Simulating of Schistosomatidae (Trematoda: Digenea) Behavior by Physarum Spatial Logic

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Abstract—**In this paper we consider possibilities of simulating behavior of the group of trematode larvae (miracidiae and cercariae) by the abstract slime mould based computer that is programmed by attractants and repellents. For describing this simulation, we appeal to the language which is a kind of π-calculus called Physarum spatial logic. This language contains labels for attractants and repellents. Taking into account the fact that the behavior of miracidiae and cercariae can be programmed only by attractants (repellents for miracidiae and cercariae are not known still), we can claim that the behavior of miracidiae and cercariae is a restricted (poorer) form of Physarum spatial logic.**

I. Introduction

IN *Physarum Chip Project: Growing Computers From Slime Mould* [3] supported by FP7 we are going to implement programmable amorphous biological computers in plasmodium of Physarum. This abstract computer we are going to obtain is called *slime mould based computer*. The plasmodium behaves and moves as a giant amoeba and its behavior can be considered as a biological implementation of Kolmogorov-Uspensky machines [2]. This allows us to use the plasmodium of Physarum for solving different tasks that can be solved in Kolmogorov-Uspensky machines as well. The slime mould based computer is programmed using attractants and repellents (fig. 1). On the one hand, it was experimentally proved that the slime mould prefers substances with potentially high nutritional value, e.g. it is attracted by peptones, aminoacids phenylalanine, leucine, serine, asparagine, glycine, alanine, aspartate, glutamate, and threonine. On the other hand, repellents for Physarum polycephalum can be presented by some illumination-, thermo- and salt-based conditions. Usually the plasmodium forms a congregation of protoplasm in food sources to surround them, secret enzymes and digest the food. Slime mould based computer can be regarded as a parallel computing substrate complementary to existing massive-parallel reaction-diffusion chemical processors [1].

In papers [15; 16] we showed that the behavior of plasmodium of *Physarum polycephalum* has an own spatial logic which is one of the natural implementations of π-calculus. This logic called *Physarum spatial logic* can be used

as a programming language for the slime mould based computer. Taking into account the fact that within π-calculus we can formalize and describe different concurrent processes, within Physarum spatial logic we can do the same as well.

(a)   (b)
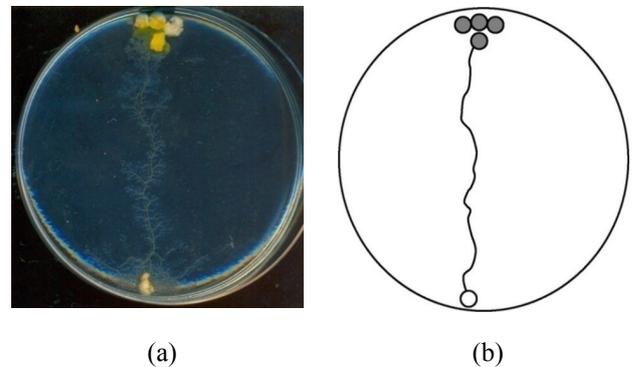
Fig. 1 An 'ideal' example of plasmodium attracted by source of nutrients. Initially an oat flake colonized by plasmodium is placed in the southern part of Petri dish, and a group of intact oat flakes in the northern part. Plasmodium propagates towards the intact flakes and occupies them. (a) Snapshot the experimental Petri dish with the plasmodium. (b) Scheme of the plasmodium attraction: initial position of the plasmodium is shown by circle, newly occupied oat flakes (attractants) by solid discs, trajectory of the plasmodium by curve. This figure is from the book [20]. *Courtesy of Andy Adamatzky*

In this paper we will show that the behavior of local group of the genus *Trichobilharzia* Skrjabin & Zakharov, 1920 (Schistosomatidae Stiles & Hassall, 1898) can be simulated by Physarum logic. This means that, first, a local group of Schistosomatidae can behave as a programmable biological computer, second, a biologized kind of π-calculus such as Physarum spatial logic can describe concurrent biological processes at all.

II. Physarum Spatial Logic

In this section we will consider some basics of Physarum spatial logic.

