Perspectives for Applied Semiotics in Artificial Life Research[1]

João Queiroz[a,b] & Charbel El-Hani[b,c,d]

a. Institute of Arts and Design, Federal University of Juiz de Fora, Brazil.
b.Research Group in History, Philosophy, and Biology Teaching, Institute of Biology, Federal University of Bahia, Brazil.
c.Graduate Studies Program in History, Philosophy, and Science Teaching, Federal University of Bahia/State University of Feira de Santana, Brazil.
d.Graduate Studies Program in Ecology and Biomonitoring, Federal University of Bahia, Brazil.

General abstract: The contributions of Peircean pragmatic theory of signs to the design and construction of artificial cognition systems have not been systematically explored. In fact, most approaches in the literature of intelligent systems and artificial life adopt a naïve definition of semiotic processes, which usually plays a secondary role in the studies. Our research, on the contrary, strives for a strong theoretical foundation for semiosis, as well as its realization within digital computers. In this lecture, a biologically inspired semiotic model is proposed in synthetic biology. At the first part of this lecture we investigate theoretical constraints about the feasibility of simulated semiosis. These constraints, which are basic requirements for the simulation of semiosis, refer to the synthesis of irreducible triadic relations (Sign – Object – Interpretant). We examine the organization of the triad S-O-I, that is, the relative position of its elements and how they relate to each other by determinative relations, and we suggest a meta-algorithm. At the second part we begin with a description of a general approach for conducting experiments with artificial creatures within a synthetic ethological context. Next, we describe how this approach was used to build a computational experiment regarding the emergence of self-organized symbols. Our experiment simulated a community of artificial creatures undergoing complex intra and inter-specific interactions in which meaning evolved over time, from a tabula rasa repertoire of random alarm-calls to a specific set of optimal referential alarm-calls. To design different kinds of creatures as well as innanimate elements of the environment, we applied theoretical constraints from the Peircean philosophy of sign and empirical constraints from neuroethology. Behaviors such as navigation, search, predation, evasion and cooperation were modeled as communication processes evolving within and across artificial brains of different kinds of creatures. Our results suggest that the constraints chosen were both necessary and sufficient to produce symbolic communication.

---

[1] This lecture is based on three articles: Loula, A., Gudwin, R., El-Hani, C. & Queiroz, J. 2010 The emergence of self-organized symbol based communication in artificial creatures. Cognitive Systems Research 11 (2): 131-147; LOULA, A. GUDWIN, R.; RIBEIRO, S. & QUEIROZ, J. 2010. On Building Meaning: A Biologically-Inspired Experiment on Symbol-Based Communication. Brain Inspired Cognitive Systems. Amir Hussain, Igor Aleksander, Leslie S. Smith, Allan Kardec Barros, Ron Chrisley and Vassilis Cutsuridis (Eds.). Springer New York. pp. 77-93; Gomes, A., El-Hani, C., Gudwin, R., & Queiroz, J. 2007. Towards the emergence of meaning processes in computers from Peircean semiotics. Mind & Society -- Cognitive Studies in Economics and Social Sciences 6: 173-187.

Part I:

1. Towards the modeling of semiosis in computers from Peircean semiotics

Computational-based methodologies have been used to design virtual experimental protocols, where it is possible to simulate the predictions derived from theoretical models (Bedau 1998). Among the predictions that can be simulated in this manner we find those describing semiotic processes in artificial systems (see Gudwin & Queiroz 2007). Computer simulations can be used to study different levels of the organization of semiotic processes (Cangelosi & Turner 2002). These levels include the simulation of syntactic structures (Kirby 1999), lexicalization phenomena (Hurford 1991, Steels 1999, Cangelosi & Parisi 1998), symbolic competence (Cangelosi 2001), communication (Hutchins & Hazlehurst 1995), and meaning creation in communication (MacLennan 2001, Smith 2001).

We proposed a computational model of Peirce's triadic notion of semiosis. In order to synthesize artificial systems able to perform some sort of simulated semiosis, we (1) introduce some principles of Peirce's theory of sign, (2) define the major theoretical constraints required to semiosis simulation, (3) specify a computational strategy to implement semiosis according to the aforementioned constraints.

2. Peircean semiotic constraints

We divide our discussion on the theoretical constraints into two sections. The first one investigates the relative positions of the elements in semiosis, and the second, the relations of determination between them.

2.1 Relative positions of S-O-I

Let a chain of triads be $T = \{\ldots, t_{i-1}, t_i, t_{i+1}, \ldots\}$, where $t_i = (a_i, b_i, c_i)$ and $i \in N$. Then, the following conditions must hold:

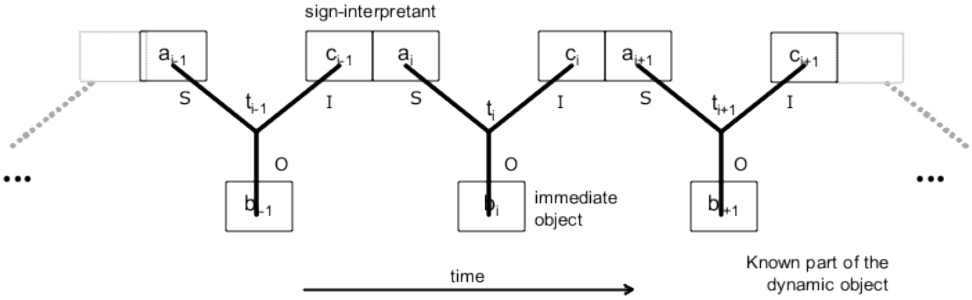


Figure 1 – Model of relative positions of S-O-I

$$\forall i: a_i = c_{i-1} \qquad (2.1.1)$$

$$\exists d\ \forall i: \text{ImmediateObject}(b_i, d) \qquad (2.1.2)$$

where the logic predicate ImmediateObject (b_i, d) denotes that b_i is an immediate object of a dynamic object d. It is of paramount importance to notice that the equality expressed in Equation 2.1.1 means that, in fact, c_{i-1} and a_i are just aliases for the same thing – c_{i-1} and a_i are roles played by this "thing" within triads t_{i-1} and t_i, respectively.

The constraints represented by equations 2.1.1 and 2.1.2 mean that, given any triad $t_i = (S_i, O_i, I_i)$ in a chain T: (1) its first term (S_i) must be equal to the third term of the preceding triad (I_{i-1}); (2) there exists at least one dynamic object such that all second terms (O_i) are immediate objects of it; (3) its third term (I_i) must be equal to the first term of the subsequent triad (S_{i+1}); and (4) a triad $t_i = (S_i, O_i, I_i)$ can only be defined as such in the context of a chain of triads $T = \{\ldots, t_{i-1}, t_i, t_{i+1}, \ldots\}$. First terms are Signs (S_i), Second terms (O_i) are Objects, and Third terms are interpretants (I_i).

2.2 Relations of determination

Determination provides the way triad elements are arranged in semiosis:

> "The sign is determined by the object relatively to the interpretant, and determines the interpretant in reference to the object in such a way as to cause the interpretant to be determined by the object through the mediation of the sign" (MS 318: 81).

These determinations can be rewritten as: (i) O determines S relatively to I and (ii) S determines I relatively to O. According to Ransdell (1983: 23), determination encompasses both a causal and a logical idea. In this context, how do these causal and logical modes operate? What does a triadic relation expressed as ‘X determines Y relatively to Z’ means? A computational approach to this problem will be provided in the following sections.

3. Preliminary approach to semiosis

Consider the assumption that semiosis is a dynamical process that happens in time. Hence, each new (simulated) triad is appended to the chain of triads according to the constraints given in Section 2, that is:

$$\ldots \rightarrow (S_{i-1}\, O_{i-1}\, I_{i-1}) \rightarrow (S_{i}\, O_{i}\, I_{i}) \rightarrow (S_{i+1}\, O_{i+1}\, I_{i+1}) \rightarrow \ldots$$

We defined this level as focal-semiosis (see Lecture 3). At the focal level, each chain of triads is simulated, and possesses some crucial properties, such as being potentially infinite (unlimited semiosis) and always referring to the same dynamic object. In the work of Peirce and many of his followers, this is the closest we get to the understanding of semiosis as a dynamic process. From a computational viewpoint, in turn, this resolution per se does not provide sufficient knowledge on how to effectively realize the evolution of chains in a computer. So, in order to simulate this sort of dynamics, we propose that semiosis is a hierarchical process and can be modeled as operating at three distinct levels, including a level below the focal level, called micro-semiotic, and another level above, called macro-semiotic (See Figure 2. See also Queiroz & El-Hani, 2006a,b).

