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Dreams and spiking neural P systems

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Abstract. We continue the study of the human phenomena of sleep and wakefulness by means of spiking neural P systems [8], advancing towards a biologically-sophisticated model (we have only "natural" features). More precisely, we propose a system where each neuron of [8] (some of which make use of extended rules) is replaced by a sub-system without modifying the global output. Hence, we can claim that the study of the neuronal dreaming process is more "realistic" in our setting.

1. Introduction

Spiking neural P systems (SNP systems) are a class of computational models which use ideas from neural computing, more precisely from the way neurons communicate among themselves by means of spikes or action potentials. The framework, initially introduced in [5], is based on the tissue-like and neural-like P system structure to which various features were added. Details can be found at the website of membrane computing [13]. For an introduction in this area, we refer to [9].

Neural computing is currently under much, frequent investigation, and spiking neurons capture the attention of more and more scientists (see [3] and [6, 7] for examples).

Briefly, an SNP system consists of a set of neurons placed in the nodes of a graph that send signals (spikes) along synapses (edges of the graph), under the control of firing rules. One also uses forgetting rules, which remove spikes from neurons. Hence, the spikes are created, moved and destroyed, but never modified (there is only one type of object in the system).

A generalization of the original model is considered in [2], where rules of the form $E/a^c \to a^p; d$ are introduced. When such a rule is used, c spikes are consumed, and

p spikes are produced. Because p can be 0 or greater than 0, we obtain at the same time a generalization of both spiking and forgetting rules.

These systems prove to be a natural and powerful tool in modeling the wake/sleep flip-flop switch, a neural process which will be detailed in the following section. Roughly speaking, the wake/sleep phenomenon involves two parts of the brain which inhibit each-other (on one side, the brain stem and forebrain which send the sleeping impulses, and on the other side, the VLPO region which contributes to the motivation of staying awake) with the help of another two regions which act as buffers between them. Our model, called *neuronal wake/sleep switch*, is presented in Section 3, while further elaborations are given throughout the paper.

2. Preliminaries

In this section, we will briefly present some basic notions related to the biological concept of the wake/sleep switch, as well as the features of spiking neural P systems used to simulate this phenomenon.

2.1. The Wake/Sleep Flip-Flop Switch

Until a human fells asleep completely, we distinguish the following stages based on factors like brain waves, eyes movements and muscle activity of the chin [10, 1]:

1. non-rapid eye movement (NREM) sleep, which lasts 90–110 minutes and is divided into the following parts:
    (a) the subject, awake (alpha waves of low voltage) enters to somnolence (theta waves), some muscle tone is lost and slow eye movements occur;
    (b) explosions of sleep spindles and K-complexes happen occasionally, no eye movements are produced, and dreaming is unlikely;
    (c) delta waves are present (20-50% of the total activity), causing the transition to slow-wave sleep (SWS);
    (d) SWS appears, where delta activity is increasing (at least 50% of the total activity) and less-memorable dreaming may occur.
2. rapid eye movement (REM) sleep, which is characterized by active dreams, observable rapid eye movements, sensibility to external stimuli and relative absence of muscle tone.

Note that sometimes stages (c) and (d) are treated as one, usually referred to as *deep sleep* or SWS.

The ascending arousal system, which originates from a series of well-defined cell groups with identified neurotransmitters, is the one responsible for promoting wakefulness. It consists of two branches, one ascending to the thalamus, activating the thalamic relay neurons by producing acetylcholine–ACh (the major source is provided by the pedunculopontine–PPT, and laterodorsal tegmental nuclei–LDT), and the other avoiding the thalamus and activating neurons (such as locus coeruleus, serotoninergic dorsal, median raphe nuclei, dopaminergic ventral periaqueductal grey matter, histaminergic tuberomammillary or peptidergic) in the lateral hypothalamic area and basal forebrain and throughout the cerebral cortex. These cell groups contain histamine, serotonin–5HT, noradrenaline–NA, orexins, melanin-concentrating hormone, γ-aminobutyric acid (GABA) and acetylcholine. Most of them fire faster during wakefulness, slow down during NREM sleep and stop altogether during REM sleep, but others are active during both wakefulness and REM sleep (e.g., basal forebrain neurons containing GABA). Also, the neurons in the PPT/LDT fire most rapidly during wakefulness and REM sleep, and are much less active during NREM sleep. For a detailed study, the reader is referred to [11] and [12, Figure 2], and references therein.

