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SYLLOGISTIC SYSTEM FOR THE PROPAGATION OF PARASITES. THE CASE OF *SCHISTOSOMATIDAE* (TREMATODA: DIGENEA)

Abstract. In the paper, a new syllogistic system is built up. This system simulates a massive-parallel behavior in the propagation of collectives of parasites. In particular, this system simulates the behavior of collectives of trematode larvae (miracidia and cercariae).

Keywords: Physarum polycephalum, Trichobilharzia szidati, Schistosomatidae, Digenea, syllogistic, cercaria, miracidium.

1. Introduction

Now we are working on designing a biological computer on the medium of *Physarum polycephalum* [2]. This project is supported by FP7 (FP7-ICT-2011-8)¹ The point is that the plasmodium of *Physarum polycephalum* behaves and moves as a giant amoeba and its behavior can be considered a computer processor [1]. This allows us to use the plasmodium of Physarum as a spatial computing programmed by different configurations of attractants (substances with potentially high nutritional value) and repellents (some illumination-, thermo- and salt-based conditions). In [24], we showed that the behavior of plasmodium of *Physarum polycephalum* has its own spatial logic which is one of the natural implementations of process calculus. This logic, called *Physarum spatial logic*, can be used as a programming language for a biological computer based on plasmodia. Also, this logic can simulate the behavior of *Schistosomatidae* (Trematoda: Digenea) [25].

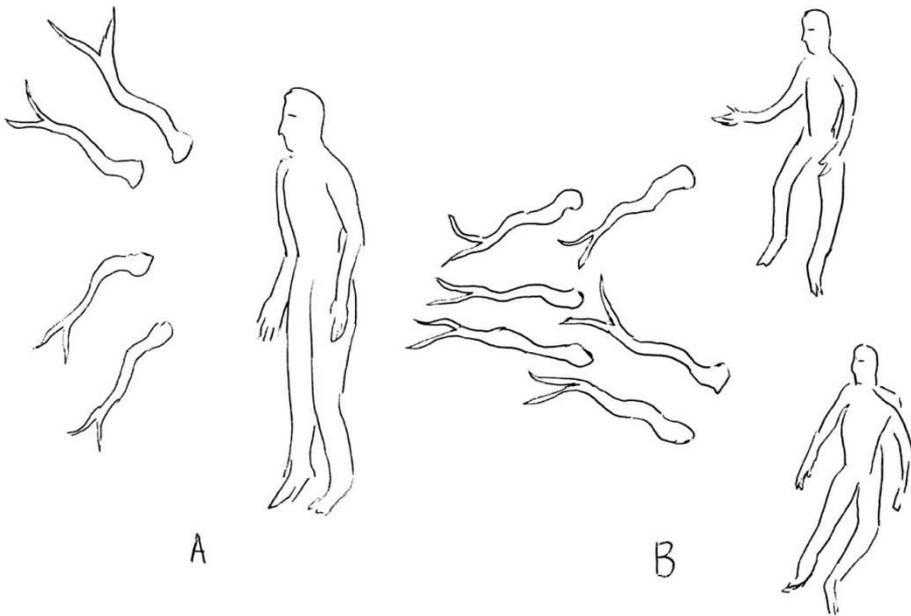


Figure 1. The stimulation of the following operations in cercariae motions: (A) the fusion of cercariae collectives, (B) the multiplication of cercariae collective, where the human beings are attractants

The basic acts of plasmodium are as follows: (i) *Direction*: the plasmodium moves towards the attractant; (ii) *Fusion*: the two plasmodia fuse after meeting the same attractant; (iii) *Split*: the plasmodium splits in front of many attractants. The same acts are observed in the behavior of *Schistosomatidae* cercariae (see Fig. 1) and many other parasites. The difference is just in different attractants: plasmodia are attracted by nutrients and cercariae are attracted by the fatty acids of bird or human skin.

We are constructing an object-oriented programming language [26] for modelling the behavior of plasmodia by thousands of attractants on the basis of the basic acts mentioned above. This complex behavior with many and many attractants, on the one hand, can implement complex computer algorithms and, on the other hand, show, how intelligent the *Physarum* plasmodium is. Within this object-oriented language we can model the behavior of collectives of the genus *Trichobilharzia* Skrjabin & Zakharov, 1920 (*Schistosomatidae* Stiles & Hassall, 1898) and the behavior of many other parasites, as well.

Schistosomatidae have been studied recently because of cercarial dermatitis which they cause in humans by the secretion of penetration glands.

Notice that the cercaria begins the incorporation into the human skin approximately in 8 seconds (the range from 0 to 80 seconds), just after first contact [9]. The process of full penetration into the skin takes about 4 minutes (the range from 83 seconds till 13 minutes 37 seconds). In human children, the cercariae can be brought by venous blood into the lungs, causing hemorrhages and inflammations [3]. Many other complications can come because of repeated infestations [3].

