Synthetic Semiotics: on modelling and simulating the emergence of sign processes

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Abstract. Based on formal-theoretical principles about the sign processes involved, we have built synthetic experiments to investigate the emergence of communication based on symbols and indexes in a distributed system of sign users, following theoretical constraints from C.S.Peirce theory of signs, following a Synthetic Semiotics approach. In this paper, we summarize these computational experiments and results regarding associative learning processes of symbolic sign modality and cognitive conditions in an evolutionary process for the emergence of either symbol-based or index-based communication.

1 INTRODUCTION

Following the motto 'build to explain', a synthetic approach (opposed to an analytical one) corresponds to a reverse methodology that builds creatures and environments describing a simple and controllable framework to generate, test and evaluate theories and hypothesis about the system being modelled. Diverse processes and systems are modelled and simulated in such synthetic experiments, including social, biological and cognitive processes [1, 2, 3, 4, 5, 6]. Particularly, we have been modelling and simulating semiotic systems and processes, following a Synthetic Semiotics approach.

Based on formal-theoretical principles about the sign processes involved, we have built synthetic experiments to investigate the emergence of communication based on symbols and indexes in a distributed system of sign users, following theoretical constraints from C.S.Peirce theory of signs. In this paper, we summarize these computational experiments and results. We investigated the associative learning processes of symbolic sign modality and the relation between different sign modalities in the transition from indexical to symbolic communication. We also studied cognitive conditions in an evolutionary process for the emergence of either symbol-based or index-based communication, relying on different types of cognitive architecture.

First, we review related work, then we describe our formal-theoretical background, the sign theory by of C.S.Peirce. Finally we present synthetic experiments that modelled and simulated the emergence of communication processes, dealing with the learning process of symbolic sign modality and also with the evolution of indexical and symbolic interpretative behaviours. The notion of responsive environments is broad, encompassing essentially every space capable of sensing and responding accordingly to entities that inhabit them (these entities can be people, animals, or any sort of identifiable objects).

2 RELATED WORK

There have been several different experiments concerning symbol grounding and also the emergence of shared vocabularies and language in simple (real or virtual) worlds [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18] (for a review of other works, see [19], [20]). Despite the fact that sign processes are in the foundations of communication, little discussion about such processes can be found, such as the emergence of fundamental types of signs and their interpretative effects.

There have been studies introducing theoretical foundations in reference to Peirce's work [11, 16, 17, 13, 8], but they just borrow Peircean definitions of symbol or of sign without generating any further consequences to the designed experiment. For example, in [17], [13] and [8], authors bring forth definitions of signs and symbols from Peirce's general theory of signs, but they end up changing them, in such a way that it is not possible to conclude whether the experiments were actually based on Peirce's theory or whether it contributed, validating it or not, some of the principles of Peirce's theory. In [11] and [16], on the other hand, presents Peirce's theory through a second hand reading of Deacon's work, which is at least a limited analysis of the Peircean theory and, in special, of his definition of a symbol. As a consequence, we can say that they were not able to recognize a symbol when it first occurred in their experiments.

Deacon's reading of Peirce's theory is the most popular example at hand of such disconnection between theoretical framework and actual research [21]. His depiction of humans as the only 'symbolic species' is based on the assumption that symbols necessarily have combinatory properties, and that only the human prefrontal cortex could possibly implement such properties. However, this proposal is incongruent with Peirce's theory and frontally collides with several empirical lines of evidence (for a discussion of this point, see [22],[23]). Poeppel [24] already recognized the 'problematic' and 'speculative' manner in which Deacon built his arguments using Peirce's theory, comparative and evolutionary approaches to language and even linguistic theories.

We claim that just bringing forward a definition from Peirce's theory without deriving any consequence or constraint to the experimental setup certainly reduces the explanatory power of the proposed model. Recognizing the inter-dependence of Peirce's concepts at different levels, such as the sign model and its derived sign classification, substantially enriches computational experiments willing to simulate communication and its relationship to meaning.