On the other hand, recent advances in neuroscience [12] show that a group of neurons in the hypothalamus, called *ventrolateral preoptic nucleus* (VLPO), are active during NREM sleep and sends outputs to all of the major cell groups in the hypothalamus and brain stem which participate in the arousal process. They contain GABA, which inhibits these neurons involved in arousal, but both noradrenaline and acetylcholine are inhibitory to VLPO neurons. Hence, the VLPO can be inhibited by the arousal systems that it inhibits during sleep. For details, see [12, Figure 3].

This observation of the mutual inhibition is the starting point in forming a flip-flop switch of two discrete states (sleep and wake), with sharp transitions between them [11]. The system may act as follows. If it is "ON", we are in the sleep state, the VLPO being active and inhibiting the regions producing the arousal. If it is "OFF", the VLPO is inhibited, the regions producing the arousal are active, and we are in the wake state. A complete visual description of the switch, its transitions and how the system is stabilized is Figure 4 of [12]. Other details and information about how sleep is induced (e.g., adenosine seems to play an essential role) and how the described system is affected can be found in [1, Chapter 9]. In what follows, *wake/sleep switch* refers to this system which regulates arousal and sleep.

2.2. Spiking Neural P Systems

We recall [5] that a *spiking neural P system* (an SNP system, for short), of degree $m \geq 1$, is a construct of the form

$$\Pi = (O, \sigma_1, \ldots, \sigma_m, syn, out),$$

where:

1. $O = \{a\}$ is the *singleton alphabet* (a is called *spike*);
2. $\sigma_1, \ldots, \sigma_m$ are *neurons*, each one of the form $\sigma_i = (n_i, R_i), 1 \leq i \leq m$, where:
    a) $n_i \geq 0$ is the *initial number of spikes* contained by the neuron;
    b) R_i is a finite set of *rules*, each one of the following two types:
        (1) $E/a^c \to a; d$, where E is a regular expression over O, $c \geq 1$ and $d \geq 0$;
        (2) $a^s \to \lambda$ for some $s \geq 1$ such that there is no rule $E/a^c \to a; d$ of type (1) in R_i with $a^s \in L(E)$;

3. *syn* $\subseteq \{1, 2, \ldots, m\} \times \{1, 2, \ldots, m\} \backslash \{(i, i) \mid 1 \leq i \leq m\}$ is the relation of *synapses*;
4. *out* $\in \{1, 2, \ldots, m\}$ indicates the *output neuron*.

The rules of type (1) are *firing* (also called *spiking*) *rules*, and the rules of type (2) are called *forgetting rules*. The first ones are applied as follows: if the neuron contains k spikes, $a^k \in L(E)$, and $k \geq c$, then the rule $E/a^c \to a; d$ can be applied, and this means that c spikes are consumed, only $k - c$ remain in the neuron, the neuron is fired, and it produces one spike after d time units (a global clock is assumed, marking the time for the whole system, hence the functioning of the system is synchronized). If $d = 0$, then the spike is emitted immediately, if $d = 1$, then the spike is emitted in the next step, and so on. In the case $d \geq 1$, if the rule is used in step t, then the neuron is *closed* in steps $t, t+1, t+2, \ldots, t+d-1$, and it cannot receive new spikes (if a neuron has a synapse to a closed neuron and sends a spike along it, then the spike is lost). In step $t + d$, the neuron spikes and becomes again open, hence can receive spikes (which can be used in step $t + d + 1$). A spike emitted by a neuron σ_i is replicated and goes to all neurons σ_j such that $(i, j) \in syn$.

The forgetting rules are applied as follows: if the neuron contains exactly s spikes, then the rule $a^s \to \lambda$ can be used, and this means that all s spikes are removed from the neuron. Note that in this paper we do not use such rules.