The meaning of the behavior of parasites such as cercariae consists in the propagation of their collectives in all possible directions in looking for hosts and then their further propagation according to their life cycle. That behavior is concurrent and not linear (it continuously splits and fuses). In this paper, we propose a syllogistic system for a computer modelling of this complex behavior within our language [26]. In this system, attractants for parasites are considered syllogistic letters. Any two neighbor attractants which can be immediately reached by the one collective of parasites are considered a syllogistic string that is true if both attractants are occupied by parasites and false otherwise. A good science-fiction example of the propagation of parasites is presented by the movie *World War Z* (2013) directed by Marc Forster. Zombies in this movie are attracted by the chemotaxis from able-bodied humans' sounds and motions, which causes the propagation of zombies in all possible directions. Cercariae are attracted by the chemotaxis from the skin of potential hosts, the turbulence of water, and lights. Note that the syllogistic system for modelling the propagation of parasites is proposed in this paper for the first time.

2. *Trichobilharzia szidati* (Digenea: Schistosomatidae) and their Life Cycle

All representatives of subclass *Digenea* Carus, 1863 (Platyhelminthes: Trematoda) including *Trichobilharzia szidati* are endoparasites of animals. Their life cycle has the form of heterogony: there are amphimictic and parthenogenetic stages. At these stages, digeneans have different outward, different ways of reproduction, and different adaptation to different specific and incompetent hosts. The majority of them have a life cycle with the participation of three hosts: intermediate, additional (metacercarial), and final. Molluscs are always the first intermediate hosts, while different classes of vertebrate animals are final hosts.

Among digeneans, there are parasites belonging to the family of *Schistosomatidae*, which have adapted to parasitizing in the circulatory system

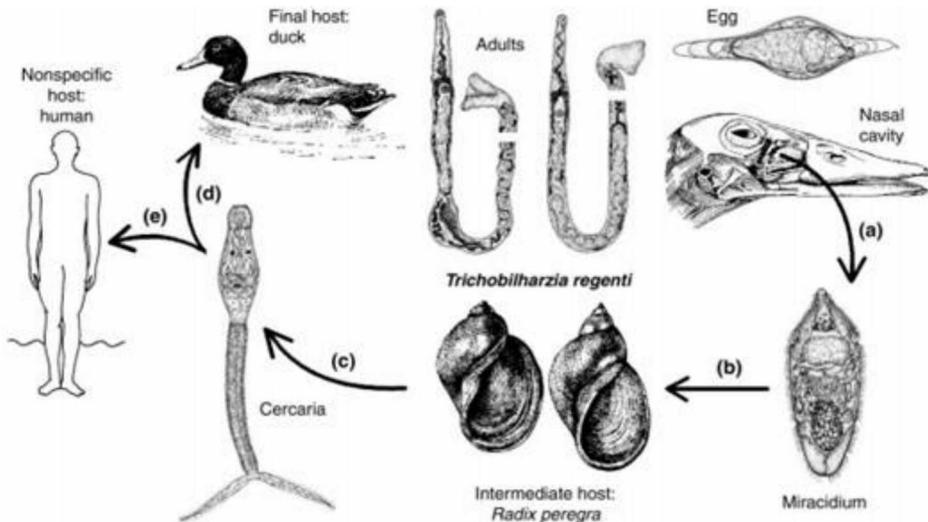


Figure 2. The life cycle of *Trichobilharzia regenti*: (a) mature worms lay the eggs in the nasal mucosa of ducks, then the eggs get to water and from these eggs miracidia hatch; (b) miracidia infect the intermediate hosts; (c) from these hosts cercariae are released; (d) they penetrate the skin of a specific host or (e) the skin of an incompetent mammalian host such as a human being (from [16])

of vertebrate animals. This family includes the following three subfamilies: *Schistosomatinae* Stiles and Hassall, 1898, which parasitize a variety of birds and mammals, including human beings; *Bilharziellinae* Price, 1929 and *Gigantobilharziinae* Mehra, 1940, which parasitize birds. *Schistosomatidae* can penetrate the human skin, where they perish and, therefore, invoke allergic dermatitis.

The life cycle of all representatives of the family *Schistosomatidae* is identical (see Fig. 2). Its members have the following two free-swimming stages: miracidia and cercariae, which actively search for their hosts (intermediate and final, respectively). Miracidial and cercarial host-finding is initiated mainly by response to some gravitational, light, and chemical attractants.

2.1. Miracidia (Genus *Trichobilharzia*): Morphology and Behavior

Miracidia are a free-swimming larval stage (Fig. 3). Their body surface is covered with four rows of epithelial plates that carry a multitude of cilia involved in the active motions of miracidia (Fig. 3, B). The anterior part of the body contains terminal openings of the following penetration unicellular glands: two cells of apical glands and two cells of lateral glands.