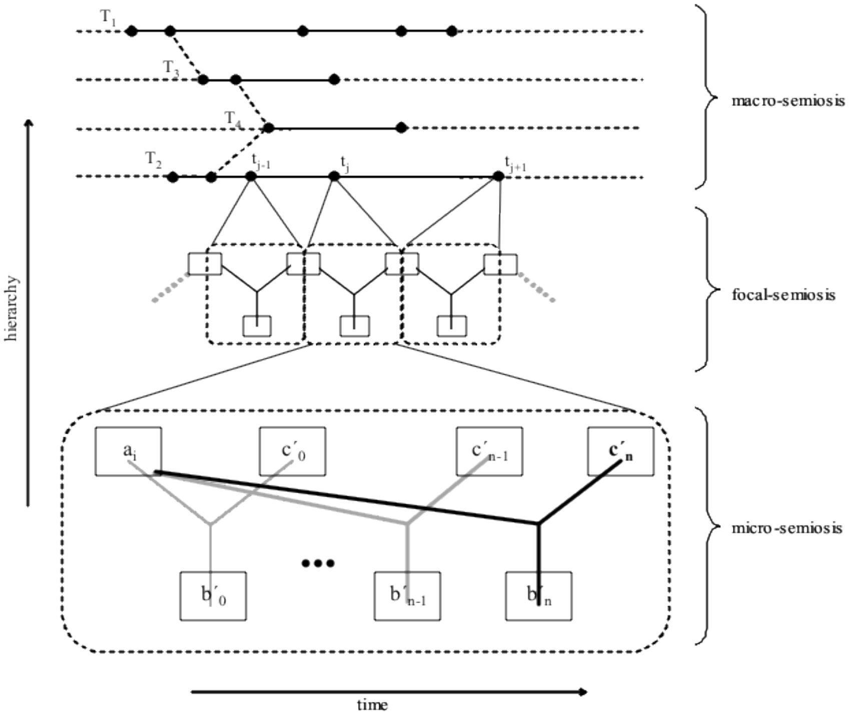


Figure 2 – A three-levels model of semiosis.

At the macro-semiotic level, we have a network of evolving chains of triads. These chains may interfere with each other. In a sense, this is what Peirce sometimes calls collateral experience. At the micro-semiotic level, relations of determination between triad elements (S-O-I) are simulated. An important consequence is that S-O-I triadic relations may be created (or simulated) by means of an iterative process. This view is suitable for implementations based on typical computational strategies, as most techniques (neural networks, genetic algorithms, etc.) are based on iterative algorithms. A relation of determination (which connects S, O and I) may be, in this sense, gradually refined until it reaches an adequate trade-off between the computational resources required and the conformity with the theoretical constraints.

4. Proposal for an algorithm

This section presents a computational strategy to implement simulated semiosis within digital computers. The iterative algorithm proposed here relies on the notions of micro-, focal- and macro-semiosis stated earlier. The level of detail provides a general framework in which computational techniques, such as neural networks, genetic algorithms, classifier systems, and so on, can be applied to effectively simulate semiosis.

4.1 General Definitions

There are three modalities of the relation between a first (Sign) and a second (Object)[2]:

(i) intrinsic quality of S (first term dependent) – such as the relation between a photograph of a cat and the cat itself. The Sign (photograph) shares an intrinsic quality (shape of the body, color, etc.) with the Object (cat), which means that the photograph, in a certain way, represents the real cat;

(ii) S-O relational quality (first-second relation dependent) – such as the relation between smoke and fire. The Sign (smoke) shares an efficient causal relation with its Object (fire), because we had a previous experience in which we perceived fire just after we perceived smoke. This means that smoke, in a sense, represents fire; and finally

(iii) imputed quality by I to S-O (third term dependent) – such as the relation between the word “car” and its meaning, a typical car. The Sign (word “car”) represents the Object (car) by a convention or habit (here given by I).

We should also define the notions of potential Signs, Objects, and Interpretants. A potential Sign is something that may be the sign of an

---

[2] This is usually referred to as the second trichotomy of relations (icon, index and symbol).

Object (stand for) to an Interpretant. A potential Object is something that may be the Object of a Sign to an Interpretant. A potential Interpretant is something that may be the Interpretant of a Sign (stand to). A potential Sign becomes a Sign only when submitted to a mediative relation of determination between Object and Interpretant. Being determined by the Object, the Sign is constrained by it. This means that the Sign can only assume its role as a Sign if attested as such by the Object. By determining the Interpretant, the Sign constrains it.

4.2 Meta-algorithm

Consider the statements: (i) O determines S relatively to I, (ii) S determines I relatively to O. Arbitrarily, let us start by the first statement. From a computational viewpoint, the first question is: which term comes first in time? If we read determination as a causal process, we will be tempted to say that S = f (O, I). One of the problems with this view is that O is not available before S, and I is not available before O. The fact that O determines S relatively to I means that S assumes its condition because of O (O contrives to determine the sign to represent it) and I, but does not mean that either O or I are available. This claim may lead us to a sort of dead-end because it provides no starting point. However, if determination is seen as a logical-causal constraint, there may be alternative ways to perform this process.

Assume that S’, which is available at a certain time t, is a potential Sign. S’ has an interpretive potential, that is, the faculty of being potentially interpretable (I) as a Sign of something (an Object). Then, we need to find an Object O’ and an Interpretant I’ that assume a triadic relation with S’. If the theoretical constraints are satisfied, then we can say that they form a semiotic process (at a time t’ > t).

We devised a very general algorithm to realize the process of finding candidates to S-O-I. Roughly speaking, it finds candidates to S and then finds candidates to O and I based on the possible types of relation between Sign and Object. The interesting thing is that a triad may be gradually constructed by means of an iterative process, that is, the simulation of a Sign does not need to be atomic.

The algorithm presupposes the notions of ‘environment’ and ‘agent’. The synthetic environment represents the reality that is being forced upon the agents’ sensors. The environment is infinitely complex (from the viewpoint of the agents[3]). Agents, who are immersed in the environment, are able to perceive and act on it.

The steps of the algorithm to simulate a triad are as follows:

---

[3] This means that the agent is able to perceive only part of its “reality”.

1. Choose a collection of potential signs $S' = \{ s'_i \}$;
2. Choose one potential sign s′ from this collection;
3. Propose a potential object o′ and a potential interpretant i′, such that there exists a relation in one of the three possible modes (see above for intrinsic, relational, and imputed qualities). Then, we say that o′ determines s′ relatively to i′.

As anything can be seen as a sign, the collection of potential signs may encompass virtually everything, including all data gathered by the agent's sensors. The idea here is to provide some sort of focus of attention. It is quite reasonable to propose some sort of selection mechanism to increase the quality of the selection of potential Signs.

Step 3 requires some sort of emergent behavior because it is the result of the interaction forces of micro-semiosis and macro-semiosis acting on the focal level. These hierarchies form a complex system of relations. Micro-semiosis represents the potentiality of things to be part of a semiosis, the initial conditions. Macro-semiosis represents boundary conditions, referring to the notion of context. Further details on these levels will be provided in the next section.

In order to implement this algorithm, one must first define some sort of cognitive architecture for the agent, in which sensors and effectors are specified. In this lecture, many details are deliberately left out. A number of required concepts for simulating semiosis will be treated in detail in a future work.

Concluding this first part, we have pointed out two fundamental constraints required to simulate a triadic model of semiosis, namely, the relative position of the elements of a triad and the relations of determination between them. Based on both sets of constraints, we proposed a general algorithm to accomplish artificial semiosis. This proposal still lacks many details, but sketches a general framework to design experimental semiotic systems. We also established the conditions which should be fulfilled for semiosis to be characterized as an emergent process in semiotic systems. Further developments will include a more detailed algorithm, and an implementation of artificial semiosis in digital computers.

In the next part (II), we describe a biosemiotic inspired ALIFE experiment. We build a digital scenario where we simulated the emergence of self-organized symbol-based communication among artificial creatures inhabiting a virtual world of unpredictable predatory events (see Loula et al. 2010). In our experiment, creatures are autonomous agents that learn symbolic relations in an unsupervised manner, with no explicit feedback, and are able to engage in dynamical and autonomous communicative interactions with other creatures, even simultaneously. In order to synthesize a behavioral ecology and infer the minimum organizational constraints for the design of our creatures, we examined the well-studied case of communication in vervet monkeys. Our results show that the creatures, assuming the role of sign users and learners, behave collectively as a complex adaptive system, where self-organized communicative interactions play a major role in the emergence of symbol-based communication.