In each time unit and for each neuron, if there exists a rule that can be used (firing or forgetting), we have to use it. Because two firing rules $E_1/a^{c_1} \to a; d_1$ and $E_2/a^{c_2} \to a; d_2$ can have $L(E_1) \cap L(E_2) \neq \emptyset$, it is possible that two or more rules can be applied in a neuron, and then one of them is chosen non-deterministically. Note, however, that we cannot interchange a firing rule with a forgetting rule, as all pairs of rules $E/a^c \to a; d$ and $a^s \to \lambda$ have disjoint domains, in the sense that $a^s \notin L(E)$.

The initial configuration of the system is described by the numbers $n_1, n_2, \ldots, n_m$ of spikes present in each neuron. Starting from the initial configuration and applying the rules, we can define transitions among configurations. A transition between two configurations C_1 and C_2 is denoted by $C_1 \longrightarrow C_2$. Any sequence of transitions starting in the initial configuration is called a *computation*. A computation halts if it reaches a configuration where all neurons are open and no rule can be used.

With any computation, halting or not, we associate a *spike train*, i.e., a sequence of digits 0 and 1, with 1 appearing in positions $1 \leq t_1 < t_2 < \ldots$, indicating the steps when the output neuron sends a spike out of the system (we also say that the system itself spikes at that time). With any spike train containing at least two spikes we associate the number $t_2 - t_1$; we say that this number *is computed by* Π. By definition, if the spike train contains only one occurrence of 1, then we say that we have computed the number zero. The set of all numbers computed in this way by Π is denoted by $N_2(\Pi)$ (the subscript indicates that we only consider the distance between the first two spikes of any computation). Then, by $Spik_2P_m(rule_k, cons_q, forg_r)$ we denote the family of all sets $N_2(\Pi)$ computed as above by spiking neural P systems with at most $m \geq 1$ neurons, using at most $k \geq 1$ rules in each neuron, with all spiking rules $E/a^c \to a; d$ having $c \leq q$, and all forgetting rules $a^s \to \lambda$ having $s \leq r$. When one of the parameters m, k, q, r is not bounded, it is replaced with $*$.

A rule of the type $E/a^c \to a^p$ is called an *extended rule*, and is applied as follows: if neuron σ_i contains k spikes, and $a^k \in L(E), k \geq c$, then the rule can fire, and its application means consuming (removing) c spikes (thus only $k - c$ remain in σ_i) and producing p spikes, which will exit immediately the neuron.

In this paper, we use SNP systems of the form introduced above but in a different way than computing numbers (as it was done in the initial paper). Here, we model the wake/sleep switch described in the previous section having as central point the paper [8] and moving a step closer to biology by eliminating the extended rules and designing sub-systems for each area of the brain involved in the neural switch.

2.3. An SNP System for the Wake/Sleep Switch

The wake/sleep switch model of [11, 12, 1] describes in a static way the informational flow between the groups of neurons participating in the circuit. Another more dynamic approach was proposed in [8] by computationally modeling the switch in terms of SNP systems. Let us now recall how this was done and what the positive aspects and drawbacks of the new paradigm are.