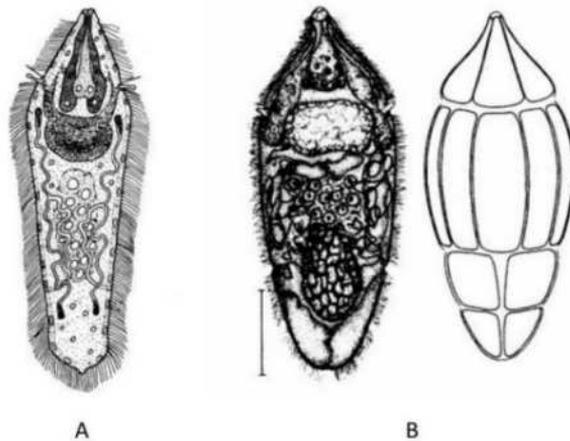


Figure 3. The morphology of miracidia. A. the general morphology of *Trichobilharzia szidati* (from [23]); B. the general morphology of *Trichobilharzia regenti* (left) and the arrangement of ciliated plates (right), scale bar = 25mm (from [16])

The posterior part of the body contains clusters of germ cells from which daughter sporosysts are formed subsequently. Miracidia lack any digestive system and they cannot feed.

Miracidia of *Trichobilharzia szidati* [23] hatch from eggs within a short time, 5-10 min. In order to survive, miracidia must infect a snail host within 20h at 24°C before they die [23]. The positive photo- and negative geotactic orientation is an adaptation to reach the preferred habitats of their host-snail species [11], [12], [14], [33], [34]. Also, it is now confirmed that miracidia are attracted by some chemical host signals [19], [23], [31], [32]. Snail-hosts release various secreted/excreted products into water. Miracidia are activated by the macromolecular components of these products, which consist of glycoproteins larger than 30 kDa, termed “miracidia attracting glycoproteins” [17]. These glycoproteins produced by different species of snails have a similar peptide-base, but differ by saccharide component. Miracidia can differentiate between these glycosylation patterns in order to find and infect mainly specific snail species [17], [18]. Thus, the chemical cues secreted by the freshwater gastropod *Lymnaea stagnalis* stimulate behavioral responses of *Trichobilharzia szidati* miracidia. In other words, a miracidium moves towards an appropriate chemical signal. Other kinds of attractants for miracidia are presented by light (there is a positive phototaxis) and gravitation (negative geotaxis). We will designate all miracidian attractants by sylogistic letters $S_{m_1}, S_{m_2}, \dots, S_{m_n}, P_{m_1}, P_{m_2}, \dots, P_{m_n}, M_{m_1}, M_{m_2}, \dots, M_{m_n}$. They can differ by their power and intensity.

2.2. Cercariae (Genus *Trichobilharzia*): Morphology and Behavior

Cercariae are free-swimming larvae of pubertal generation parasitizing vertebrate animals. Their length is about 1.0mm. They are capable of insinuating into the skin of a human being who is for them an incompetent host. As a result, they cause an allergic reaction, the so-called *cercarial dermatitis*. This term was proposed by V. V. Cort [4], who for the first time correlated this disease with molluscs of certain kinds, and then with cercariae.

Cercariae of the genus *Trichobilharzia* belong to the bunch of furcocercariae; their posterior tail part consists of two branches (furcae), and the length of furca is approximately half the length of the tail. Even in a small zoom its pigmented eye-spots are well visible. The cercarial body is translucent. During motion it is strongly reduced, receiving various forms (Fig. 4).

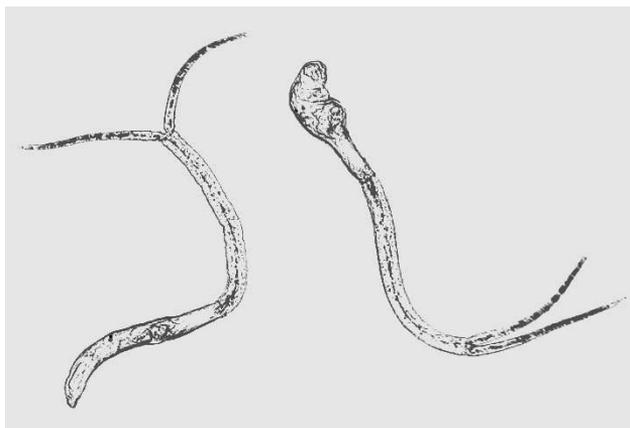


Figure 4. The appearance of *Trichobilharzia szidati*. A detection place: the lake of Naroch (the Minsk region, the Mjadelsky district). *Lymnaea stagnalis* is an intermediate host

All European species of *Trichobilharzia* possess five pairs of penetration glands (Fig. 5). Two pairs are presented by circumacetabular glands located round the ventral sucker, and the three other by postacetabular glands located sequentially one after another below. The secreta of penetration glands helps larvae to break the dermal barrier of vertebrate hosts.

Cercariae of the genus *Trichobilharzia* after leaving a mollusc actively swim in the water for an hour. Such active behavior of larvae after leaving a mollusc provides a cercarial distribution in the water space. Then cercariae pass to a passive behavior. Free-swimming cercariae need to insinuate into a final host during a limited time interval (1–1.5 days

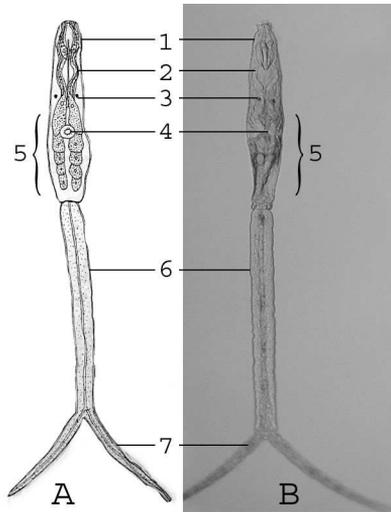


Figure 5. The constitution of *Trichobilharzia szidati*. A. The schematic structure of cercaria (from [5]), B. The photo of cercaria. 1. Penetration organ, 2. Penetration gland ducts, 3. Pigmented eye-spots, 4. Ventral sucker, 5. Penetration glands (5 pairs), 6. Tail stem, 7. Furcae

at temperature 24°C) [23]. 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 a pot or by water interfusion.