Part II:

5.Simulating Symbolic Creatures

In building the experimental setup, we considered further constraints following from biological motivations, inspired by ethological case studies of intra-specific communication for predator warning (e.g. Griesser & Ekman, 2004; Proctor, Broom, & Ruxtona, 2001; Manser, Seyfarth, & Cheney, 2002). More specifically, we examined alarm calls from vervet monkeys. These primates possess a sophisticated repertoire of vocal signs that are used for intra-specific social interactions, as well as for general alarm purposes regarding imminent predation on the group (Seyfarth, Cheney, & Marler, 1980). Field studies revealed three main kinds of alarm calls which are used to warn about the presence of (a) terrestrial stalking predators such as leopards, (b) aerial raptors such as eagles, and (c) ground predators such as snakes. When a “leopard” call is uttered, vervets escape to the top of nearby trees; “eagle” calls cause vervets to hide under trees; and “snake” calls elicit rearing on the hindpaws and careful scrutiny of the surrounding terrain. Playback experiments produced evidences that referential properties might be involved, and, thus, that symbols might be present in this communication case.

Empirical research about the vervet monkey alarm-call system revealed in particular that infantile and young adult vervets do not have the competence of either interpreting or emitting these calls efficiently (Cheney & Seyfarth, 1990). Learning is involved in vocal production, in the use of calls for specific events, and in the response to the calls. Infant vervets already babble alarms for broad and mutually exclusive categories like ‘flying birds’, but they are unable to recognize whether the birds are predators of their group or not (Seyfarth & Cheney, 1986). Although vervet monkeys appear to have an innate predisposition to vocalize calls which are similar to alarm calls for predator-like objects, they have to learn to recognize and respond to those calls. The assumption that the mapping between calls and predators can be learned is also supported by the observation that cross-fostered vervet monkeys, although unable to modify their call production, “did learn to recognize and respond to their adoptive mothers’ calls, and vice versa” (Cheney & Seyfarth, 1998). In our experiment, we assume that an associative learning competence is used for the acquisition and response to all alarm calls.

This well-studied case of communication for predator warning in vervet monkeys inspired the creatures' design and the ecological conditions in our experiment. Our creatures are autonomous agents inhabiting a virtual bi-dimensional environment (Figure 3). The environment is the place where the agents interact with one another and with things present in the virtual world. As part of a project on artificial life, we are simulating an ecosystem that allows agents' cooperative interaction, including intra-specific communication by alarm calls to alert about the presence of predators.

The virtual world is composed of creatures divided into preys and predators (terrestrial, aerial, and ground predators), and also of things such as trees (climbable objects) and bushes (used to hide) (Figure 3). We propose two different roles for preys: teachers (sign vocalizers) and learners (sign apprentices), both inhabiting and interacting within the same environment, but with teachers emitting pre-defined alarms for predators and learners trying to find out without explicit feedback which predators each alarm is associated with (Loula et al., 2004). In the present lecture, we will focus on asking what would happen if there were no previous alarm calls and the creatures needed to create their own repertoire of alarms. We introduced a special type of prey, which is able to create alarms, vocalize them to other preys, and learn from other preys, even simultaneously. We designed these creatures without any pre-defined alarm-predator associations that could be initially used, attempting to demonstrate how a simple learning mechanism might make it possible to acquire those associations. These preys are called here self-organizers[4], because each prey learns the sign it hears and uses them in future interactions, permitting a circular relation to happen: the effect preys have on one another is also the cause of this effect, because sign learning depends on sign usage, which in turn depends on sign learning. The aim of the experiment was to investigate a potentially self-organizing dynamics of signs, in which, starting with no specific signs for predators, symbol-based communication can emerge with convergence to a common repertoire of symbol-based alarm calls, via local communicative interactions.

---

[4] This experiment about the self-organization of referential vocabulary is inspired by related works, such as Steels (1999, 2000), Cangelosi (2001), Hutchins & Hazlehurst (1995).

Figure 3: The Symbolic Creatures Simulation, used to simulate the creatures' interactions (for further technical details, check http://www.dca.fee.unicamp.br/projects/artcog/symbcreatures).

The creatures have sensors and motor abilities that allow their interaction with the virtual environment. The sensorial modalities found in the preys include hearing and seeing, and each prey has parameters that determine its sensory capabilities, such as range, aperture, and direction. For the sake of simplicity, predators can see but not hear. Visual perception is also simplified and there is no visual data categorization, i.e., creatures perceive directly what kind of item they are seeing: a tree, a bush, a prey, or any of the three predators. The creatures also have interactive abilities defined by a set of possible individual actions – adjustment of sensors, movement, attack, climb on tree, hide under bush, and vocalize alarms. The last three actions are specific for preys, while attacks are specific for predators. To perform the connection between sensors and actuators, the creatures need an artificial mind, which is seen as 'control structures for autonomous agents' (Franklin, 1995). Both preys and predators are controlled by an architecture inspired by behavior-based approach (Brooks, 1990) and dedicated to action selection (Franklin, 1997). This architecture allows the creature to choose between different conflicting actions, given the state of the environment and the internal state of the creature. We will briefly describe the control architecture for predators and preys, and concentrate in describing the associative learning mechanism. Further details can be found in Loula et al. (2004).

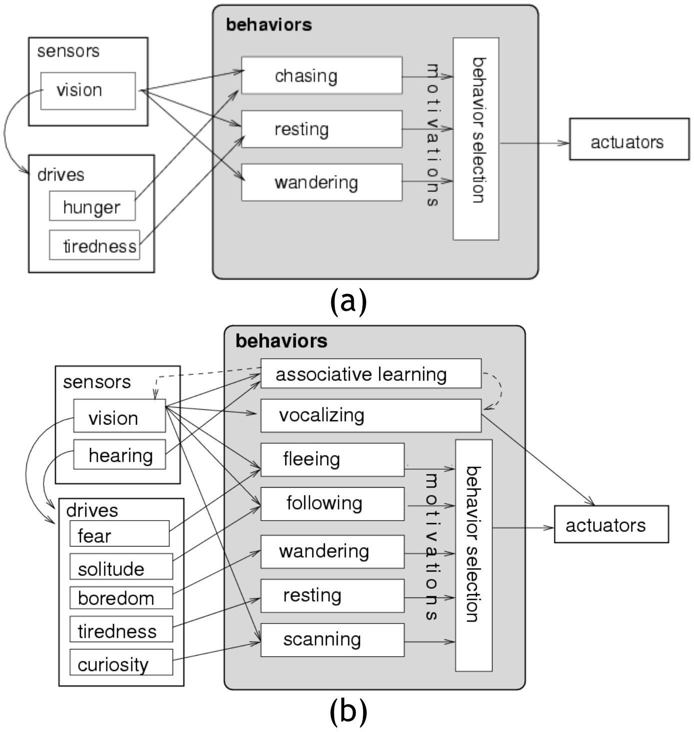


Figure 4: Predators' (a) and preys' (b) control architectures: behaviors, motivations and drives. The associative learning behavior in preys affects the associative memory and, therefore, the vocalizing behavior may change, concerning the signs which are vocalized, and other behaviors may also be affected as if an alarm-associated predator was seen (dashed lines, b).

The control mechanism used by the creatures is composed of behaviors, drives and motivations (Figure 4). Each behavior is an independent module that competes to be the active one and control the creature. The drives define basic instincts or needs such as fear or hunger, and are represented by numerical values, updated at each instant based on external stimuli or time passing. Based on the sensorial data and the creature's internal drives, a motivation value is calculated for each behavior, which is used, then, in the behavior selection process. The behavior with the highest motivation value is selected to control the creature. This mechanism is not learned but rather designed, being simple to implement and yet having a rich dynamics, enabling the creatures to act in a variety of ways.

In every iteration, visual and hearing stimuli are determined (depending on the sensorial range and location of every item in the environment) for each creature and sent to their control architecture that will use it to update drives and behaviors. The motivation value for each behavior is determined and the one with the highest value is selected to define the actions that will be carried out. The actions are executed and a new iteration starts.