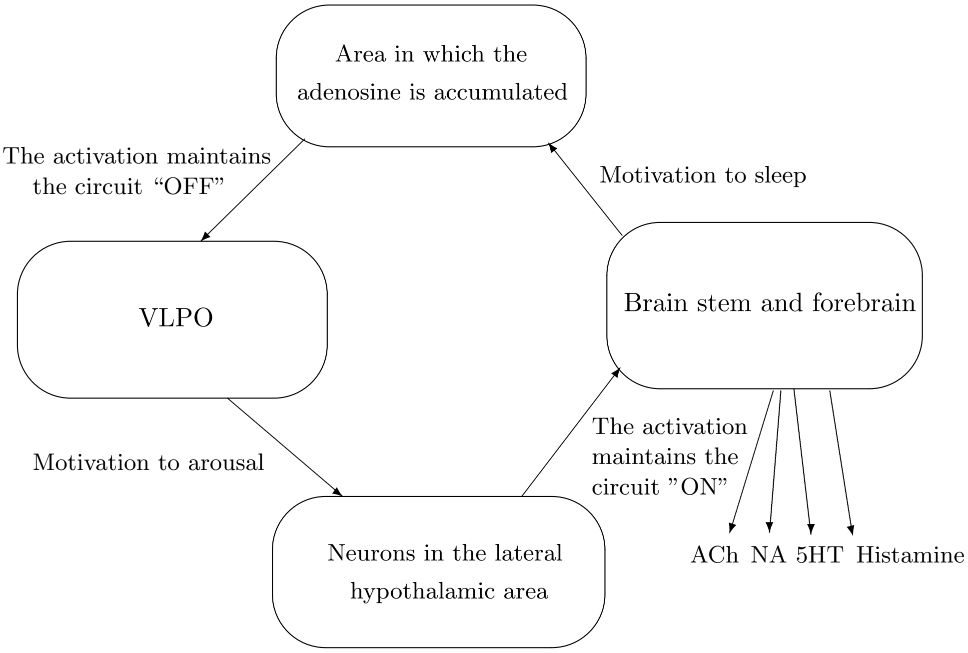

Fig. 1. Diagram of the wake/sleep switch.

To model the wake/sleep switch of Section 2.1. in a clear, simple fashion, two assumptions were needed. First, the neurons in forebrain and brain stem which maintain the wakefulness are active for a long time producing a cumulate amount of adenosine (i.e., when one is awake, the substance which induces the sleep is accumulated).

Second, the VLPO contributes to the motivation of staying awake (when one sleeps, the substance which induces the arousal is accumulated). Thus, the simplified system can be now visualized in Fig. 1.

It is clear that SNP systems can help us describe the above model: when a neuron has a determined (necessary) quantity of spikes, it fires, and when it does not, it remains inhibited. Equivalent to the wake/sleep switch of Fig. 1, an SNP system with four neurons is proposed in [8]: **Naad** (the one which accumulates adenosine), **Nvlpo** (the one which simulates the VLPO), **Nhip** (the one which simulates the lateral hypothalamic area) and **Nsact** (the one which simulates the activity in brain stem and forebrain), with the corresponding rules and spikes as depicted in Fig. 2 (given in its pictorial way without further explanation since its functioning is very easy to follow). For further details see [8].

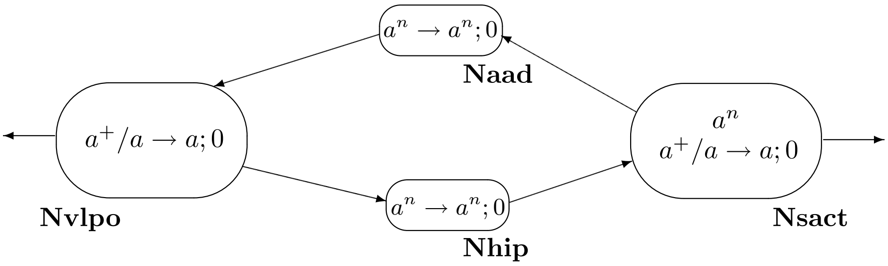

Fig. 2. Spiking neural P system simulating the wake/sleep switch.

Beyond the advantages of representing the wake/sleep switch as an SNP (and hence, in a formal manner), there is a simplicity and clarity to the model, which may offer a better comprehension, and the model's abstractness, which translates to a lack of ambiguities and a possible future implementation. Important drawbacks are that neurons represent isolated entities more than a group of neurons, and the synapses are simplified such that they do not consider the different types of neurotransmitters involved. The improvement of the original model by adding more and only "natural" ingredients is the aim of the next section.

3. A Neuronal Wake/Sleep Switch

As we could see above, the model proposed in [8] is using four neurons, one for each region of the brain involved into the wake/sleep mechanism. We will replace this model (in two phases) with a new one in which four different sub-systems of neurons are used, one for each region previously mentioned. It is obvious that we do not look for optimizing the system from a mathematical point of view, but we focus on making it more "realistic", using only "natural" ingredients.