The cercarial behavior of bird schistosomes (family *Schistosomatidae*) has been well studied due to representatives of the genus *Trichobilharzia* [16]. Their behavior is characterized by the specific taxis implying their looking for specific hosts, their affixion to the surface of a host body as well as their incorporation into a host's cutaneous covering, and their penetration into a circulatory system, where a parasite reaches sexual maturity. Thus, taxis is presented by a large enough family of attractants: larvae of digeneans of *Trichobilharzia* possess a positive phototaxis, negative geotaxis, chemotaxis, and also actively react to turbulence of water [8].

Larvae have chemoreceptors which receive appropriate chemical signals proceeding from the skin of a potential host. The similarity of compound of fatty acids of bird and human skin leads to cercariae equally reacting to bird or human appearance in water: they move in their direction, and then they are attached to the skin and begin penetration into it [10]. In experimental research, it has been shown that any attachment of cercariae of *Trichobilharzia* to the skin is stimulated by cholesterol and ceramides,

and incorporation into the skin by linoleic and linolenic acids, all materials present on the skin of both the bird and the human being [9], [20]. Thereby the surface lipids of human skin invoke a higher frequency of cercarial incorporations into the skin than the surface lipids of birds [10].

Hence, the chemotaxis from the skin of potential hosts, the positive phototaxis, the negative geotaxis, and the water turbulence should be considered cercarial attractants, which will be designated by $S_{c_1}, S_{c_2}, \dots, S_{c_n}, P_{c_1}, P_{c_2}, \dots, P_{c_n}, M_{c_1}, M_{c_2}, \dots, M_{c_n}$.

3. Syllogistic System for the Propagation of *Schistosomatidae*

The alphabet of the syllogistic system for modelling the propagation of *Schistosomatidae* contains

- as descriptive signs the syllogistic letters S_x, P_x, M_x, \dots , where $x \in \{m, c\}$;
- as logical-semantic signs the syllogistic connectives
 - $\mathbf{a}_t, \mathbf{e}_t, \mathbf{i}_t, \mathbf{o}_t$ at time $t = 0, 1, \dots, n, \dots$,
 - $\mathbf{a}_\infty, \mathbf{e}_\infty, \mathbf{i}_\infty, \mathbf{o}_\infty$ for infinite time;
- and the propositional connectives $\neg, \vee, \wedge, \Rightarrow$.

Simple propositions are defined as follows: $S_x \star P_x$, where $\star \in \{\mathbf{a}_t, \mathbf{e}_t, \mathbf{i}_t, \mathbf{o}_t, \mathbf{a}_\infty, \mathbf{e}_\infty, \mathbf{i}_\infty, \mathbf{o}_\infty\}$. All other propositions are defined thus: (i) each simple proposition is a proposition, (ii) if X, Y are propositions, then $\neg X, \neg Y, X \star Y$, where $\star \in \{\vee, \wedge, \Rightarrow\}$, are propositions, too.

Syllogistic letters S_m, P_m, M_m, \dots are interpreted as attractants for miracidia as follows: a data point S_m is evaluated as empty if and only if an appropriate attractant for miracidia denoted by S_m is not occupied by any miracidium. Syllogistic letters S_c, P_c, M_c, \dots are interpreted as attractants for cercariae in the following manner: an item S_c is evaluated as empty if and only if an appropriate attractant for cercariae denoted by S_c is not occupied by any cercaria.

Let us define syllogistic strings of the form $S_m P_m$ and $S_c P_c$ at time t with the following notation: ' $S_m is_t P_m$ ' and ' $S_c is_t P_c$,' and with the following meaning:

- $S_m P_m$ at time $t = 0, 1, 2, \dots$ is true if and only if S_m and P_m are cells occupied by miracidia at t and there is a path between S_m and P_m and this path consists of cells also occupied by miracidia at t (i.e. both S_m and P_m are not empty at t and between them there is a path of non-empty cells), otherwise $S_m P_m$ is false (e.g. in Fig. 6 there are paths $S_4 S_5, S_4 S_{10}$ at $t = 0$);

- $S_c P_c$ at t is true if and only if both S_c and P_c are not empty cells at t and between them there is a path of non-empty cells at t , otherwise $S_c P_c$ is false.