The predators have a simple control architecture that only tries to resolve the action selection problem. It has three basic behaviors - wandering, prey chasing, and resting - and two drives - hunger and tiredness. The preys are the central elements of the experiment, since they are the ones involved in communicative acts, vocalizing, interpreting and learning alarms. Among the preys' behaviors, the communication-related behaviors are the ones that provide the preys with the ability to engage in communicative acts. Such behaviors are vocalizing, (visual) scanning, following, and associative learning. And besides communicating, the preys should also have other tasks to perform (basic behaviors) in order to keep them busy even when not communicating: wandering, fleeing, and resting. Related to all these behaviors, the preys have different drives: boredom, tiredness, fear, solitude, and curiosity.[5]

The behavior of 'following' makes the preys stay together trying to follow each other, allowing communicative interaction to happen more often, since it makes it more likely that there will be a prey around to hear an alarm emitted by another one. When a prey hears an alarm, the scanning behavior is usually activated and makes the prey direct its vision towards the alarm emitter and its surroundings, in search for possible referents for the vocalized alarm. The vocalizing behavior makes the prey produce an alarm, when it sees a predator, which can be heard by any other prey, provided the alarm call is within its hearing range. Self-organizers do not have a pre-defined repertoire of alarm-predator associations, and, thus, their vocalizing repertoire depends on the associative memory. When a predator is seen, they use the alarm with the highest association strength for that predator, or create a new alarm if none is known. Alarms are created by randomly choosing one among 100 possible (numerical) alarms that preys can emit. Running simultaneously with all other behaviors, associative learning is the most important behavior in the experiment.

As stated, symbols correspond to signs that are connected with their objects by the 'symbol-using agent', i.e., an internal association should be established to link them together, without which the sign could not be interpreted, at least not as a symbol. Associative learning allows the prey to learn temporal and spatial relations from the external stimuli and, thus, acquire association rules necessary to interpret signs as symbols. When a prey vocalizes an alarm, a nearby prey may hear it and scan the surroundings, searching for possible co-occurring events. There is an obvious association between an alarm call and the possible scanned referents at a given episode, which can be treated as indexical, but the prey must be able to find out which referents are suitable, i.e., it should generalize an association for future occurrences, and, thus, engage in symbol-based communication.

---

[5] For further technical details about the creatures's control (e.g. drives, motivations, sensors, actions), see Loula et al. (2004a).

Sensorial data from vision and hearing are received by the respective work memories. The work memory is a temporary repository of sensorial stimuli: when a stimulus is received from the sensor, it is put in the work memory and kept for a few iterations, and then taken out of the work memory. This makes it possible for stimuli received in different instants to coexist for some time in the memory, preserving indexical (spatio-temporal) relations. The items in the work memory are used by the associative memory to create, reinforce or weaken associations between the items from the visual work memory and hearing work memory (Figure 5).

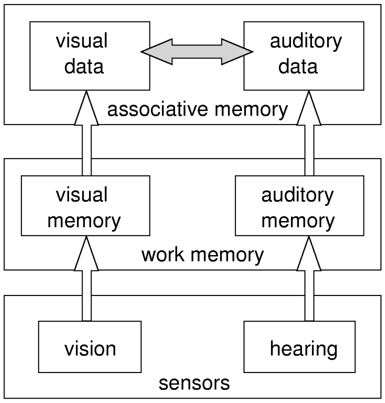


Figure 5: The associative learning modules: sensors, work memories, and an associative memory. Stimuli coming from the sensors are kept in the work memory for a few iterations and are used by the associative memory to learn the co-relations between visual and hearing stimuli.

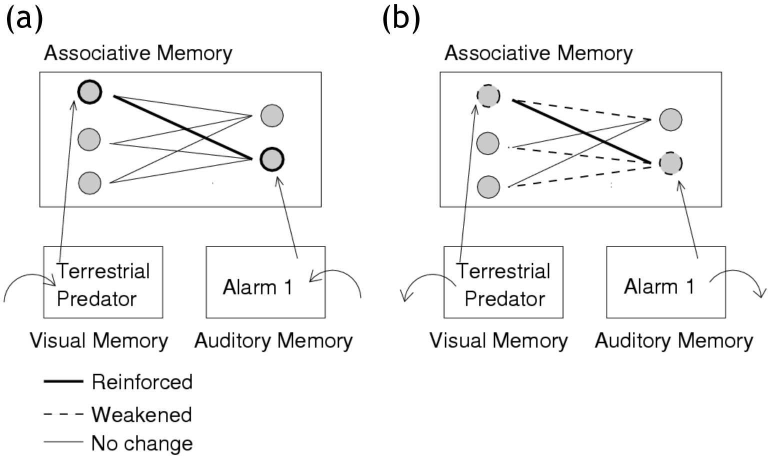


Figure 6: Reinforcement and weakening. (a) When an item is present in both of the work memories, the association between visual items and hearing items are reinforced in the associative memory and cannot be adjusted momentarily. (b) When an item leaves either of the work memories, any related association that was not reinforced is weakened. When both items are dropped, the associations which were reinforced can be adjusted in subsequent iterations.

Following Hebbian learning principles (Hebb, 1949), when sensorial data enters the work memories, the associative memory creates, or reinforces, the association between the visual item and the hearing item, and restrains changes in this association (Figure 6). Adjustment restrictions avoid multiple reinforcements in the same association caused by persisting items in the work memory. When an item is dropped from the work memory, related associations can be weakened, if changes were not restricted, i.e., if it was not already reinforced. When the two items of a reinforced association are dropped out of the work memories, the association is subject again to changes in its strength in further iterations. The positive (reinforcement) and negative (weakening) adjustment cycles in the associative memory allow preys to self-organize their repertoire, and permit common alarm-predator associations to emerge. The reinforcement and weakening adjustments for non-inhibited associations, with strengths limited to the interval [0.0; 1.0], are done as follows[6]:

- reinforcement, given a visual stimulus i and a hearing stimulus j in the work memories

$strength_{i\,j}(k+1) = strength_{i\,j}(k) + 0.1\ (1.0 - (topstrength_{j}(k) - strength_{i\,j}(k))) + 0.01$

where $topstrength_{j}(k) = max_{i}\ strength_{i\,j}(k)$

- weakening, for a dropped visual stimuli i
  - j associated with i,

$strength_{i\,j}(k+1) = strength_{i\,j}(k) - 0.1\ (topstrength_{j}(k) - strength_{i\,j}(k)) - 0.01$

- weakening, for a dropped hearing stimuli j
  - i associated with j,

$strength_{i\,j}(k+1) = strength_{i\,j}(k) - 0.1\ (topstrength_{j}(k) - strength_{i\,j}(k)) - 0.01$

As stated in these equations, the reinforcement and weakening rates are variable, depending on the current strength. This makes the positive adjustment cycle stronger at each step, since the higher the strength, the higher the reinforcement is. The same goes for the negative cycle, but in the opposite direction, the lower the strength, the higher the weakening is. The changes also depend on the strongest association related to a specific hearing stimulus, and the stronger this association is, the weaker is the reinforcement of the other associations with the same stimulus. This characterizes a ‘lateral inhibition’ from the strongest association to the competitors and provides stability to the highest association.

---

[6] A detail from the formulas should be explained here, the 0.01 added or subtracted will guarantee a minimal reinforcement or weakening, even if the current association is the strongest one, which would cancel out the middle term.

The associative learning mechanism also provides a response when a vocalization associated with a predator is heard. Depending on the association strength, it can influence the creature's behavior as if the related predator was seen, and an escape response can be elicited. At first, when no association have been established yet, the prey responds indexically to an alarm call through the visual scanning behavior searching for co-occurrent events, and this helps the learning process. But after the association between alarm and predator gets near maximum value, it is used to interpret the sign and an internal feedback can activate the fleeing behavior, even if a predator is not seen. Hence, at this optimum value, the prey stops scanning after an alarm is heard, and flees right away; consequently, the communicative behavior can be interpreted as a symbol-based one. Now, the interpretation of a Sign (alarm), i.e., the establishment of its relation to a specific Object (a predator type) depends upon an acquired habit, and not on a physical correlation between Sign and Object. This is evidence that the alarm has become a symbol.

5. Creatures in Operation

In order to study the self-organizing and emergent dynamics in communicative acts, we performed experiments by placing together preys and predators in the environment. During the simulations, we observed the associative memory items and the behavior responses of the preys to alarm calls. Results show that there was a convergence to a common repertoire of associations between alarms and predators. This is a repertoire of symbols that make the preys engage in escape responses when an alarm is heard, even in the absence of visual cues.