The behavior of Physarum plasmodium can be divided into the following elementary processes: inaction, fusion, cooperation, and choice, which could be interpreted as unconventional (spatial) falsity, conjunction, weak and strong disjunction respectively, denoted by *Nil*, &, |, and +. These

operations differ from conventional ones, because they cannot have a denotational semantics in the standard way. However, they may be described as special spatial transitions over states of Physarum machine: inaction (*Nil*) means that pseudopodia has just stopped to behave; fusion (&) means that two pseudopodia come in contact one with another and then merge; cooperation (|) means that two pseudopodia behave concurrently; choice (+) means a competition between two pseudopodia in their behaviors.

A π-calculus for describing the dynamics of Physarum machine is presented as a labeled transition system with some logical relations.

Assume that there are N active species or growing pseudopodia and the state of species i is denoted by $p_i \in$ L. These states are time dependent and they are changed by plasmodium's active zones interacting with each other and affected by attractants or repellents. Plasmodium's active zones interact concurrently and in a parallel manner. Foraging plasmodium can be represented as a set of the following abstract entities.

• The set of actions (growing pseudopodia), T' = {α, β, ...}, localized in *active zones*. The actions from T' are called the *simplest transitions*, the latter are defined as $\left\{ p \xrightarrow{\alpha} q : p, q \in L, \alpha \in T' \right\}$. Notice that we also have transitions that do not belong to T'. Assume that the set of all transitions is denoted by T.

On a nutrient-rich substrate plasmodium propagates as a typical circular, target wave, while on the nutrient-poor substrates localized wave-fragments are formed. Each action $\alpha \in$ T', starts on a state p_i, which is its current position, and says about a transition (propagation) of a state p_i to another state of the same or another computation cell. Part of plasmodium feeding on a source of nutrients may not propagate, so its transition may be *Nil*, but this part can always start moving.

• The set of *attractants* {A_1, A_2, ...} $\subset$ T \ T' are sources of nutrients, on which the plasmodium feeds. It is still subject of discussion how exactly plasmodium feels presence of attractants. Each attractant A is a function from T' to T'.

• The set of *repellents* {R_1, R_2, ...} $\subset$ T \ T'. Plasmodium of Physarum avoids light and some thermo- and salt-based conditions. Thus, domains of high illumination are repellents such that each repellent R is characterized by its position and intensity of illumination, or force of repelling. In other words, each repellent R is a function from T' to T'.

• The set of *protoplasmic tubes* {C_1, C_2, ...} $\subset$ T \ T'. Typically plasmodium spans sources of nutrients with protoplasmic tubes/veins. The plasmodium builds a planar graph, where nodes are sources of nutrients, e.g. oat flakes, and edges are protoplasmic tubes. $C(\alpha)$ means a diffusion of growing pseudopodia $\alpha \in$ T'.

Hence, T = T' $\cup$ {A_1, A_2, ...} $\cup$ {R_1, R_2, ...} $\cup$ {C_1, C_2, ...}.

Our process calculus contains the following basic operators: *Nil* (inaction), · (prefix), | (cooperation), \ (hiding), &

(reaction/fusion), + (choice), a (constant or restriction to a stable state), $A(\cdot)$ (attraction), $R(\cdot)$ (repelling), $C(\cdot)$ (spreading/diffusion). Let T = {a, b, ...}, the set of all actions (evidently, this set is finite), be considered as a set of names. A name refers to a communication link or channel. With every $a \in$ T we associate a complementary action $\bar{a}$. Let us suppose that a designates an input port and $\bar{a}$ designates an output port. Any behavior of Physarum will be considered as outputs and any form of outside control and stimuli as appropriate inputs. For instance, T' is to be regarded just as the set of output ports and thereby T \ T' contains ports that can be interpreted under different conditions as input ports or output ports. So, for each $X \in$ {A_1, A_2, ...} $\cup$ {R_1, R_2, ...}, we take that $X(\gamma) = \delta$ is a function from T' to T' such that X is a stimulus for γ and X makes an output $\delta \in$ T' along γ. Evidently that $X(Nil) = Nil$. Let $X(\gamma)$ denote an input and $\overline{X(\gamma)}$ an output.