Now, we define syllogistic propositions ‘All ... are ...’, ‘No ... are ...’, ‘Some ... are ...’, ‘Some ... are not ...’ in a non-Aristotelian way to construct a syllogistic of propagation. The meaning of the proposition ‘All S are P ’ is that between points S and P we observe a propagation in all possible directions. The meaning of the proposition ‘Some S are P ’ is that between points S and P we cannot observe a propagation in all possible directions and the propagation is just contingent and casual. So, while in the Aristotelian syllogistic the propositions ‘All ... are ...’ and ‘No ... are ...’ are contrary, in the syllogistic of propagation the propositions ‘All ... are ...’ and ‘Some ... are ...’ are contrary. Other propositions are understood conventionally: ‘No ... are ...’ := It is false that ‘Some ... are ...’; ‘Some ... are not ...’ := It is false that ‘All ... are ...’. The point of this non-Aristotelian interpretation is that we cannot exclude propagation at all. There are always some forms of propagation from massive-parallel (when ‘All ... are ...’ is true) to casual (when ‘Some ... are ...’ is true). For more details about this non-Aristotelian system, please see [27], [28].

Thus, using the definition of syllogistic strings, we can define simple syllogistic propositions as follows:

1. ‘All S_m are P_m at time t ’ ($S_m \mathbf{a}_t P_m$): there is a string $A_m S_m$ at time t and for any A_m which is a neighbor for S_m or P_m , there are strings $A_m S_m$ and $A_m P_m$ at t . This means that we have a massive-parallel occupation of the region at t , where the cells S_m and P_m are located, i.e. the propagation holds in all possible directions.
2. ‘All S_c are P_c at time t ’ ($S_c \mathbf{a}_t P_c$): there is a string $A_c S_c$ at time t and for any A_c which is a neighbor for S_c or P_c , there are strings $A_c S_c$ and $A_c P_c$ at t .
3. ‘Some S_m are P_m at time t ’ ($S_m \mathbf{i}_t P_m$): for any A_m which is a neighbor for S_m or P_m at t , there are no strings $A_m S_m$ and $A_m P_m$. This means that the collective of miracidia cannot reach S_m from P_m or P_m from S_m immediately at t , but it does not mean that there are no propagating miracidia. Some forms of their propagation ever exist.
4. ‘Some S_c are P_c at time t ’ ($S_c \mathbf{i}_t P_c$): for any A_c which is a neighbor for S_c or P_c at t , there are no strings $A_c S_c$ and $A_c P_c$.
5. ‘No S_m are P_m at time t ’ ($S_m \mathbf{e}_t P_m$): there exists A_m at time t which is a neighbor for S_m or P_m such that there is a string $A_m S_m$ or there is a string $A_m P_m$. This means that the collective of miracidia occupies S_m or P_m , but surely not the whole region at time t , where the cells S_m and P_m are located.

6. ‘No S_c are P_c at time t ’ ($S_c\mathbf{e}_tP_c$): there exists A_c at time t which is a neighbor for S_c or P_c such that there is a string A_cS_c or there is a string A_cP_c .
7. ‘Some S_m are not P_m at time t ’ ($S_m\mathbf{o}_tP_m$): for any A_m which is a neighbor for S_m or P_m at time t there is no string A_mS_m or there exists A_m which is a neighbor for S_m and P_m such that there is no string A_mS_m or there is no string A_mP_m . This means that at time t the collective of miracidia does not occupy S_m or there is a neighbor cell which is not connected with S_m or P_m by the same propagated collective of miracidia.
8. ‘Some S_c are not P_c at time t ’ ($S_c\mathbf{o}_tP_c$): for any A_c which is a neighbor for S_c or P_c at time t there is no string A_cS_c or there exists A_c which is a neighbor for S_c or P_c such that there is no string A_cS_c or there is no string A_cP_c .

Formally:

$$S_m\mathbf{a}_tP_m := (\exists A_m(A_m\text{ is}_t S_m) \wedge (\forall A_m(A_m\text{ is}_t S_m \wedge A_m\text{ is}_t P_m))); \quad (1)$$

$$S_c\mathbf{a}_tP_c := (\exists A_c(A_c\text{ is}_t S_c) \wedge (\forall A_c(A_c\text{ is}_t S_c \wedge A_c\text{ is}_t P_c))); \quad (2)$$

$$S_m\mathbf{i}_tP_m := \forall A_m(\neg(A_m\text{ is}_t S_m) \wedge \neg(A_m\text{ is}_t P_m)); \quad (3)$$

$$S_c\mathbf{i}_tP_c := \forall A_c(\neg(A_c\text{ is}_t S_c) \wedge \neg(A_c\text{ is}_t P_c)); \quad (4)$$

$$S_m\mathbf{e}_tP_m := \neg\forall A_m(\neg(A_m\text{ is}_t S_m) \wedge \neg(A_m\text{ is}_t P_m)), \text{ i.e.} \\ \exists A_m(A_m\text{ is}_t S_m \vee A_m\text{ is}_t P_m). \quad (5)$$

$$S_c\mathbf{e}_tP_c := \neg\forall A_c(\neg(A_c\text{ is}_t S_c) \wedge \neg(A_c\text{ is}_t P_c)), \text{ i.e.} \\ \exists A_c(A_c\text{ is}_t S_c \vee A_c\text{ is}_t P_c). \quad (6)$$