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3 THE THEORY OF SIGNS OF C.S. PEIRCE

North-American pragmatist Charles Sanders Peirce, founder of the modern theory of signs, defined semiotics as a kind of logic: a science of the essential and fundamental nature of all possible varieties of meaning processes (*semiosis*). Peirce's concept of semiotics as the 'formal science of signs', and the pragmatic notion of meaning as the 'action of signs', have had a deep impact in philosophy, in theoretical biology and in cognitive science (see [25]). Peircean approach to semiotic process (semiosis) is also related to formal attempts to describe cognitive processes in general. His framework provides: (i) a list of fundamental varieties of representations based on a theory of logical categories; (ii) a model to approach the emergence and evolution of semiotic complexity in artificial and biological systems.

Peirce defined semiosis (meaning process) as an irreducible triadic relation between a sign (S), its object (O) and its interpretant (I). That is, according to Peirce, any description of semiosis involves a relation constituted by three irreducibly connected terms: "A sign is anything which determines something else (its interpretant) to refer to an object to which [it] itself refers (its object) in the same way, the interpretant becoming in turn a sign, and so on ad infinitum" [26, CP 2.303]. Semiosis is also characterized as a behavioural pattern that emerges through the intra/inter-cooperation between agents in a communication act, which involves an utterer, a sign, and an interpreter. Meaning and communication processes are defined in terms of the same "basic theoretical relationships" [27], i.e., in terms of a self-corrective process whose structure exhibits an irreducible relation between three elements. In a communication process, "[i]t is convenient to speak as if the sign originated with an utterer and determined its interpretant in the mind of an interpreter" [28, MS 318].

As it is well known, sign-mediated processes show a notable variety. There are three fundamental kinds of signs underlying meaning processes – icons, indexes, and symbols [26, CP 2.275]. They correspond to similar, reactive, and law relationship which can be established between a sign and its object. Icons are signs that stand to objects by similarity, without regard to any space-time connection with existing objects [26, CP 2.299]. An icon stands to the object independently of any spatio-temporal presence of the latter; it refers to the object merely by virtue of its own properties. This is an important feature distinguishing iconic from indexical sign-mediated processes. Indices are signs that refer to objects due to a direct physical connection between them. Accordingly, spatio-temporal co-variation is the most characteristic aspect of indexical processes. Finally, symbols are signs that are related to their object through a determinative relation of law, rule or convention. A symbol becomes a sign of some object merely or mainly by the fact that it is used and understood as such.

4 EXPERIMENTS IN SYNTHETIC SEMIOTICS

4.1 Learning and the emergence of symbol-based communication

Inspired by the vervet monkey alarm call ethological study case ([29], see [23], for a neurosemiotic analysis), we have simulated an ecosystem for artificial creatures' interactions, including intra-specific communication for predators' presence. We investigated the learning processes (habit acquisition) of symbolic sign modality and the relation between different sign modalities in the transition from indexical to symbolic behaviour through associative learning.

The creatures were autonomous agents inhabiting a virtual bi-dimensional environment. This virtual world was composed of prey and predators (terrestrial, aerial and ground predators), and of things such as trees (climbable objects) and bushes (used to hide). Preys could produce vocalizations (alarm calls) indicating that a predator was seen. That vocalization could become immediately available to nearby preys by way of a hearing sensor. We proposed two scenarios: with apprentices and tutors [30], and with self-organizers [31]. Apprentices and tutors, as seen in the contrast between infant and adult vervet monkeys, defined a learning relation. Tutors, that had already established vocalizations for each predator, were the only ones to vocalize and as the preys heard them, they tried to establish the connections relations between the auditory and the visual stimuli. Self-organizer creatures were apprentices and tutors at the same time, but there was no initially established repertoire of alarms calls, and the group of preys had to create and share alarm calls for each predator, by vocalizing to and learning from each other.

Associative learning was the mechanism used by preys to gradually acquire association rules between auditory and visual data necessary to interpret signs as symbols. It involved working memories and an associative memory. Working memories allows the persistence of spatio-temporal relations. Associative memory formation followed Hebbian learning principles [32] and allowed the creatures to, not only, learn temporal and spatial relations from the external stimuli and the associations to be created, but also reinforced or weakened them (varying association strength between 0 and 1) according to the co-occurrence of stimuli in the working memories (figure 1).

After hearing a vocalization, preys initially responded with a sensorial scan for the utterer and co-occurring events, a typical indexical behaviour. As the strength of sign-predator associations reached a certain threshold, after multiples reinforcements, a new action rule was established, 'flee with no scanning'. In this situation, the prey used an established association to interpret the alarm, and we can say that the sign-object relation depended on the interpreter and no more in a physical, spatial-temporal evidence, and therefore the alarm became a symbol.