Define **L** be the set of labels built on T (under this interpretation, $a = \bar{\bar{a}}$). Suppose that an action a communicates with its complement $\bar{a}$ to produce the internal action τ and τ belongs to **L**, too.

We use now the symbols γ, δ, ... , etc., to range over labels (actions), with $a = \bar{\bar{a}}$, and the symbols P, Q, etc., to range over processes on states p_i. The processes are given by the syntax:

$$P, Q ::= Nil \mid \gamma.P \mid A(\gamma).P \mid \overline{A(\gamma)}.P \mid R(\gamma).P \mid \overline{R(\gamma)}.P \mid$$
$$C(\gamma).P \mid (P \mid Q) \mid P \setminus Q \mid P \& Q \mid P + Q \mid a$$

Each label is a process, but not vice versa, because a process may consists of many labels combined by the basic operators.

An operational semantics for this syntax is defined as follows: $\gamma ::= p_i$, where $p_i \in$ L.

$$\text{Prefix} : \frac{}{\gamma.P \xrightarrow{\gamma} P},$$

$$\frac{}{A(\gamma).P \xrightarrow{\delta} P} (A(\gamma) = \delta), \quad \frac{}{\overline{A(\gamma)}.P \xrightarrow{\delta} P} (\overline{A(\gamma)} = \delta),$$

$$\frac{}{R(\gamma).P \xrightarrow{\delta} P} (R(\gamma) = \delta), \quad \frac{}{\overline{R(\gamma)}.P \xrightarrow{\delta} P} (\overline{R(\gamma)} = \delta),$$

(the conclusion states that the process of the form $\gamma.P$ (resp. $A(\gamma).P$, $\overline{A(\gamma)}.P$, $R(\gamma).P$, $\overline{R(\gamma)}.P$) may engage in γ (resp. $A(\gamma)$, $\overline{A(\gamma)}$, $R(\gamma)$, $\overline{R(\gamma)}$) and thereafter they behave like P; in the presentations of behaviors as trees, $\gamma.P$ (resp. $A(\gamma).P$, $\overline{A(\gamma)}.P$, $R(\gamma).P$, $\overline{R(\gamma)}.P$) is understood as an

edge with two nodes: γ (resp. $A(\gamma)$, $\overline{A(\gamma)}$, $R(\gamma)$, $\overline{R(\gamma)}$) and the first action of P),

Diffusion: $\dfrac{P \overset{\gamma}{\to} P'}{P \overset{\gamma}{\to} C(\gamma)}$ $\quad (C(\gamma) = P')$,

Constant: $\dfrac{P \overset{\gamma}{\to} P'}{a \overset{\gamma}{\to} P'}$ $\quad (a = P, a \in L)$,

Choice: $\dfrac{P \overset{\gamma}{\to} P'}{P + Q \overset{\gamma}{\to} P'}$, $\dfrac{Q \overset{\gamma}{\to} Q'}{P + Q \overset{\gamma}{\to} Q'}$,

(these both rules state that a system of the form $P + Q$ saves the transitions of its subsystems P and Q),

Cooperation: $\dfrac{P \overset{\gamma}{\to} P'}{P | Q \overset{\gamma}{\to} P' | Q}$, $\dfrac{Q \overset{\gamma}{\to} Q'}{P | Q \overset{\gamma}{\to} P | Q'}$,

(according to these rules, the cooperation | interleaves the transitions of its subsystems),

$$\dfrac{P \overset{\gamma}{\to} P' \quad Q \overset{\overline{\gamma}}{\to} Q'}{P | Q \overset{\tau}{\to} P' | Q'},$$

(i.e. subsystems may synchronize in the internal action τ on complementary actions γ and $\overline{\gamma}$),

Hiding : $\dfrac{P \overset{\gamma}{\to} P'}{P \setminus Q \overset{\gamma}{\to} P' \setminus Q}$ $(\gamma \notin Q, Q \subseteq \mathbf{L})$,

(this rule allows actions not mentioned in Q to be performed by $P \setminus Q$),