$$S_m\mathbf{o}_tP_m := \neg(\exists A_m(A_m\text{ is}_t S_m) \vee (\forall A_m(A_m\text{ is}_t P_m \wedge A_m\text{ is}_t S_m))), \quad (7) \\ \text{i.e.} (\forall A_m\neg(A_m\text{ is}_t S_m) \wedge \exists A_m(\neg(A_m\text{ is}_t P_m) \vee \neg(A_m\text{ is}_t S_m)));$$

$$S_c\mathbf{o}_tP_c := \neg(\exists A_c(A_c\text{ is}_t S_c) \vee (\forall A_c(A_c\text{ is}_t P_c \wedge A_c\text{ is}_t S_c))), \quad (8) \\ \text{i.e.} (\forall A_c\neg(A_c\text{ is}_t S_c) \wedge \exists A_c(\neg(A_c\text{ is}_t P_c) \vee \neg(A_c\text{ is}_t S_c)));$$

Notably, this system is essentially non-Aristotelian, in particular $S_m\mathbf{a}_tP_m \Rightarrow S_m\mathbf{e}_tP_m$; $S_m\mathbf{i}_tP_m \Rightarrow S_m\mathbf{o}_tP_m$; $S_m\mathbf{a}_tP_m \Rightarrow P_m\mathbf{a}_tS_m$; $S_m\mathbf{e}_tP_m \Rightarrow P_m\mathbf{e}_tS_m$; $S_m\mathbf{i}_tP_m \Rightarrow P_m\mathbf{i}_tS_m$; $S_m\mathbf{o}_tP_m \Rightarrow P_m\mathbf{o}_tS_m$.

The topology of attractants changes permanently (see Fig. 6), because different attractants become occupied in due course. Therefore for different time $t = 0, 1, 2, \dots$, we observe different true syllogistic propositions (see Fig. 6).

Syllogistic system for the propagation of parasites...

