multisets over Γ. Let $m_1 = (\Gamma, f_1)$, $m_2 = (\Gamma, f_2)$ be multisets over Γ, then the union of m_1 and m_2, denoted by $m_1 + m_2$, is the multiset (Γ, g), where $g(x) = f_1(x) + f_2(x)$ for each $x \in \Gamma$. The relative complement of m_2 in m_1, denoted by $m_1 \setminus m_2$, is the multiset (Γ, g), where $g(x) = f_1(x) - f_2(x)$ if $f_1(x) \geq f_2(x)$, and $g(x) = 0$ otherwise.

We denote by $NFIN$ the family of all finite sets of positive integers. By NRE we denote the family of recursively enumerable sets of natural numbers.

A *register machine* is a tuple $M = (m, H, l_0, l_h, I)$, where

- m is the number of registers;
- H is a set of labels;
- $l_0, l_h \in H$ are distinguished labels, where l_0 is the initial, and l_h is the halting one;
- I is a set of labeled program instructions of the following forms (each label from H labels only one instruction from I, thus precisely identifying it):
  - $l_i : (\mathtt{ADD}(r), l_j, l_k)$ (add 1 to register r and then go to one of the instructions with labels l_j, l_k, non-deterministically chosen);
  - $l_i : (\mathtt{SUB}(r), l_j, l_k)$ (if register r is non-zero, then subtract 1 from it, and go to the instruction with label l_j; otherwise, go to the instruction with label l_k);
  - $l_h : \mathtt{HALT}$ (the halt instruction).

A register machine M generates a set $N(M)$ of numbers in the following way: the machine starts with all registers being empty (i.e., storing the number zero); the machine applies the instruction with label l_0 and continues to apply instructions as indicated by the labels (and made possible by the contents of registers); if it reaches the halt instruction, then the number n presented in specified register 1 at that time is said to be generated by M. If the computation does not halt, then no number is generated. It is known that register machines generate all sets of numbers which are Turing computable, hence they characterize NRE [18].

3. Tissue P systems with promoters and cell division

In this section, we first introduce the definition of tissue P systems with promoters and cell division, then the notion of recognizer tissue P systems with promoters and cell division is given.

3.1. Tissue P systems with promoters and cell division

Definition 1. A tissue P system with promoters and cell division, of degree $q \geq 1$, is a tuple

$$\Pi = (\Gamma, \mathcal{E}, w_1, \ldots, w_q, \mathcal{R}, i_{out}),$$

where