Fusion : $\dfrac{}{\gamma.P \ \& \ \breve{P} \overset{\gamma}{\to} Nil}$

(the fusion of dual processes are to be performed into the inaction, e.g. a fusion of an attractant/repellent P and appropriate repellent/attractant $\breve{P}$),

$$\dfrac{P \overset{\gamma}{\to} P' \quad Q \overset{\gamma}{\to} P'}{P \wedge Q \overset{\gamma}{\to} P'}, \quad \dfrac{P \overset{\gamma}{\to} P' \quad Q \overset{\gamma}{\to} P'}{Q \wedge P \overset{\gamma}{\to} P'}$$

(this means that if we obtain the same result P' that is produced by the same action γ and evaluates from two different processes P and Q, then P' may be obtained by that action γ started from the fusion $P \ \& \ Q$ or $Q \ \& \ P$),

$$\dfrac{P \overset{\gamma}{\to} P'}{P \wedge Q \overset{\gamma}{\to} Nil + C(\gamma) + P'}, \quad \dfrac{P \overset{\gamma}{\to} P'}{Q \wedge P \overset{\gamma}{\to} Nil + C(\gamma) + P'}$$

(these rules state that if the result P' is produced by the action γ from the processes P, then a fusion $P \ \& \ Q$ (or $Q \ \& \ P$) is transformed by that same γ either into the inaction or diffusion or process P').

These are inference rules for basic operations. The ternary relation $P \overset{\gamma}{\to} P'$ means that the initial action P is capable of engaging in action γ and then behaving like P'.

Now we can show that in the behavior of any local group of Schistosomatidae we can observe the same elementary processes: inaction, fusion, cooperation, and choice, which are defined in the same way.

III. LIFE CYCLE OF SCHISTOSOMATIDAE (TREMATODA : DIGENEA)

All representatives of subclass Digenea Carus, 1863 (Platyhelminthes: Trematoda) are exclusively endoparasites of animals. The digenean life cycle has the form of heterogony, i.e. there is a natural alternation of amphimictic (usually synarmophytous) and parthenogenetic stages. At these stages digeneae have different outward, different means of reproduction and different adaptation to different hosts. The interchange of hosts is necessary for a successful realization of digenean flukes life cycle. The majority of representatives of this subclass have a complete life cycle with participation of three hosts: intermediate, additional (metacercarial) and definitive. Molluscs are always the first intermediate hosts, while different classes of vertebrate animals are definitive hosts.

Among digeneae there is a bunch of parasites, belonging to the family of Schistosomatidae, which represents an isolated bunch which has adapted to parasitizing in the circulatory system of vertebrate animals. Puberal representatives of this family are diecious individuals (in other digenean families maritas are hermaphrodites). The family includes the following three subfamilies: Schistosomatinae Stiles and Hassall, 1898, they parasitize a variety of birds and mammals, including human being; Bilharziellinae Price, 1929 and Gigantobilharziinae Mehra, 1940, they parasitize birds. Representatives of the first subfamily (in particular the genus *Schistosoma* Weinland, 1858) parasitize mammals, including human being. In the tropical and subtropical countries, about 200 million persons are infected by them from which 11 thousand persons annually die because of the given infestation [13]. Representatives of the latter two subfamilies, the so-called avian schistosomatidae, have been observed on all continents, including Europe. In a puberal state they parasitize birds, however they are capable to incorporate into a human organism as nonspecific host. After they penetrate human skin, where they perish, they invoke thereby allergic dermatitis. The fact of incorporation of these larvae into nonspecific hosts invokes interest to avian schistosomatidae. Therefore the simulation of behavior of their local groups can be interesting from a medicine view, be-

cause it allows to perceive better features of digenean be-
havior. Simulating their behavior is possible by means of
Physarum spatial logic as we will show.

The life cycle of all representatives of the family Schisto-
somatidae is identical, it passes with participation of two
hosts.