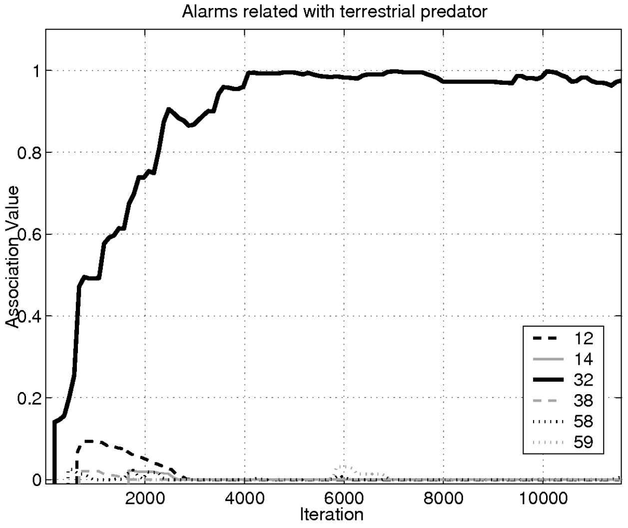
Here we present results from a typical simulation run[7], using 4 self-organizers and 3 predators, together with various bushes and trees. The self-organizers can create alarms by randomly selecting one out of 100 possible alarms (from 0 to 99), when no alarm is known for a predator. We let the simulation run until the community of preys converged to a common sign repertoire for the predators. Initially none of the preys have alarms associated with predators. Therefore, at the beginning of the simulation, new alarms are randomly created when they meet predators. This creates an explosion in the available alarms, that tends to be in greater number than the existing predator types. In figure 6, we see that various alarms were created to refer to each predator at first, but soon they stop appearing because every prey will know at least one alarm for each predator. Based on the observation of co-occurrence of alarms and predators, the association values are increased or decreased, but there is no guarantee that preys will always perceive this co-occurrence, e.g.,

---

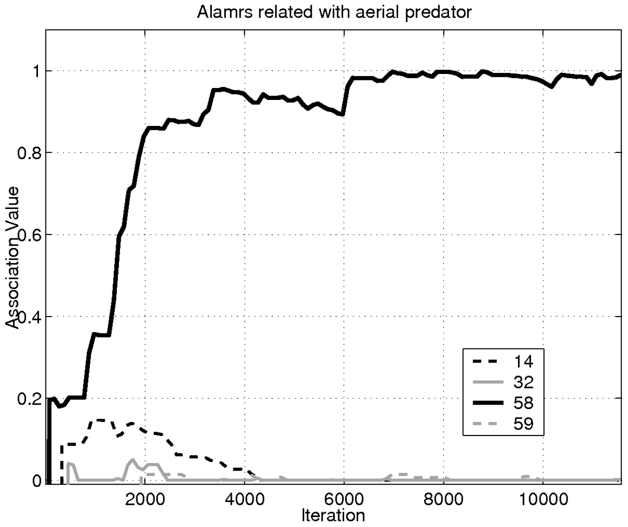
[7] Since there are random processes going on, such as the initial choice of alarms when none of them is known or unpredictable movements of the creatures due to the wandering behavior, we present only a single typical run. Nevertheless, the results presented are representative of the overall expected outcome in the experiment.

an alarm is heard but the predator can be out of sight. Besides, there’s no explicit feedback from the vocalizing prey about whether the alarm emitted refers to a certain predator or not.

(a)


Alarms related with terrestrial predator

(b)


Alamrs related with aerial predator

(c)

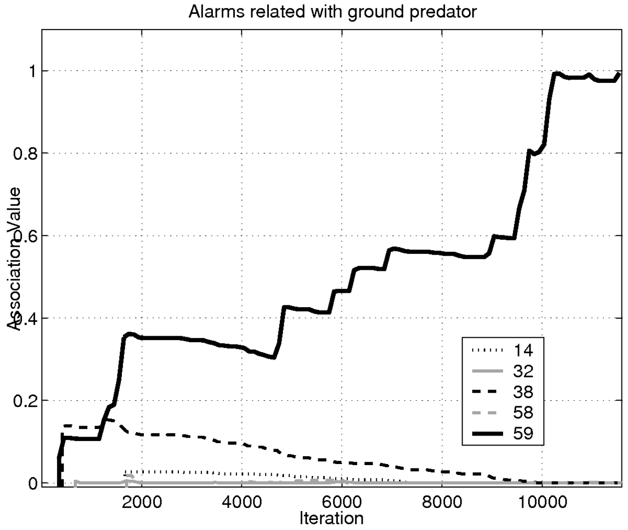
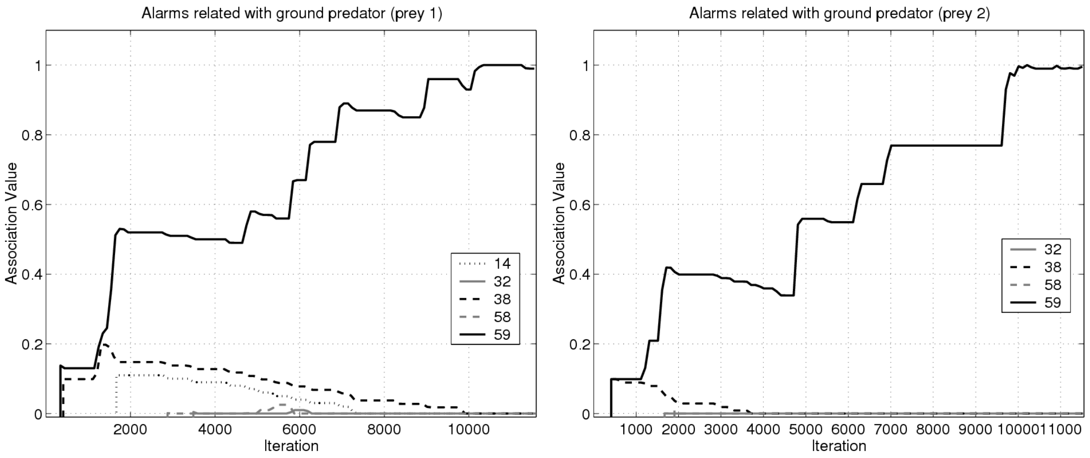
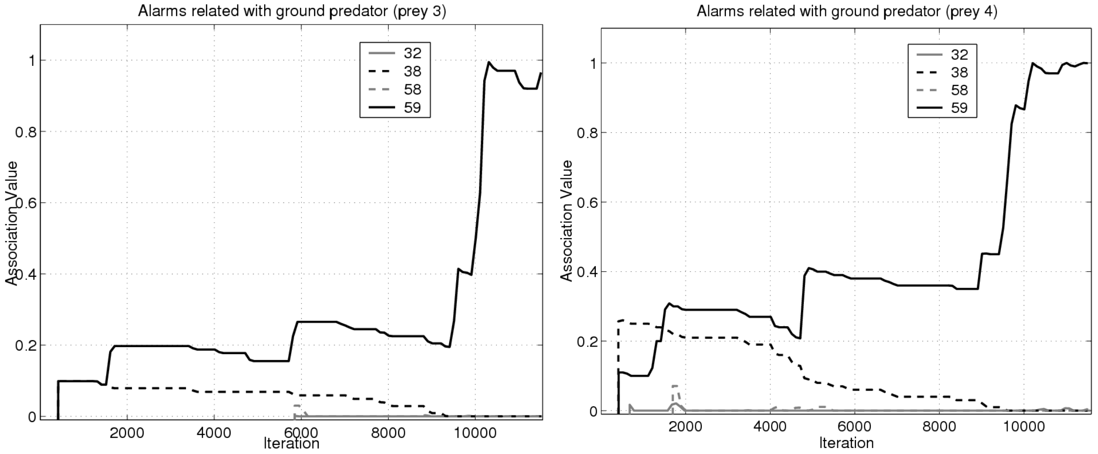

Alarms related with ground predator

Figure 7: The mean association values of the alarm-referent associations for 4 self-organizers: (a) terrestrial predator, (b) aerial predator, (c) ground predator. Numbers in the legend represent the alarms created, used and learned by the preys during a run. Alarms are also associated with other items that the preys see, such as trees and bushes, but these associations never reach more than 0.2 during the simulation.



prey 1

prey 2



prey 3

prey 4

Figure 8: The individual association values of the associations between alarms and the ground predator for the four preys.

In the graph shown in figure 7a, the terrestrial predator is associated with alarms 12, 14, 32, 38, 58, and 59, but only alarm 32 reaches the maximum value of 1.0, and the competing alarms are not able to overcome it at any time. Similar results were found in the case of alarms 14, 32, 58, and 59 associated with the aerial predator (figure 7b): only alarm 58 reached a maximum value. But among the alarms for the ground predator (figure 7c), there was a more intense competition that led to the inversion of positions between alarms 38 and 59. They were created almost at the same time in the community, and initially alarm 38 had a greater mean value than alarm 59. But between iteration 1000 and 2000, the association value of alarm 59 overcame the value of alarm 38, which slowly decayed, reaching the minimum value after iteration 9000.