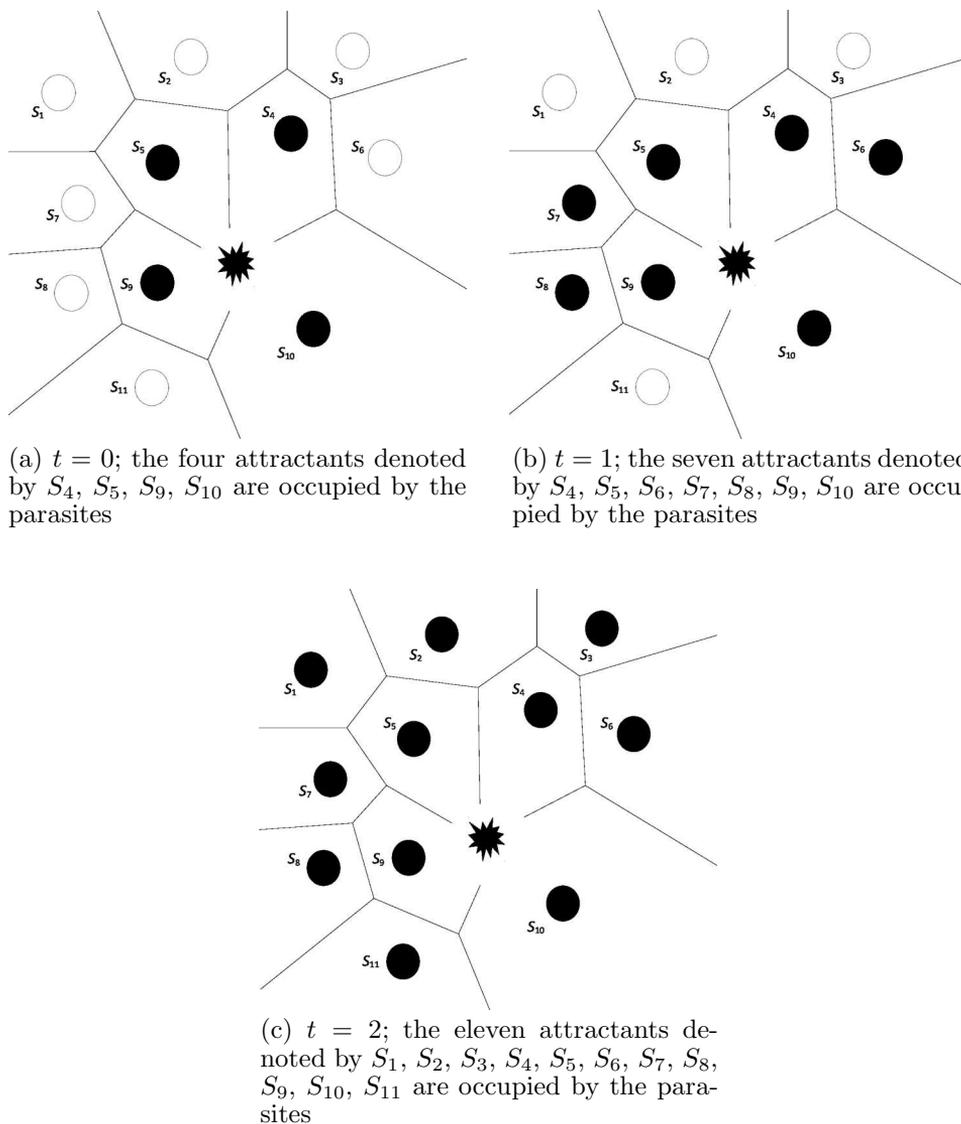


Figure 6. Example of propagation of parasites. First of all, parasites are located in the center of pictures (a), (b), (c). Attractants which are not occupied by parasites are denoted by white circles. Attractants which are occupied by parasites are denoted by black circles. Each attractant is the center of a suitable Voronoi cell. The radius of Voronoi cell is a maximal distance of power to attract parasites in one direction. At time $t = 0, 1, 2$, different syllogistic propositions are true: (a) $S_{7i_0}S_{11}, S_{11i_0}S_7, S_{1i_0}S_3, S_{3i_0}S_1, S_{1e_0}S_{10}, S_{10e_0}S_1, S_{1e_0}S_9, S_{9e_0}S_1, S_{1e_0}S_4, S_{4e_0}S_1$, etc.; (b) $S_{1i_1}S_{11}, S_{11i_1}S_1, S_{2o_1}S_6, S_{6o_1}S_2$, etc.; (c) $S_7a_2S_{11}, S_{11a_2}S_7, S_{1a_2}S_3, S_{3a_2}S_1, S_{1a_2}S_{10}, S_{10a_2}S_1, S_{1a_2}S_9, S_{9a_2}S_1, S_{1a_2}S_4, S_{4a_2}S_1$, etc.

Also, we can assume that the attractants can move at $t = 0, 1, 2 \dots$. Let us postulate that their motions at different time are limited by the following rules, where $t + 1$ means the next step of life cycle:

$$S_m \mathbf{a}_t P_m \Rightarrow S_m \mathbf{e}_{t+1} P_m. \quad (9)$$

$$S_c \mathbf{a}_t P_c \Rightarrow S_c \mathbf{e}_{t+1} P_c. \quad (10)$$

From this we have

$$S_m \mathbf{i}_{t+1} P_m \Rightarrow S_m \mathbf{o}_t P_m. \quad (11)$$

$$S_c \mathbf{i}_{t+1} P_c \Rightarrow S_c \mathbf{o}_t P_c. \quad (12)$$

Attractants for miracidia and cercariae are different, but they live in the same lake. We can postulate that if the whole region is occupied by miracidia (cercariae) at time t , then surely the part of this region is occupied by cercariae (miracidia) at time $t + 1$. So, the propagation of collectives of miracidia at t causes the propagation of collectives of cercariae at $t + 1$:

$$S_m \mathbf{a}_t P_m \Rightarrow S_c \mathbf{e}_{t+1} P_c. \quad (13)$$

$$S_m \mathbf{i}_{t+1} P_m \Rightarrow S_c \mathbf{o}_t P_c. \quad (14)$$

Furthermore, the propagation of collectives of cercariae at t causes the propagation of collectives of miracidia at $t + 1$:

$$S_c \mathbf{a}_t P_c \Rightarrow S_m \mathbf{e}_{t+1} P_m. \quad (15)$$

$$S_c \mathbf{i}_{t+1} P_c \Rightarrow S_m \mathbf{o}_t P_m. \quad (16)$$

Now, we can define simple syllogistic propositions for infinite time: $S_{\mathbf{x}\infty} P := \lim_{t \rightarrow \infty} S_{\mathbf{x}t} P$, where $\mathbf{x} \in \{\mathbf{a}, \mathbf{e}, \mathbf{i}, \mathbf{o}\}$. The informal meaning of these propositions is that we put forward syllogistic propositions about the whole of one life cycle of *Schistosomatidae* in the same lake. So, we may generalize equations (9)–(16) in the following way:

$$S_m \mathbf{a}_{\infty} P_m \Rightarrow \exists t. S_m \mathbf{a}_t P_m; \quad (17)$$

$$S_c \mathbf{a}_{\infty} P_c \Rightarrow \exists t. S_c \mathbf{a}_t P_c; \quad (18)$$

$$S_m \mathbf{a}_{\infty} P_m \Rightarrow \exists t. S_c \mathbf{a}_t P_c; \quad (19)$$

$$S_c \mathbf{a}_{\infty} P_c \Rightarrow \exists t. S_m \mathbf{a}_t P_m; \quad (20)$$

$$S_m \mathbf{i}_{\infty} P_m \Rightarrow \forall t. S_m \mathbf{i}_t P_m; \quad (21)$$

$$S_c \mathbf{i}_{\infty} P_c \Rightarrow \forall t. S_c \mathbf{i}_t P_c; \quad (22)$$

$$S_m \mathbf{i}_{\infty} P_m \Rightarrow \forall t. S_c \mathbf{i}_t P_c; \quad (23)$$

$$S_c \mathbf{i}_{\infty} P_c \Rightarrow \forall t. S_m \mathbf{i}_t P_m. \quad (24)$$

Formula (17) means that if the whole region is occupied by miracidia for one life cycle of *Schistosomatidae*, then there exists time t such that the whole region is occupied by miracidia. Formula (18) means that if the whole region is occupied by cercariae for one life cycle of *Schistosomatidae*, then there exists time t such that the whole region is occupied by cercariae. Formula (19) means that if the whole region is occupied by miracidia for one life cycle of *Schistosomatidae*, then there exists time t such that the whole region is occupied by cercariae. Formula (20) means that if the whole region is occupied by cercariae for one life cycle of *Schistosomatidae*, then there exists time t such that the whole region is occupied by miracidia.