From an egg which got to water from an organism of de-
finitive host, a miracidia hatchs. It is a settle free-swimming
larval stage of parthenogenetic generation of Schistosomati-
dae. Miracidia for a short span should find a molluc of a cer-
tain kind to insinuate into it, otherwise it perishes. Molluscs,
thus, are attractants for miracidiae. More precisely, in re-
spect to miracidiae the chemotaxis as attractant holds
(miracidia moves towards a chemical signal proceeding
from a molluc). Other kinds of attractants for miracidiae are
presented by light (there is a positive phototaxis) and gravi-
tation (negative geotaxis). We will designate all miracidian
attractants by A^m_1, A^m_2, ..., A^m_n.

Miracidian repellents have not been detected still, i.e.
$\{R^m_1, R^m_2, ..., R^m_n\} = \varnothing$.

The continuation of digenean life cycle will take place
just in case a miracidia detects a mollusc for which a certain
kind of digeneas has a hostal specificity [10]. Otherwise the
miracidia dies. Miracidiae *Trichobilharzia szidati* Neuhaus,
1952 can look for a intermediate host only for the period of
20 h at temperature 20 °C [14].

In a body of mollusc, a miracidia undergoes metamorpho-
sis and it is transformed into a mother sporocyst in which
daughter sporocysts educe. In the latter then cercariae start
to be formed. This state can be called the miracidian diffu-
sion. We will designate these diffusions by C^m_1, C^m_2, ..., C^m_n.

Now we can construct a version of Physarum spatial logic
for simulating the behavior of local groups of miracidiae.
The processes have the following syntax which is defined in
the way of Physarum logic:

$$P, Q ::= Nil \mid \gamma.P \mid A^m(\gamma).P \mid \overline{A^m(\gamma)}.P \mid$$
$$C^m(\gamma).P \mid (P \mid Q) \mid P \setminus Q \mid P \& Q \mid P + Q \mid a$$

For the simulation we need also to have two sets of ac-
tions T and T^m, where T contains actions of Physarum plas-
modium, T^m includes actions of local group of miracidiae.
These sets should have the same number of members (the
same cardinality), namely we should have the same number
of active zones (growing pseudopodia and active
miracidiae), the same number of attractants, and the same
number of diffusions (motions of protoplasmic tubes to-
wards food and miracidian motions towards chemical sig-
nals of eventual hosts to transform into a maternal sporo-
cyst). For instance, if we have five molluscs in one experi-
mental dish with water and a suspension of miracidiae, then
we can try to simulate the miracidian processes by Physarum
spatial logic for stimuli of five nutrient sources with similar
localizations as that for molluscs.

IV. THE BEHAVIOR OF CERCARIAE OF BIRD SCHISTOSOMES (GENUS *TRICHOBILHARZIA*)

The cercarial behavior of bird schistosomes (family
Schistosomatidae) is well studied due to representatives of
the genus *Trichobilharzia* [11]. Their behavior is character-
ized by specific taxises which are referred to an effective
search of necessary definitive hosts. These taxises developed
by evolution of larvae of bird schistosomes allow their look-
ing for specific hosts to be successful, forward their affixion
to a surface of host body as well as their incorporation into a
host cutaneous covering and their penetration into a circula-
tory system, where a parasite reaches sexual maturity. Thus,
taxises form an enough large family of attractants for cer-
cariae.

In a resting state, cercariae are attached to a vascular wall
or on a water film by means of acetabulum. Active motions
are characteristic only by the strong shaking of pot or by the
water interfusion. At a weak rotation of pot it is visible that
the cercarial body and its tail follow the water stream, while
their acetabulums keep cercariae on the pot wall. Any con-
tinuous active motion is not observed.

Cercariae of the genus *Trichobilharzia* after leaving a
mollusc actively swiming in the water for an hour. Such an
active behavior of larvae after leaving a mollusc provides a
cercarial allocation in water space. Then cercariae pass to a
passive behavior. They are attached by a ventral sucker to a
surface film of water or to various subjects near a water sur-
face, getting thus a characteristic resting state. The resting
state allows cercariae in absence of specific to them stimu-
lants to stop the search of host and to conserve their energy.

Free-swiming cercariae need to insinuate into a definitive
host during the limited time interval (1–1.5 days at tempera-
ture 24°C) since otherwise larvae perish [14].