To better understand what happened in the competition between alarms 59 and 38, we present the individual graphs for each prey (figure 8). In these graphs, we see that the associations evolved in distinct ways. Alarm 59 was created by prey 1 and alarm 38 by prey 4. Preys 2 and 3 learned these alarms, and they had similar association values before iteration 2000. But notice that prey 2 employed alarm 59 to vocalize, because it was learned first, while prey 3 preferred alarm 38 for the same reason. This led to a situation where each two preys preferred a particular alarm (38 or 59). After iteration 2000, the frequency of usage determined the alarm success, and alarm 59 eventually overcame alarm 38. If an alarm is heard more often or before another, its chance of success is greater, because it will be reinforced more frequently or before the competing alarms. This was the reason why alarm 59 won the competition and was adopted by all preys.

6. Self-Organization and Emergence of Symbol-based Communication

Together, the self-organizers constitute a complex adaptive system, with local interactions of communicative acts. By communicating, a vocalizing prey affects the Sign repertoire of the hearing preys, which will adjust their own repertoire to adapt to the vocalized alarm and the context in which it is emitted. Thus, the vocalizing competence will also be affected as it relies on the learned sign associations. This implies an internal circularity among the communicative creatures, which leads to the self-organization of their repertoires (Figure 9). This circularity is characterized by positive and negative feedback loops: the more a sign is used the more the creatures reinforce it (and weaken others), and, as a result, the frequency of usage of that sign increases (and others decrease); in turn, the less a sign is used the less it is reinforced, and, consequently, its usage decreases.

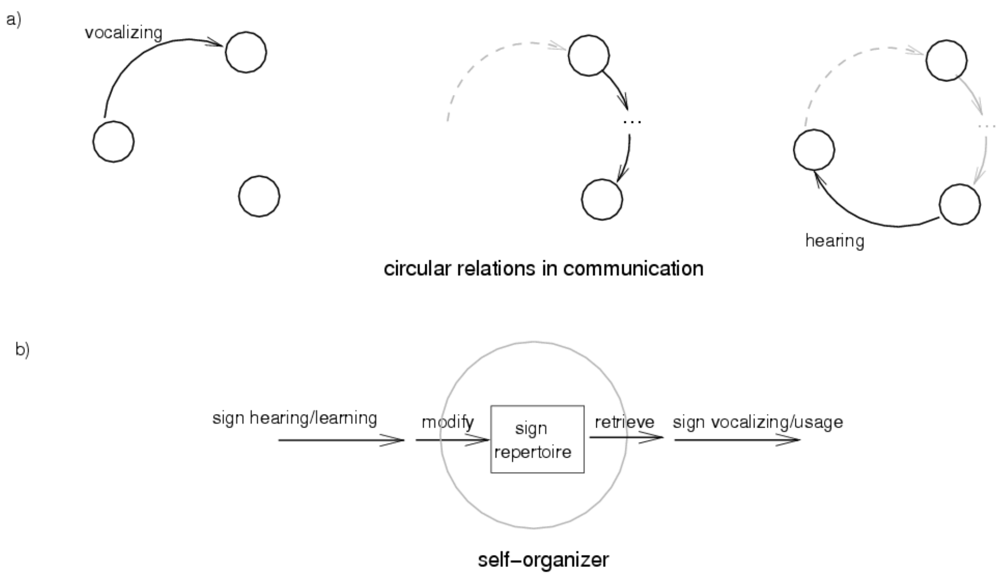


Figure 9: a) Self-organizers establish a circularity of sign usage and learning: an individual affects another one by vocalizing a sign and is affected by others when hearing a sign. The influence of an individual over others may affect it back later, and, thus, causes may be determined by effects. b) Hearing a sign induces an adjustment in an individual's sign repertoire, thus affecting also its vocalizing competence.

Moreover, as preys are both Sign users and Sign learners, they work as media for Signs to compete, being tested every time they are used. If they are successful, i.e., if the interpreter associates the Sign with the referent the utterer used it for, they will be reinforced, but if not, they will be weakened. The stronger the Sign association is, the more it will be used, and the more it is used, the more it will be reinforced. This positive feedback loop allows the self-organization of the community Sign repertoire, with alarm-referent associations getting stronger, making it possible that, at some point, Signs become symbols.

The system can be seen as moving in a state space defined as composed of all individual Sign repertoires. The system moves from point to point each time a creature adjusts its repertoire, i.e., when learning takes place. In this search space, attractors are defined as points in which all individual repertoires converge to a common one, thus stabilizing the system. When the system stabilizes, creatures will be relating predators and alarms in the same way, and vocalizing and interpreting Signs in the same manner. The search in this state space, as we will describe, is constrained by boundary conditions and by initial conditions and association possibilities available.

A fundamental aspect is the presence of random perturbations ('noise') in the system dynamics, which can be amplified so as to conduct to order. These perturbations shake the system, moving it in the search space, so as to place it near a basin of an attractor (a possible common repertoire). In the absence of a previous learned sign for a predator, the prey creates one randomly, which can be adopted by the community or not. The creation of new random alarms introduces perturbations in the system, which has its state changed, possibly closer to an attractor. Noise may also be present when a Sign is heard and the creature scans its surroundings trying to establish a relation with items that can be seen, since lots of different things can be seen, providing new relations to be established and already existing ones to have their strength changed. The presence of these perturbations also entails an unpredictability of the system's final ordered state, due to probabilistic trajectories.

In this self-organizing system, a systemic process (symbol-based communication), as much as a global pattern (a common repertoire of symbols), emerges from local communicative interactions, without any external or central control. This complex system of communicative creatures can be viewed as a semiotic system of symbol-based communication with three different hierarchical levels.

The semiotic processes of symbol-based communication emerge at the focal level through the interaction of a micro-semiotic level, containing a repertoire of potential sign, object, and interpretant relations within an interpreter or an utterer, and a macro-semiotic level, amounting to a self-organized network of all communication processes that occurred and are occurring, involving vocalizing and hearing preys, and their predators. It is in this hierarchical system that things in the environment become elements in triadic-dependent processes, i.e., alarms (Signs) come to be associated with predators (Objects) in such a manner that their relationship depends on the mediation of a learned association (i.e., they become symbols). In order to give a precise meaning to the idea that symbol-based communication emerges in the simulations we implemented, we argue that the semiotic processes at stake are emergent in the sense that they constitute a class of processes in which the behavior of Signs, Objects, and Interpretants in the triadic relations actualized in communication processes cannot be deduced from their possible behaviors in simpler relations. That is, their behaviors, and, consequently, the semiotic process these behaviors realize, are irreducible due to their non-deducibility from simpler relations (Boogerd et al., 2005).

The mapping of the proposed triadic hierarchical structure onto our synthetic experiment must be further detailed in order to elucidate the dynamics and emergence of communication events. The focal level corresponds to the communicative local interactions between utterers and interpreters. As described, the Peircean Sign model irreducibly relates three elements in a communication processes: sign-utterer-interpreter. More explicitly, we can talk about a vocalizing prey (the utterer) producing an alarm for a hearing prey (the interpreter), trying to transmit a warning escape alert. This communication triad can be connected to a chain of communication events, with the interpreter receiving the Sign and turning into an utterer of this same meaning to another interpreter (Figure 10a). This implies a possible circularity as mentioned before, when the utterer of the first episode becomes the interpreter at a future event (Figure 10b). This succession of triads can become rather complicated if we notice that different utterers can communicate with the same interpreter or one utterer can vocalize to different interpreters, both simultaneously (Figura 10c).