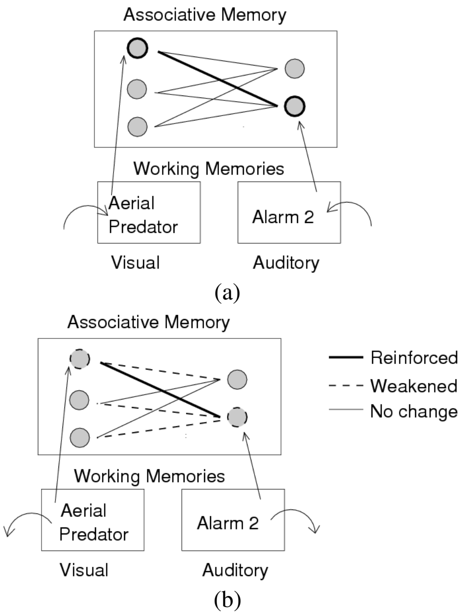


Figure 1. Associative learning: reinforcement and weakening. (a) The co-occurrence of visual and auditory stimuli in working memories reinforces the association between them. (b) When sensory stimuli are dropped from working memories, associations involving them and that were are not reinforced, are weakened.

During simulations, we observed the associative memory items and behaviour responses of the preys to alarm calls. Results showed that both apprentice and self-organizer preys were able to acquire symbolic competence. Preys initially exhibited an indexical behaviour to alarm calls, but a symbolic response emerged by means of communicative interactions. Apprentices were able to establish the same alarm-predator relations used by tutors (alarm 1 - terrestrial predator, alarm 2 - aerial predator, alarm 3 - ground predator). Even though apprentices, eventually associated alarms with the presence of elements such as trees and bushes, the associative learning mechanism was able to gradually reinforce the correct links, going up to its maximum value of 1.0 at the end of simulation, while weakening the other links, which went down the minimum value of zero (figure 2; see [30], for more detailed results).

On the other side, self-organizers, starting with no a priori relation between alarms and predators, were able, at the end, to converge to a common repertoire of associations between alarms and predators. As there were no predefined alarms for each predator, each creature could create a random alarm (from 0 to 99) for a predator if it had not had one associated with that predator before. As a consequence, various alarms were created for the same predator, and even the same alarm could be used for different predators. And some alarms could also be associated with elements other than predators. Nevertheless, associative learning was responsible for a gradual convergence of the community of preys to use the same alarms for the same predators (figure 3; see [31], for more detailed results).

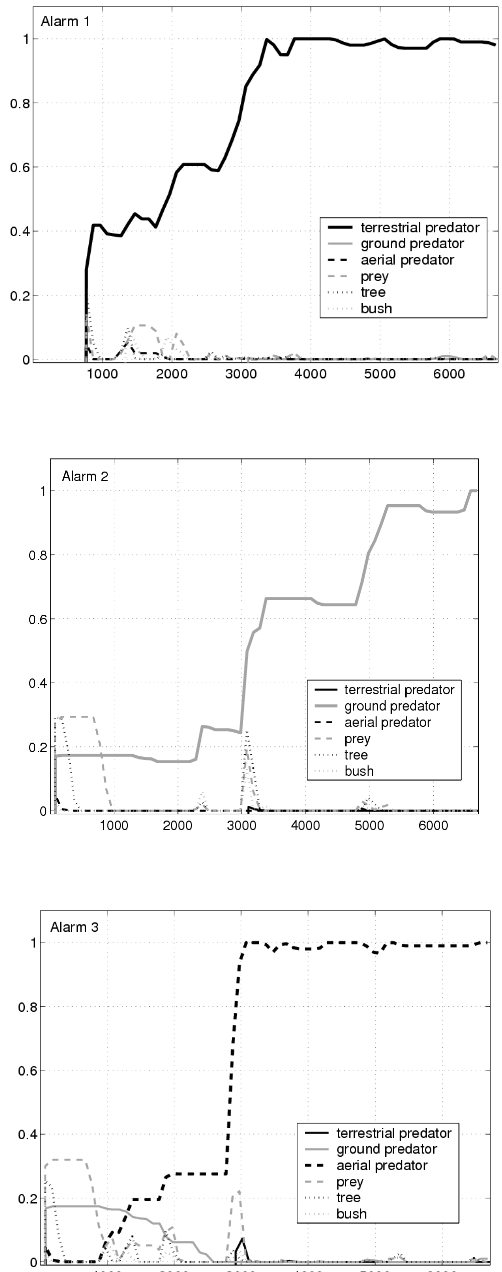


Figure 2. Associations' strength values for one apprentice, for each alarm, during simulation.