Formula (21) means that if there is just a casual propagation of miracidia for one life cycle of *Schistosomatidae*, then for all time t of this life cycle there is just a casual propagation of miracidia. Formula (22) means that if there is just a casual propagation of cercariae for one life cycle of *Schistosomatidae*, then for all time t of this life cycle there is just a casual propagation of cercariae. Formula (23) means that if there is just a casual propagation of miracidia for one life cycle of *Schistosomatidae*, then for all time t of this life cycle there is just a casual propagation of cercariae. Formula (24) means that if there is just a casual propagation of cercariae for one life cycle of *Schistosomatidae*, then for all time t of this life cycle there is just a casual propagation of miracidia.

Other axioms are as follows (for $x \in \{m, c\}$):

$$S_x \mathbf{a}_t P_x \Rightarrow S_x \mathbf{e}_t P_x; \quad S_x \mathbf{a}_\infty P_x \Rightarrow S_x \mathbf{e}_\infty P_x; \quad (25)$$

$$S_x \mathbf{a}_t P_x \Rightarrow P_x \mathbf{a}_t S_x; \quad S_x \mathbf{a}_\infty P_x \Rightarrow P_x \mathbf{a}_\infty S_x; \quad (26)$$

$$S_x \mathbf{i}_t P_x \Rightarrow P_x \mathbf{i}_t S_x; \quad S_x \mathbf{i}_\infty P_x \Rightarrow P_x \mathbf{i}_\infty S_x; \quad (27)$$

$$S_x \mathbf{a}_t M_x \Rightarrow S_x \mathbf{e}_t P_x; \quad S_x \mathbf{a}_\infty M_x \Rightarrow S_x \mathbf{e}_\infty P_x; \quad (28)$$

$$M_x \mathbf{a}_t P_x \Rightarrow S_x \mathbf{e}_t P_x; \quad M_x \mathbf{a}_\infty P_x \Rightarrow S_x \mathbf{e}_\infty P_x; \quad (29)$$

$$(M_x \mathbf{a}_t P_x \wedge S_x \mathbf{a}_t M_x) \Rightarrow S_x \mathbf{a}_t P_x; \quad (30)$$

$$(M_x \mathbf{i}_t P_x \wedge S_x \mathbf{i}_t M_x) \Rightarrow S_x \mathbf{i}_t P_x; \quad (31)$$

$$(M_x \mathbf{a}_\infty P_x \wedge S_x \mathbf{a}_\infty M_x) \Rightarrow S_x \mathbf{a}_\infty P_x; \quad (32)$$

$$(M_x \mathbf{i}_\infty P_x \wedge S_x \mathbf{i}_\infty M_x) \Rightarrow S_x \mathbf{i}_\infty P_x. \quad (33)$$

Some basic formal properties of that axiomatic system closed over axioms (1)–(8) and (25)–(33), where \mathbf{a} , \mathbf{e} , \mathbf{i} , \mathbf{o} do not depend on time, are considered in [27], [28]. Probabilistic semantics for the time-dependent version of that system for slime mould behavior is proposed in [29].

Notice that formulas (31) and (33) are axioms of the syllogistic system of propagation, while they are not valid in the Aristotelian system. Indeed, $(M_x \mathbf{i}_t P_x \wedge S_x \mathbf{i}_t M_x) \Rightarrow S_x \mathbf{i}_t P_x$ means that

$$\begin{aligned} & [\forall A_x (\neg(A_x \mathbf{i} s_t M_x) \wedge \neg(A_x \mathbf{i} s_t P_x)) \wedge \forall A_x (\neg(A_x \mathbf{i} s_t S_x) \wedge \neg(A_x \mathbf{i} s_t M_x))] \\ & \quad \Rightarrow \forall A_x (\neg(A_x \mathbf{i} s_t S_x) \wedge \neg(A_x \mathbf{i} s_t P_x)), \end{aligned}$$

the latter formula is valid.

4. Conclusion

In this paper, we have constructed a syllogistic system for the propagation of *Schistosomatidae*. This system contains all tautologies of the syllogistic system for the propagation of *Physarum polycephalum* proposed in [29], but not vice versa. And in return, the syllogistic system for the propagation of *Physarum polycephalum* contains all tautologies of the performative syllogistic proposed in [27], [28], but not vice versa. This means that as more complex intelligent behavior is observed in propagations, more axioms are contained in an appropriate syllogistic system.

In syllogistics for the explication of propagations, the inverse relations hold true for all syllogistic connectives:

$$SaP \Rightarrow PaS;$$

$$SeP \Rightarrow PeS;$$

$$SiP \Rightarrow PiS;$$

$$SoP \Rightarrow PoS.$$

This is inferred from definitions (1)–(8). These properties fix propagations in all possible directions.

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N O T E

¹ <http://www.phychip.eu/>.

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