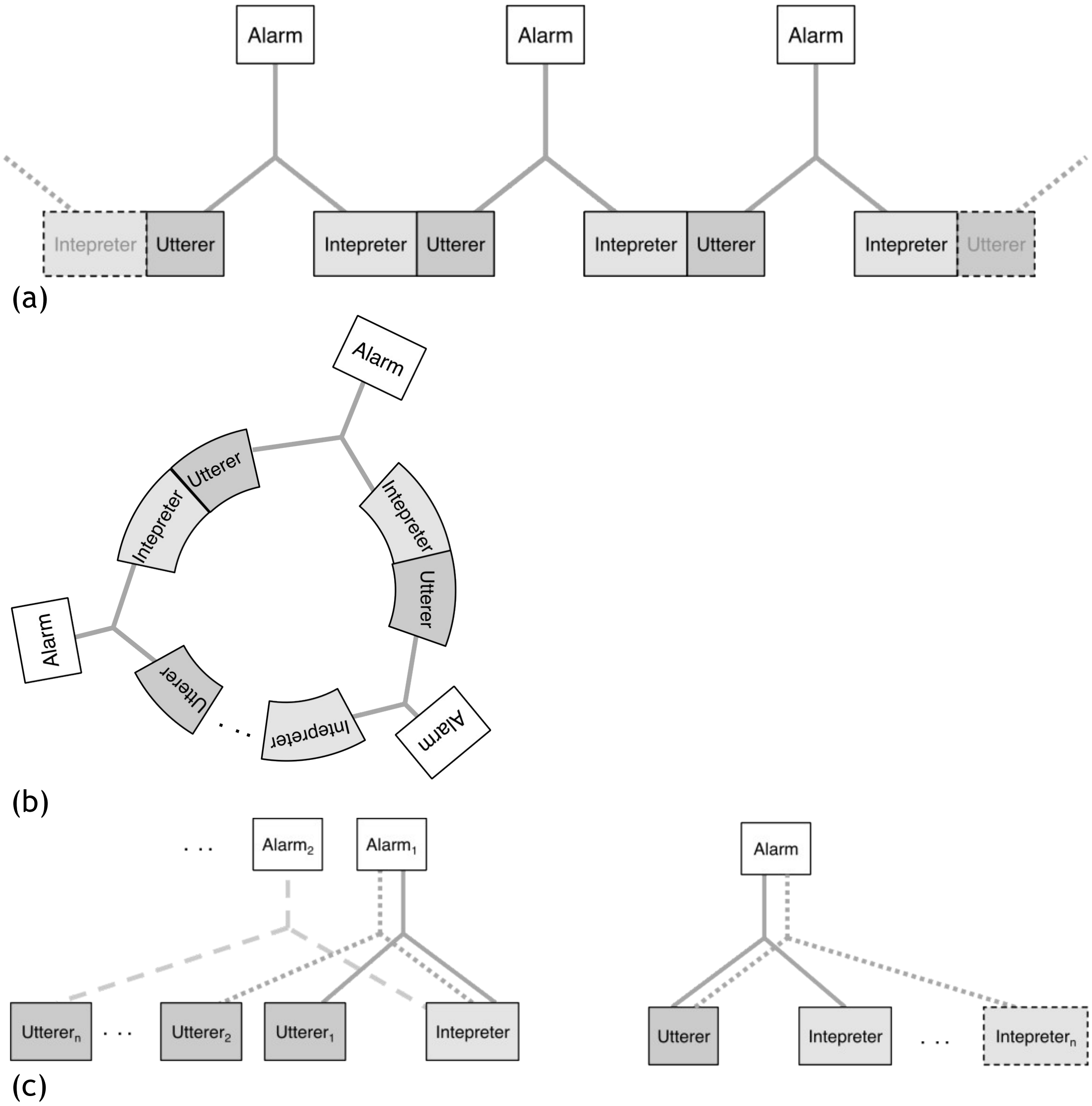


Figure 10: Communication triads involving sign-utterer-interpreter.(a) Individual triads can be connected with interpreters becoming utterers. (b) Utterers can become interpreters in future events establishing circular relations. (c) Interpreters might hear alarms from multiple utterers, and utters might vocalize to multiple interpreters, all at the same time.

As we argued, this focal-level, at which communication events are actualized, is constrained by a macro-semiotic level of networks of communication triads and a micro-semiotic level of potential Sign relations (Figure 11). The micro-semiotic level establishes initiating conditions or possibilities for communication acts, since it comprises potential Signs from 0 to 99 that can be related to any kind of predator by the utterer, while, in the case of the interpreter, a potential Sign can be associated with any type of entity in the environment (potential Object), and can elicit a variety of scanning or fleeing behaviors (potential Interpretants). The environment also plays an essential role in the system dynamics by providing physical contextual constraints (visual cues). When potential Sign relations are actualized, the environment in which the semiotic system is situated will establish specific constraints for the utterer's Sign production (presence of predators) and for the interpreter's Sign interpretation (any surrounding entity). At the macro-semiotic level, we consider focal-level processes as embedded into an interrelated network of chains of triads, which amounts to the system's history. This history is condensed as the communicative preys develop habits based on learning from the past communicative events, precisely located in their individual associative memories, once the associations established are a product of the past communication events and subsequent associations creation and adjustments. Hence, the system's history at the macro-semiotic level establishes constraints for the system's dynamics, which can be treated as boundary conditions, being the system variability reduced with utterers using established signs in its associative memory, and interpreters being able to use the same repository to interpret alarms, which ultimately become symbols.

At first, initiating conditions exert a stronger influence on the focal level, as triadic, semiotic relations are created on the grounds of the available potential Signs, Objects, and Interpretants, and a macro-semiotic level is still under construction. As the system's dynamics goes on, the macro-semiotic level constrains more and more the communicative events actualized at the focal level, and, ultimately, the boundary conditions established by that level guide the system to an ordered state, which amounts to a common repertoire. At this step, symbol-based communication emerges, as a new irreducible property of the semiotic system at stake.

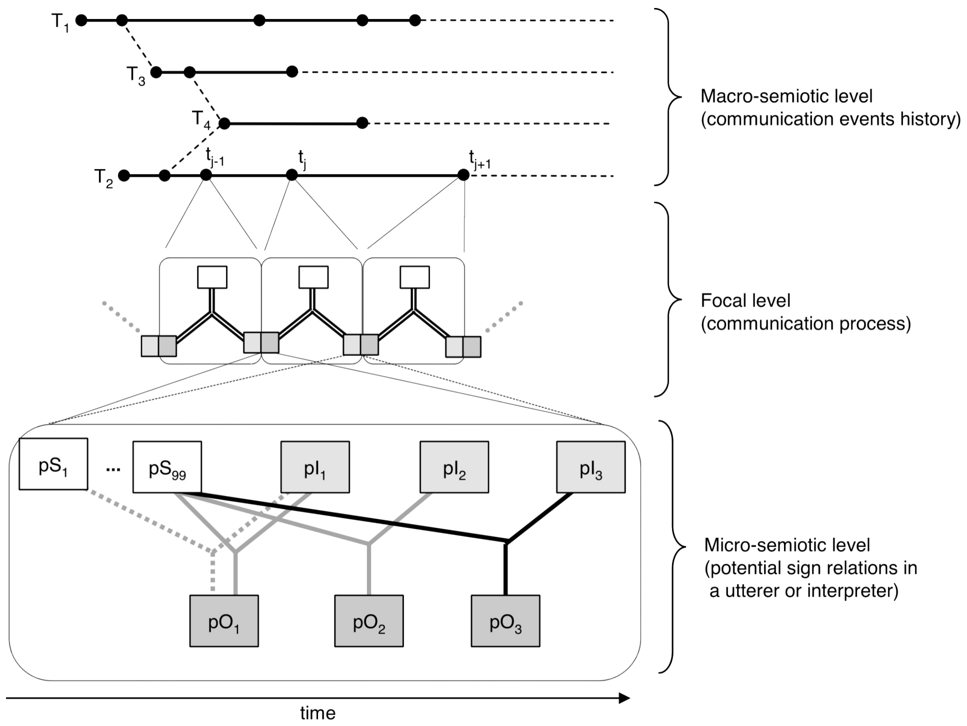


Figure 11: The triadic hierarchy of levels. Symbol-based communication emerges as focal-level semiotic processes evolve, constrained at each step by the communication processes history at the macro-semiotic level and by potential Sign relations at the micro-semiotic level. See Figure 2.

(pS = potential Sign, pI = potential Interpretant, pO = potential Object,
t = single triad, T = sequence of triads)

7. Conclusion of Part II

The design and synthesis of the creatures we present here, along with the digital ecosystem, are guided by biosemiotic meta-principles and motivations. The virtual world we implemented works as a laboratory to simulate the emergence of anti-predatory alarm call vocalization among creatures under the risk of predation.

Although there have been other synthetic experiments simulating the development and evolution of Sign systems, this work is one of the few to deal with multiple distributed agents performing self-organized autonomous communicative interactions, converging to a repertoire of symbols. We did not establish a pre-defined ‘script’ of what could happen in communicative acts, stating a sequence of fixed tasks to be performed by one speaker and one hearer. In our work, creatures self-govern their communication actions, they can be speakers and hearers (utterers and interpreters), vocalizing and hearing from many others at the same time, in a variety of situations. Besides, creatures learn by observing the surroundings after vocalizations are heard and do not rely on any explicit feedback from each other, i.e., no other creature is pointing to referents or evaluating associations made as correct or not.