In Fig. 2 one can see that the system proposed in [8] has two neurons, namely **Naad** and **Nhip**, where extended rules are used. Since a "real" neuron only fires one spike at once, the use of this kind of rules are unrealistic from a biological point of view (actually the initial motivation for introducing such rules in SNP systems is purely mathematical [2]). Hence, the replacing of each such neuron with a group of neurons is more adequate especially if we think at the nature of synapses: each will fire independently carrying with it various pieces of information (e.g., substances and neurotransmitters involved).

It is easy, though, to replace them as suggested in the following diagram:

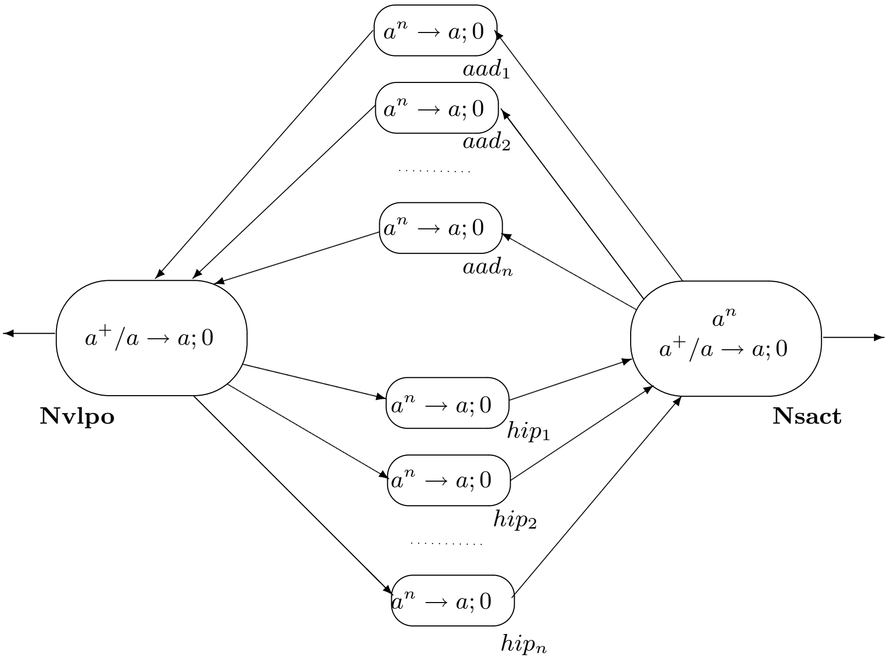

Fig. 3. Spiking neural P system without extended rules simulating the wake/sleep switch.

One can see that neuron **Naad** (having the rule $a^n \to a^n; 0$) was replaced by a sub-system of n neurons (called aad_i, for $1 \leq i \leq n$), each of them being empty in the initial configuration and having one rule inside, namely $a^n \to a; 0$. The purpose of neuron **Naad** was to host, for n steps, the neurons coming one by one from neuron **Nsact** until threshold n was reached, and then to send all of them to neuron **Nvlpo**.

Obviously, the evolution of the system does not change in the current setup. Neuron **Nsact** sends one by one the spikes it initially hosts to all the neurons from the **aad** sub-system. After n steps the threshold is reached and each of this neurons will send one spike to neuron **Nvlpo**, exactly as in the initial model.

The same explanations work for the neuron **Nhip** and the sub-system **hip**.

As described above the **Nvlpo** neuron and the **Nsact** neuron, respectively, were simulating the (neurons in the) regions that promote the dreaming, and systems of activation in the brain stem and the forebrain, respectively. We also replace these neurons with the sub-systems **sact** and **vlpo** depicted in Fig. 4.

We only describe the sub-system **sact** since **vlpo** behaves in the same manner.

We replace neuron **Nsact** with a sub-system called **sact** in the following way. We have used n neurons (denoted $sact_i$ for $1 \leq i \leq n$) each of them having one rule inside: $a \rightarrow a; i$, for $0 \leq i \leq n-1$. We have also equally divided the number of spikes initially present in **Nsact** to all neurons from the sub-system **sact**.