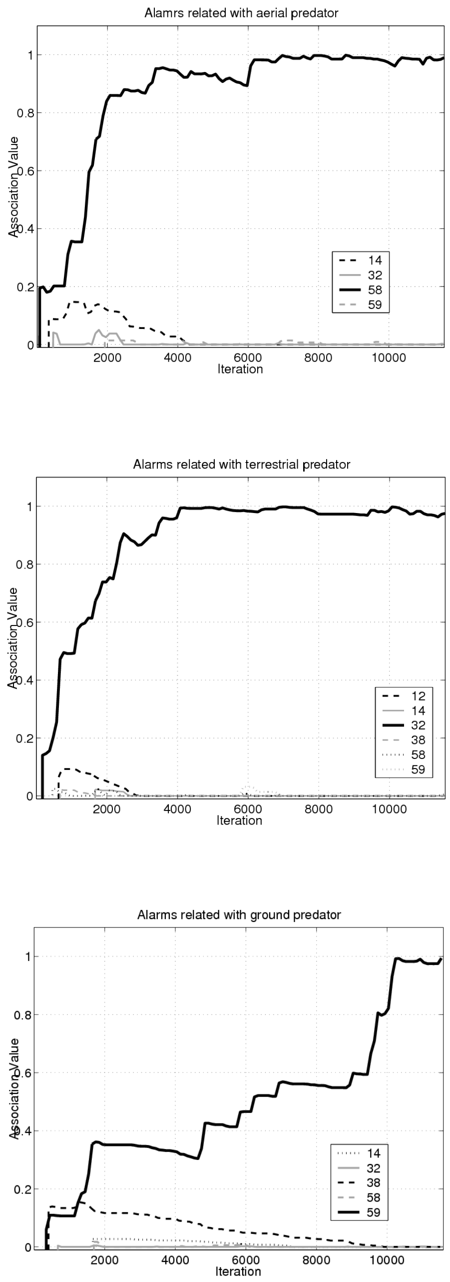


Figure 3. Associations' strength values for self-organizers, for each type of predator.

4.2 Evolution and the emergence of different classes of sign processes

Based on the fact that signs can be of different types and that communication processes rely on the production and interpretation of signs, we have modeled the emergence of indexical and symbolic interpretative behaviors in communication processes, when none of them was initially available, and we have studied how they emerge, and the cognitive conditions for the emergence of such interpretation processes. To model those interpretation-communication processes, we also followed the minimum brain model for vocalization behavior in from [23] and the biological motivations from animal communication, specifically, for food calls [33].

Indexical interpretation is a reactive interpretation of signs, so for our creatures to have this competence, they had to be able to reactively respond to sensory stimulus with prompt motor answer. But then again a symbolic interpretation undergoes the mediation of the interpreter to connect the sign to its object, in such a way that a habit (either inborn or acquired) must be present to establish this association. Also, in symbolic interpretation, an associative memory must be present as it is the only domain able to establish connections between different representation modes. Thus, our artificial creatures had to be able to receive sensory data, both visual and auditory, that could be connected directly to motor responses (Type 1 architecture), or else they should be connected to motor responses indirectly, through the mediation of an associative memory, that associates auditory stimulus to visual stimulus (Type 2 architecture) (see figure 4).