Our experiment relies heavily on theoretical principles originated from different sources (such as Peirce's semiotics and pragmatism, emergentist philosophy, Salthe's hierarchical structuralism), which played a valuable role in assisting the development and interpretation of our experiment. On the grounds of the theoretical and empirical principles (from studies about communicative behaviors in vervet monkeys) assumed, we investigated symbol emergence from lower-level semiotic processes. Here we apply Peirce's theory of sign to the problem of the emergence of communication in artificial creatures. Moreover, we exercise care in dealing with the concept of emergence in the context of our simulations, something that unfortunately has not been as usual as it should be in the sciences of complexity.

The idea that a community of semiotic creatures can be understood as a complex system follows from works that view language as precisely such a kind of system (see Briscoe, 1998; Steels, 2000). Nevertheless, in our approach, viewing Signs as competing entities trying to spread through a community of Sign users provides a more general approach to the study of communicative interactions, since the framework we applied is not primarily committed to linguistic phenomena. The creatures behave as Sign exchangers, which reproduce the learned Signs, making them able to be used by other creatures, as Signs disseminate in the community.

Characterized as a self-organizing system, the community of Sign-manipulating individuals is seen as being formed by components interacting in a distributed manner, with emergent global properties, besides an inherent unpredictability and non-linearity. These properties make self-organizing systems hard to be studied by simply analyzing their parts separately. This suggests that a synthetic approach, in combination with an analytical one, can be an interesting strategy to study this kind of complex system, and computer simulations can have an important role in our attempts to design, model, and experiment with self-organizing systems.

Acknowledgement: João Queiroz and Charbel El-Hani are indebted to the Brazilian National Research Council (CNPq) and the State of Bahia Foundation for Research Support (FAPESB).

References

Bedau, M. (2002). Downward causation and autonomy of weak emergence. Principia 6 (1), 5-50.

Briscoe, T. (1998). Language as a complex adaptive system: Coevolution of language and of the language acquisition device. In Van Halteren, H. et al

(Eds). Prooceedings of the 8th Meeting of Computational Linguistics in the Netherlands Conference (pp.3-40), Amsterdam.

Brooks, R.A.(1990). Elephants don't play chess. Robotics and Autonomous Systems 6, 3-15.

Cangelosi, A. (2001) Evolution of communication and language using signals, symbols, and words. IEEE Transactions on Evolutionary Computation, 5(2), 93-101.

Cangelosi, A, & Turner, H. (2002). L'emergere del linguaggio. In Borghi, A. M., & Iachini, T. (Eds.) Scienze della Mente (pp.227-244). Bologna: Il Mulino.

Cangelosi A., Parisi D. (1998). The emergence of a language in an evolving population of neural networks. Connection Science 10 (2), 83-97.

Cheney, D.L. and Seyfarth R. (1990). How Monkeys See the World. Chicago: University of Chicago Press.

Cheney, D., & Seyfarth, R. (1998) Why animals don't have language. In Pearson, G.B. (Ed.), The Tanner Lectures on Human Values (pp. 175-209). Salt Lake City: University of Utah Press.

Franklin, S. (1995). Artificial Minds. Cambridge, MA: MIT Press.

Franklin, S. (1997). Autonomous agents as embodied AI. Cybernetics and Systems, 28(6), 499-520.

Griesser, M. & Ekman, J. (2004) Nepotistic alarm calling in the Siberian jay, Perisoreus infaustus. Animal Behaviour, 67(5), 933-939.

Gudwin, R. & Queiroz, J. (eds.). 2007. Semiotics and Intelligent Systems Development. IDEA GROUP.

Hebb, D.O. (1949) The Organization of Behavior. New York: John Wiley.

Hurford J. (1991). The evolution of the critical period for language acquisition. Cognition. 40 (3), 159-201.

Hutchins, E., & Hazlehurst, B. (1995). How to invent a lexicon: the development of shared symbols in interaction. In Gilbert, G. N., & Conte, R. (Eds.) Artificial Societies: The Computer Simulation of Social Life. London: UCL Press.

Kirby S. (1999). Learning, bottlenecks and infinity: a working model of the evolution of syntactic communication. In Dautenhahn K., Nehaniv C. (eds.), Proceedings of the AISB'99 Symposium on Imitation in Animals and Artifacts. Cambridge University Press: Cambridge. 55-63.

Loula, A., Gudwin, R., Ribeiro, S. & Queiroz, J. (2010). On Building Meaning: A Biologically-Inspired Experiment on Symbol-Based Communication. Brain Inspired Cognitive Systems. Amir Hussain, Igor Aleksander, Leslie S. Smith, Allan Kardec Barros, Ron Chrisley and Vassilis Cutsuridis (Eds.). Springer New York. pp. 77-93.

Loula, A., Gudwin, R., El-Hani, C. & Queiroz, J. (2010) The emergence of self-organized symbol based communication in artificial creatures. Cognitive Systems Research 11 (2): 131-147.

Loula, A., Gudwin, R. & Queiroz, J. (2004) Symbolic Communication in Artificial Creatures: an experiment in Artificial Life. Lecture Notes in Artificial Intelligence, 3171, 336 – 345 (Advances in Artificial Intelligence - SBIA 2004, Proceedings of the 17th Brazilian Symposium on Artificial Intelligence)

MacLennan. B. J. (2001). The emergence of communication through synthetic evolution. In Patel, M., Honavar, V. & Balakrishnan, K. (Eds.) Advances in the Evolutionary Synthesis of Intelligent Agents (pp. 65-90). Cambridge, Mass.: MIT Press.

Manser, M. B., Seyfarth, R. M., & Cheney, D. L. (2002) Suricate alarm calls signal predator class and urgency. Trends in Cognitive Sciences 6(2), 55-57.

Peirce, C.S. (1931-1935). The Collected Papers of Charles Sanders Peirce. Vols. I-VI. (Eds.) C. Hartshorne and P. Weiss. Cambridge, Mass.: Harvard University Press. [quoted as CP, followed by the number and paragraph]

__. (1958). The Collected Papers of Charles Sanders Peirce. Vols. VII-VIII. (Ed.) A.W. Burks. Cambridge, Mass.: Harvard University Press. [quoted as CP, followed by the number and paragraph]

__. (1998) (1893-1913). The Essential Peirce: Selected Philosophical Writings. Vol. II. (Ed.) Peirce Edition Project. Indiana: Indiana University. [quoted as EP2, followed by the number of the page]

Proctor, C.J., Broom, M., & Ruxtona, G.D. (2001) Modelling antipredator vigilance and flight response in group foragers when warning signals are ambiguous. Journal of Theoretical Biology, 211(4), 409-417.

Queiroz, J. & Ribeiro, S. (2002). The biological substrate of icons, indexes, and symbols in animal communication, In: The Peirce Seminar Papers – The State of the Art. Vol. V (Ed.) M. Shapiro. Berghan Books. pp. 69-78.

Queiroz, J. & El-Hani, C. N. (2006a). Semiosis as an emergent process. Transactions of C.S.Peirce Society: A Quarterly Journal in American Philosophy 42 (1): 78-116.

Queiroz, J. & El-Hani, C. N. (2006b). Towards a multi-level approach to the emergence of meaning processes in living systems. Acta Biotheoretica 54(3): 174-206.

Ransdell, J. 1983 . Peircean semiotics. (unpublished).

Seyfarth, R., Cheney, D.L. and Marler, P. 1980. Monkey responses to three different alarm calls: evidence of predator classification and semantic communication. Science (210): 801-803.

Seyfarth, R. & Cheney, D. (1986). Vocal development in vervet monkeys. Animal Behaviour, 34: 1640–1658.

Smith, A. D. M. (2001). Establishing Communication Systems without Explicit Meaning Transmission. In Kelemen, J. & Sosik, P. (Eds.), Proceedings of the 6th European Conference on Artificial Life, ECAL 2001 (pp. 381-390). Berlin Heidelberg: Springer-Verlag.

Steels, L. (1999). The Talking Heads Experiment: Volume I. Words and Meanings. VUB Artificial Intelligence Laboratory, Brussels, Belgium. Special pre-edition.

Steels, L. (2000) Language as a Complex Adaptive System. In Schoenauer, M. (Ed.) Proceedings of Parallel Problem Solving from Nature (PPSN) VI. Berlin, Germany: Springer-Verlag.