For successful search of hosts, larvae of digeneae of *Tri-
chobilharzia* have developed by evolution a behavior facili-
tating this problem. They possess a positive phototaxis, neg-
ative geotaxis, chemotaxis, and also actively react to turbu-
lence of water [7]. It means that for cercariae there are al-
ready many other attractants.

The light sensitivity of cercariae of *Trichobilharzia* is
very high. As experiments show, cercariae always move to-
wards a light source, and then take a resting state on the
lighted side of capacity in which they are. The given taxis,
and also negative geotaxis allow cercariae to be kept in the
nature at a surface of water in expectation of suitable hosts.

Cercariae actively react to changes in intensity of illumi-
nation (shadings) and to turbulence of water [5]. These ex-
ternal factors, corresponding to possible appearances of de-
finitive hosts in water, stimulate the cercarial transition from
a resting state into actions that enlarge their chances to meet
hosts.

Cercariae possess a chemotaxis in relation to specific
hosts. On body surfaces larvae of the genus *Trichobilharzia*
have chemoreceptors which receive appropriate chemical
signals proceeding from a skin of potential host. The simi-
larity of compound of fatty acids of bird and human skin
leads to that cercariae equally react to the bird and human
appearance in water: they move in their direction, and then

they are attached to skin and begin penetration into it [9]. So, the chemotaxis from a skin of potential hosts (surface lipids of skin of human being and swimming bird), the positive phototaxis, the negative geotaxis and the water turbulence present cercarial attractants of different degree of appeal. We will designate these attractants by A^c_1, A^c_2, …, A^c_n.

In experimental researches it has been shown that any attachment of cercariae of *Trichobilharzia* to skin is stimulated by cholesterol and ceramides, and incorporation into skin by linoleic and linolenic acids, all these materials are present on skin of both bird and human being [12; 8]. Thereby surface lipids of human skin invoke higher frequency of cercarial incorporations into skin, than surface lipids of birds [9]. One more reason that cercariae of *Trichobilharzia* successfully insinuate into human skin is the fact of that the skin of duck foots has thicker keratinized surface which, possibly, is more difficult for overcoming, than that of human being [8].

On the basis of experiments the rate of penetration of larvae of schistosomes *Trichobilharzia szidati* into human skin [8] has been defined. The larva begins incorporation into human skin approximately in 8 seconds (range from 0 to 80 seconds) after first contacts. The process of full penetration into skin takes about 4 minutes (range from 83 till 13 minutes 37 seconds). The given numerals testify that it is enough if the person has even a short-term contact to water where there are cercariae of bird schistosomes to give them possibility to incorporate into skin.

In some cases, for example children, cercarial larvae can "chip" skin and be brought by venous blood to lungs, invoking there hemorrhages and inflammation. If cercariae are lucky to insinuate into blood and then to lungs, the disease can get harder by the pulmonary syndrome from small cough to symptoms of bronchial obstruction [18].

At the same time, repellents for cercariae have not been found yet. For example, Ludmila Akimova's experience shows that cercarial motions towards a smaller concentration of material which invokes a destruction of larvae are not observed at all. The experience principle consists in that in a small cavity with the length of 10 cm, the width and depth of 0.5 cm there is water with a suspension of cercariae. Then a thin essential oil is added in one of the side of this small cavity. Cercariae, which are nearby, quickly perish, although other cercariae do not move aside where the reacting material is absent. Cercariae simply freely float and as soon as they appear in that part where there is the reacting material they perish. Thus, $\{R^c_1, R^c_2, …, R^c_n\} = \varnothing$.

In definitive hosts cercariae reach diffusion states. We will designate these diffusions by C^c_1, C^c_2, …, C^c_n.

The behavior of local groups of cercariae can be simulated within a version of Physarum spatial logic, where the processes have the following syntax defined in section II:

$$P, Q ::= Nil \mid \gamma.P \mid A^c(\gamma).P \mid \overline{A^c(\gamma)}.P \mid$$
$$C^c(\gamma).P \mid (P \mid Q) \mid P \setminus Q \mid P \,\&\, Q \mid P + Q \mid a$$

The sets of actions T and T^c, where T consists of actions of Physarum plasmodium, T^c contains actions of local group

of cercariae, should have the same number of members. For example, if we have three human beings in one lake with cercariae, then we can simulate the cercarial processes by Physarum spatial logic where three nutrient sources with similar localizations as that for human beings act as stimuli. Hence, the behavior of local groups of cercariae is another biological implementation of Kolmogorov-Uspensky machines. It can build planar graphs as well.

