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Monodirectional evolutional symport tissue P systems with channel states and cell division

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Bioinspired computing is a research framework that solves computer science problems based on the principles of biology and the natural world, including DNA and membrane computing. Membrane computing (MC), an active subfield of bioinspired computing based on the biological cell structure, emerged as an unconventional computational paradigm and has generated an extensive fundamental research scope in theoretical computer science [1]. The models discussed in the MC paradigm are termed as P systems. In summary, P systems have three basic models: neural-like P systems [2], tissue-like P systems [3] (models are associated with a structure of directed graph), and cell-like P systems (models are associated with a structure of rooted tree) [4]. For a comprehensive guide to membrane computing, the Handbook of Membrane Computing is suggested [5].

An interesting genre of tissue P systems, termed as tissue P systems with channel states (TC P systems), was raised in [6], where the movement of objects among regions is controlled by special objects called states of channels. Results showed that the TC P systems are Turing complete by assembling the ingredients of states, cells, antiport rules, and symport rules. In [7], the conception of "monodirectionality" was raised and studied in multiset rewriting P systems, wherein the transfer of objects between the neighboring domains is unidirectional. In [8], tissue P systems with promoters associated with a monodirectional feature (MTP P systems) were designed, and their computational properties were investigated. In [9], the notion of "monodirectional" was investigated in TC P systems; moreover, the model of monodirectional tissue P systems with channel states (MTC P systems) was raised, only symport rules were permitted, and the objects between any two regions could only be moved in one direction. The results show that MTC P systems are universal, and by introducing cell division, such a model can solve the problem of SAT in polynomial time [9].

The latter proposes a novel genre of tissue P system model, termed as monodirectional evolutional symport tissue P system with channel states (MESTC P systems), where the systems can only use evolutional symport rules; furthermore, for any two given areas, objects are transferred in one direction, and the involved objects may be modified when their places are changed. Results demonstrate that MESTC P systems are universal if such P systems use two cells, a maximum of two states, and evolutional symport rules having a maximal length of three or use any number of cells, a maximum of two states, and evolutional symport rules having a maximal length of two. In addition, by adding cell division into MESTC P systems, another novel type of tissue P system, named monodirectional evolutional symport tissue P systems with channel states and cell division (MESTCD P systems), is designed. The result shows that MESTCD P systems can solve the SAT in polynomial time, wherein the system uses an arbitrary number of states and all evolutional symport rules have length two.

Preliminaries and model description. Γ is a nonempty finite set, called alphabet and the elements in such a set are called symbols. The set of all strings produced by connecting any sequence of symbols is indicated as Γ^*. The set $\Gamma^* \setminus \{\lambda\}$ of strings is indicated as Γ^+. The length of a string u is the number of symbols presented as u, indicated as $|u|$. A multiset $\mathcal{M}$ over Γ is an ordered pair (Γ, f), where f is a function, defined from Γ to $\mathbb{N}$ (natural number set). Furthermore, $\mathcal{M}^+(\Gamma)$ and $\mathcal{M}(\Gamma)$ indicate the sets of all nonempty multisets and all multisets, respectively. If $\Gamma = \{a_1, \ldots, a_k\}$, then multiset $\mathcal{M}$ can be expressed by $\{a_1^{f(a_1)}, \ldots, a_k^{f(a_k)}\}$.

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 the labels of the initial and halting instructions, respectively; I is a set of labeled program instructions, containing two forms: (1) $l_i : (\mathtt{ADD}(r), l_j, l_k)$ (register r increases by one, and then selects a instruction l_j, l_k non-deterministically); (2) $l_i : (\mathtt{SUB}(r), l_j, l_k)$ (subtract 1 from register r if it is

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nonzero, and go to the instruction l_j; otherwise, go to the instruction l_k).

Definition 1. A monodirectional evolutional symport tissue P system (of degree $q \geqslant 1$) with channel states and cell division (MESTCD P system, shortly) has a construct

$$\Pi = (\Gamma, K, \mathcal{E}, \mathcal{M}_1, \ldots, \mathcal{M}_q, \mathrm{ch}, (s_{(i,j)})_{(i,j)\in \mathrm{ch}}, \mathcal{R}, i_{\mathrm{out}}),$$

where

- Γ is a finite alphabet, each element in Γ is termed as object;
- K is a set, elements in this set are named states, such that $K \cap \Gamma = \emptyset$;
- $\mathcal{E} \subseteq \Gamma$ is a set for environment, every object in $\mathcal{E}$ is sufficient;
- $\mathcal{M}_i$, $1 \leqslant i \leqslant q$, are multisets of objects, which are initially placed in cell i;
- $\mathrm{ch} \subseteq \{(i,j) \mid i \neq j, i, j \in \{0, 1, \ldots, q\}\}$ is a channels set among regions, ch includes at most one of channels $(i,j), (j,i)$ (0 represents environment);
- $s_{i,j}$ is an state initially located on channel $(i,j) \in \mathrm{ch}$;
- $\mathcal{R}$ is a set of rules including the following two forms:

– Division rules: $[a]_i \to [b]_i [c]_i$, such that $a, b, c \in \Gamma$, $i \neq i_{\mathrm{out}}$;

– Evolutional symport rules $\mathcal{R}_{(i,j)}$ bound with channel $(i,j) \in \mathrm{ch}$: $(s, u \to v/\lambda, s')$, such that $s, s' \in K$, $u \in \mathcal{M}^+(\Gamma)$, $v \in \mathcal{M}(\Gamma)$;

- $i_{\mathrm{out}} \in \{0, 1, \ldots, q\}$ refers to output region.

If cell division rules are not applied in such systems, they are termed as monodirectional evolutional symport tissue P systems with channel states. The weight of an evolutional symport rule $(s, u \to v/\lambda, s')$ is defined as an ordered pair $(|u|, |v|)$, and the length of an evolutional symport rule is defined as $|u| + |v|$. The rules in MESTCD P systems are applied in maximal parallelism with a sequential behavior on channels: on each channel between two regions, at most one rule can be used in one step, and all channels that can use a rule must do it.

A configuration of MESTCD P systems at an instant t is defined by a tuple $(N_1, \ldots, N_q, N_e)$, where N_i $(1 \leqslant i \leqslant q)$ are the multisets of objects over Γ and N_e is a multiset of objects over $\Gamma \setminus \mathcal{E}$. A sequence of transitions starting in the initial configuration is a computation; in a computation, every configuration must be connected with the previous one through a computation step. The system reaches a halting configuration when no rule can be used in the system. The computation result of the MESTCD P system is encoded by the multiset of specified objects appearing in i_{out} only when it reaches a halting configuration.

The set of natural numbers, computed by MESTC P systems, is expressed as $N(\Pi)$. The family of all sets of natural numbers computed by MESTC P systems Π is expressed by $\mathrm{NOtP}_m^{\mathrm{mon}}(\mathrm{state}_k, \mathrm{esym}^l_{(t_1,t_2)})$, where m indicates the number of cells, k indicates the number of states, (t_1, t_2) indicates the maximal weight of evolutional symport rules (i.e., t_1 is the maximal length of $|u|$ for all evolutional symport rules, t_2 is the maximal length of $|v|$ for all evolutional symport rules), and l indicates the maximal length of evolutional symport rules. If parameters m, k, l, t_1, t_2 are unbound, we apply $*$ to replace them. For the notions of recognizer MESTCD P systems and a uniform solution to a decision problem, one can refer to Appendix A. We indicate as $\mathrm{PMC}_{\mathrm{MESTCD}(\mathrm{state}_k, \mathrm{esym}^l_{(t_1,t_2)})}$, the set of all decision problems is efficiently solvable in a uniform manner by the families of recognizer MESTCD P systems.

Main results. We investigated the computational power of MESTC P systems by combining the parameters regarding the numbers of states and cells and the length of evolutional symport rules. The following results were obtained.

Theorem 1. $\mathrm{NOtP}_2^{\mathrm{mon}}(\mathrm{state}_2, \mathrm{esym}^3_{(2,2)}) = \mathrm{NRE}$.

Theorem 2. $\mathrm{NOtP}_*^{\mathrm{mon}}(\mathrm{state}_2, \mathrm{esym}^2_{(1,1)}) = \mathrm{NRE}$.

In addition, a uniform solution to the `SAT` problem by MESTCD P systems is presented.

Theorem 3. $\mathtt{SAT} \in \mathrm{PMC}_{\mathrm{MESTCD}(\mathrm{state}_*, \mathrm{esym}^2_{(1,1)})}$.

The proofs of Theorems 1–3 can be found in Appendixes B–D, respectively.

Conclusion and further work. A monodirectionality regulating strategy of applying evolutional symport rules is incorporated into evolutional symport TC P systems. Therefore, MESTC P systems are useful models for some actual applications demanding a monodirectional nature.

Until now, various mechanisms exist for using rules based on several biological facts, for instance, asynchronous (in every region, any number of workable rules can be applied); minimal parallelism (when more than one rule is workable in a membrane; thus, the system should use at least one rule); sequentiality (exactly one rule is applied in one derivation step). An interesting issue is to discuss the computational power of MESTCD P systems working in different modes.

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Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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