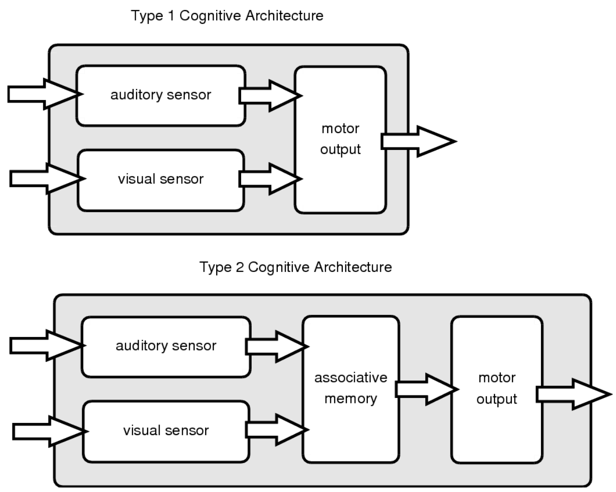


Figure 4. Cognitive architectures for representations' interpretations. Top: Type 1 architecture. Bottom: Type 2 architecture.

Lower quality resources were scattered throughout the environment and a single location received highest quality resources, where one creature (vocalizer) was placed. The other creatures (interpreters) were controlled by finite state machines

(FSM) and had visual and auditory sensors and motor capabilities. These interpreter creatures could respond to visual inputs with one of the motor actions, and could also respond to auditory input with a direct motor action (a reactive, indexical process) (Type 1 architecture). Alternatively, before an input was sent to the FSM, they could also choose to establish an internal association between the heard stimulus and the visual representation domain (Type 2 architecture). This internal association linked what was heard with the view of a collectible resource, i.e. the creature could interpret the sign heard as a resource and act as if the resource was seen.

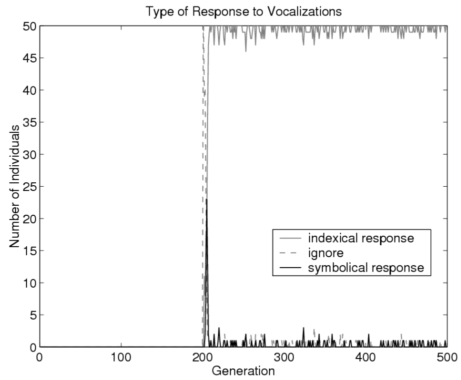
At the start of the simulations, interpreter creatures were randomly defined, so creatures did not respond appropriately to sensory inputs. But an evolutionary process of variation and selection was applied, allowing the evolution of individuals to better accomplish the task of resource foraging. During the evolutionary process, for each start-up conditions, we observed the types of cognitive architecture used by creatures and their motor responses to sensory input.

We performed two initial experiments to evaluate the emergence of either an indexical interpretation or a symbolic interpretation of vocalizations. Such experiments involved 2 cycles, but only in the second cycle, the vocalizer was present. In the first experiment, creatures just had to have a specified action as output of the FSM to execute that action. We observed that the indexical interpretation was the competence acquired by creatures to deal with communication, with the direct association between auditory signs and motor actions. But, in a second experiment, for motor actions to be executed, the creatures needed to first output a null action before any movement action was done. In this case, learning motor coordination was harder. In this alternative scenario, symbolic interpretation was the emerging competence, instead of an indexical one. We asserted the hypothesis that acquiring symbolic competence would act as a cognitive shortcut, by reusing a previously acquired ability in cycle 1 to appropriately respond to visual data with motor actions. We proposed that a symbolic interpretation process can happen if a cognitive trait is hard to be acquired and the symbolic interpretation of a sign will connect it with another sign for which the creature already has an appropriate response (figure 5; see [34] for detailed results).

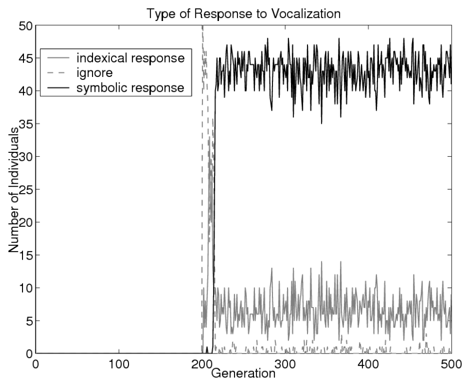
Once symbolic interpretation needed a competence to benefit from, we investigated the availability and reliability of such previous competence in a subsequent set of experiments. We first proposed an experiment where this first cycle did not occur, therefore visual-motor coordination was not established before vocalizations started. From this single cycle experiment, it was possible to observe that even though the vocalizer was available from start, creatures did not use signs at all in a first moment. But, as trying to acquire visual-motor coordination and also a sign-motor coordination was a hard task route, the symbolic interpretation diminished this effort and became the dominant strategy (figure 6; see [35], for more detailed results).