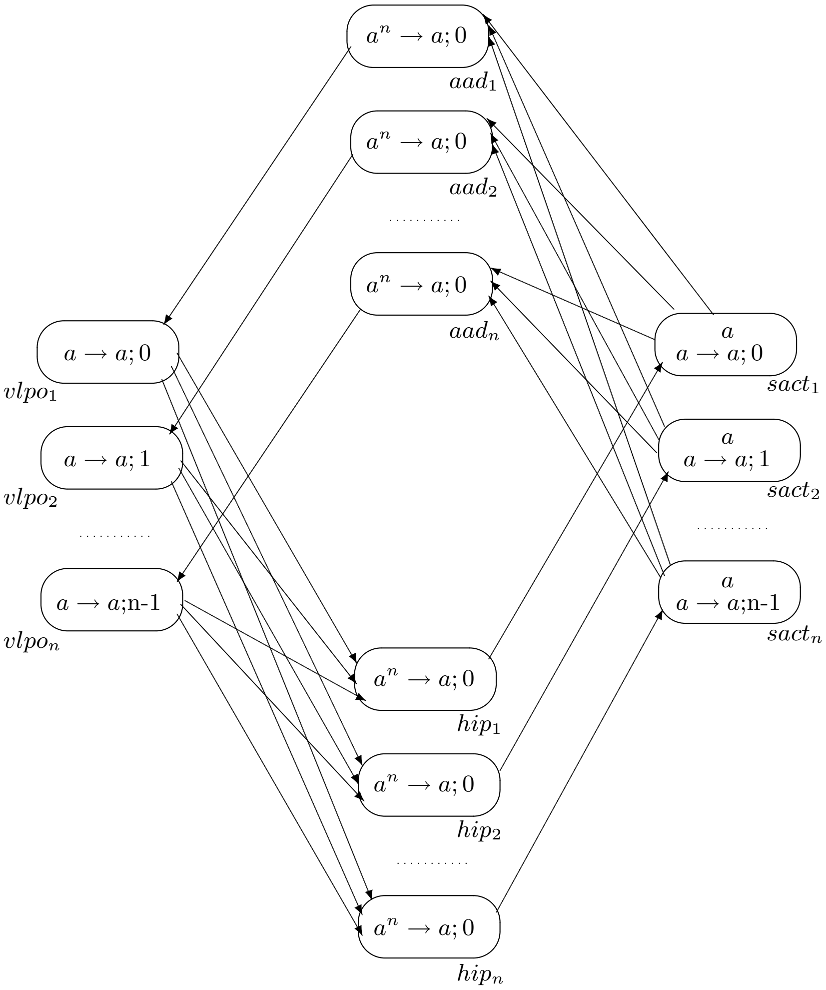

Fig. 4. Sub-systems of spiking neural P systems modeling the wake/sleep switch.

When the computation starts, neuron $sact_1$ sends immediately a spike to all neurons in the sub-system **aad** and will have no activity until it receives a spike from neuron hip_1 which will reactivate him. In the second step of the computation, neuron $sact_2$ will send a spike to all neurons in sub-system **aad** since its period of inactivity expires; he had to stay one step due to the delay on the rule. The computation continues, and in the n^{th} step of computation neuron $sact_n$ sends a spike (last one in this round from sub-system **sact**) to all the neurons in sub-system **aad**.

In the $n^{\text{th}}+1$ step of the computation, since each neuron from the sub-system **aad** has n spikes inside, each neuron from sub-system **vlpo** will receive a spike.

In n steps sub-system **vlpo** will send n spikes to sub-system **hip** in the same manner as described before, and the computation is reiterated after $2n+2$ steps.

We recall that in the initial model, neurons **Nvlpo** and **Nsact** had a synapse with the environment of the system in order to indicate its status: asleep or awake, respectively. For the same reason we can add two more neurons, one for each of the sub-systems **vlpo** and **sact**, thus. Each neuron from these sub-systems will have an outgoing synapse to the output neuron, the latter one having inside only one rule: $a \to a; 0$. It is obvious that the environment will be informed at each step about the status of the whole system, with the difference that, this time, with a delay of one step.

Another possibility to output the status of the system is to consider all the neurons, in the two sub-systems above, as being output neurons. It is easy to see that the environment will receive the same information, this time without delay.

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