V. Arithmetic Operations in Physarum Spatial Logic and in Schistosomatidae Behavioral Logic

We know that within π-calculus we can convert expressions from λ-calculus. In particular, it means that we can consider arithmetic operations as processes. Physarum spatial logic as well as its modification in the form of behavioral logic for local groups of miracidiae (cercariae) is a biologized version of π-calculus. Therefore we can convert arithmetic operations into processes of either Physarum spatial logic or schistosomatidae behavioral logic.

Indeed, growing pseudopodia may represent a natural number n by the following parametric process:

$$\underline{n}(x, z) ::= \underbrace{\overline{x}.\overline{x}.\cdots.\overline{x}}_{n}.\overline{z}.Nil$$

The process $\underline{n}(x, z)$ proceeds n times on an output port called the successor channel $\overline{x} \in \{A_1, A_2, ...\} \cup \{R_1, R_2, ...\}$ (e.g. it is the same output of attractant) and once on the zero output port $\overline{z} \in \{A_1, A_2, ...\} \cup \{R_1, R_2, ...\}$ before becoming inactive *Nil*. Recall that it is a "Church-like" encoding of numerals used first in λ-calculus. Notice that in case of miracidiae or cercariae $\overline{x} \in \{A_1, A_2, ...\}$ and $\overline{z} \in \{A_1, A_2, ...\}$.

An addition process takes two natural numbers i and j represented using the channels $x[i]$, $z[i]$ and $x[j]$, $z[j]$ and returns their sum as a natural number represented using channels $x[i+j]$, $z[i+j]$:

$$Add(x[i], z[i], x[j], z[j], x[i+j], z[i+j]) ::=$$
$$(x[i].\ \overline{x}[i+j].\ Add(x[i], z[i], x[j], z[j], x[i+j], z[i+j])) +$$
$$z[i].Copy(x[j], z[j], x[i+j], z[i+j])).$$

A multiplication process takes two natural numbers i and j represented using the channels $x[i]$, $z[i]$ and $x[j]$, $z[j]$ and returns their multiplication as a natural number represented using channels $x\big[\underbrace{i+...+i}_{j}\big]$, $z\big[\underbrace{i+...+i}_{j}\big]$:

$$Mult(x[i], z[i], x[j], z[j], x[i*j], z[i*j]) ::= Add(x[i], z[i],$$
$$x[j], z[j], x[i+...+i], z[i+...+i]).$$

The *Copy* process replicates the signal pattern on channels x and y on to channels u and v. It is defined as follows:

$$Copy(x, y, u, v) ::= (x.\ \overline{u}.\ Copy(x, y, u, v) + y.\ \overline{v}.\ Nil)$$

As we see, within Physarum spatial logic and its poorer version in the form of schistosomatidae behavioral logic we can consider some processes as arithmetic operations. Also, we can combine several arithmetic operations within one process. Let us regard the following expression:

$$(10 + 20) * (30 + 40)$$

An appropriate process is as follows:

$$Mult(Add(x[10], z[10], x[20], z[20], x[10+20], z[10+20]),$$
$$z[10+20], Add(x[30], z[30], x[40], z[40], x[30+40],$$
$$z[30+40]), z[30+40], Add(x[30], z[30], x[70], z[70], x[2100],$$
$$z[2100])).$$

VI. Conclusion

We show that many biologized versions of π-calculus are possible: Physarum spatial logic, schistosomatidae behavioral logic, etc. One of its basic versions, Physarum spatial logic, can be used for constructing slime mould based computer. This logic is richer than schistosomatidae behavioral logic and may be involved for simulations of the latter. The fact that we can formalize biological behaviors as kind of logic confirms that biological processes can be considered as forms of concurrent and parallel computations.

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