To go further in our investigation, we set up another experiment, in which cycle 1 was present but there was a failure chance in the visual-motor coordination after cycle 1, simulating a malfunctioning cognitive module. At first, with a 20% of motor action selection failure, symbolic processes were still established, with reuse of a degraded module, with a relative increase in foraging efficiency, however. A higher failure of 50% proved to worsen the performance of the visual control module considerably more, and allowed indexical interpretation of sign to be established, as a way to avoid reusing it.

At the end of our experiments, we confirmed our hypothesis that symbolic competence acted as a cognitive shortcut, and, as such, the cognitive module to which the symbolic interpretation was connecting to must be already established. Nevertheless, it does need to be fully functional, as minimal visual-motor coordination is sufficient to begin a symbolic interpretation process and even a moderately damaged module can also be reused.

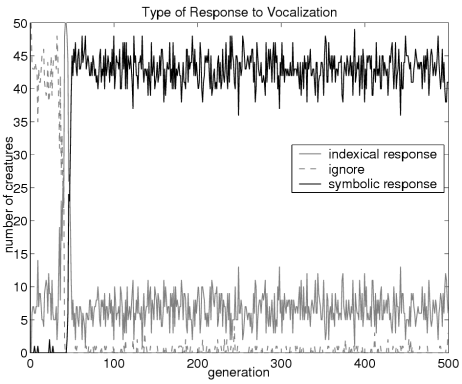


(a)

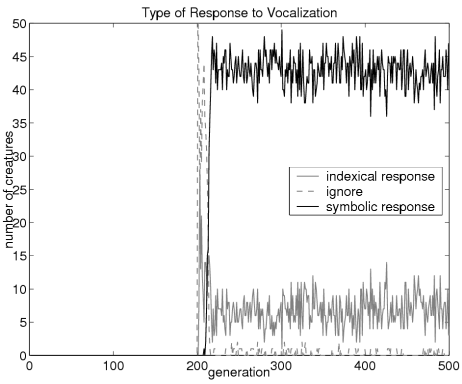


(b)

Figure 5. Evaluation of the type of response to vocalizations along the generations for (a) the direct motor action experiment and (b) the previous null action experiment.



(a)



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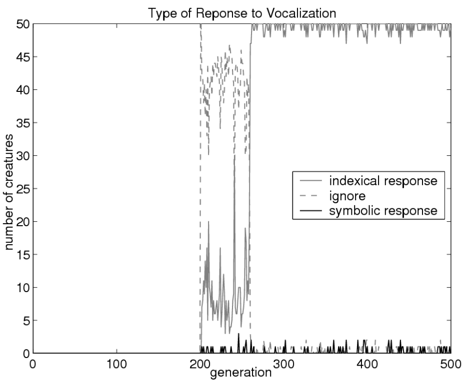

(c)

Figure 6. Evaluation of the type of response to vocalizations along the generations for (a) the one cycle only experiment, (b) 20% failure experiment, and (c) 50% failure experiment.

5 CONCLUSIONS

The relation between simulations and theories is a 'two-way road' (see [36]). Simulations offer to the theory an opportunity to formalize and quantify, in terms of programming language. Following a synthetic approach, a computational model is built based on basic theoretical assumptions about the target-system. Here, we applied the sign theory of C.S.Peirce in building synthetic experiments to investigate the transition to symbolic communication by means of associative learning and cognitive conditions in a evolutionary processes for either symbol-based communication or index-based communication.

Even though Peirce's pragmatic approach have established a rigorous distinction between different classes of sign processes as well as between semiotic behaviour and brute reactive behaviour, he did not describe: (i) the dynamics responsible for the emergence of semiosis in an evolutionary scenario, and (ii) the dynamics responsible for the transition from iconic and indexical semiotic systems to symbolic and meta-semiotic ones. Synthetic Semiotics can define a methodology for better understanding the dynamics related to the emergence of indexical and symbolic-based semiosis. Formal-theoretical principles act not only as theoretical background but also as constraints in designing the artificial systems and as bridges for contributions to the sign theory that originally provided the principles.

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