Analyzing the Evolution of Communication from a Dynamical Systems Perspective*

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Abstract. We study the evolution of communication where concepts are developed individually by agents and relations between concepts and forms (words, signals) are learned through interaction with other agents. By constructing concepts based on experience with the same environment, agents develop similar conceptual systems. Concepts represent situations in the environment. The system of associations between forms and meanings is viewed as a dynamical system. This paper presents first results with investigating the phase space of the system. The analysis contributed to understanding the interaction between association strengths of different agents and of different meanings.

Introduction

In studying the evolution of communication, an important question is that of how stable systems connecting concepts and forms (words, signals) may come about. In this paper, we will be investigating the case where these connections are learned by a group of agents in a shared environment. The concepts themselves are formed by the agents based on experience within the environment using *autonomous concept formation* [de Jong, 1999].

Although the fact that simple local adaptive behavior of agents causes a system of communication to emerge is interesting in itself, a deeper understanding of this process is valuable. Since the complete system of agents, concepts and forms is a complex adaptive system (see e.g. [Steels, 1996a], [Steels, 1997]) containing a large and varying number of changing elements, it is difficult to predict the behavior of the system given the rules which govern it. A viewpoint that has been found to be more appropriate for these types of systems is the dynamic systems approach.

In the literature, several examples of dynamic systems approaches to language exist. A number of researchers have investigated motor behavior during speech,

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e.g. [Saltzman, 1995], [Browman and Goldstein, 1995], [Tuller and Kelso, 1990]. In [Elman, 1995], an analysis of the activation space of recurrent neural networks is presented as a dynamical view on grammar and embedding. A difference between that work and ours, is that grammar does not play a role here. Instead, the focus here is on the use of language, and concepts are grounded by use in the environment, see [Steels, 1996b].

In section 1 the alarm calls experiment and the association adaptation mechanism are briefly explained. In section 2 the resulting system of communication is described and the phase space of the system is examined. The final section presents conclusions.

1 Environment and Behavior of Individual Agents

In this section we describe the environment used in the experiments and the mechanism that, when used by individual agents in that environment to adapt form-meaning associations and to determine their situation, leads to a stable system of communication.

The Environment The task faced by the agents is to occupy a safe position within a 10 by 3 grid whilst being hunted by predators. At each timestep, each agent in turn selects an action and receives a success value. The action consists of choosing the vertical position (bottom, middle or top row) and a horizontal displacement (1 step to either side, or staying). Three predators exist. When one is present, only a single row is safe (success 1); agents in the other two rows receive success 0. Sensor information consists of an agent's horizontal and vertical position, and a number indicating the predator (none, or predator 1, 2 or 3). The predator indicator is not completely reliable though; this is where the benefit of communication comes in. In 10% of the cases when a new predator arrives, an agent is not able to see it, depending on its horizontal position, and this remains so until it leaves (after 25 timesteps).

Formation of Situation Concepts Based on the relationship between sensor information and success, agents learn to distinguish different *situations*. Knowing in which situation it is allows an agent to choose optimal actions. *Situation concepts* are formed using autonomous concept formation, described in [de Jong, 1999]. Briefly, the method as it is used here identifies regions in the sensor-action space where success is constant. Since concepts are formed based on experience, the number of concepts an agent will develop is not known in advance, and may differ among agents.

Adaptation of Form-Meaning Association Strength Once agents have concepts at their disposal that capture relevant situations in the environment, a basis for developing communication is present. At each timestep, every agent produces a signal corresponding to its perceived situation. When some agent does not receive sensory information that would allow it to determine its situation, this information may be obtained through communication. If the association between a signal received and a situation concept other than the one indicated by the sensors is strong enough, the agent can deduce its actual situation from that signal and act accordingly. This has been shown in [de Jong, 1999]. Associations between meanings (situation concepts) and forms (words, signals) are adapted locally by each agent based on (1) frequency of occurrence and (2) success in determining the situation. The system is open with respect to the signals the agents use, and the number of signals is not fixed.

2 Results

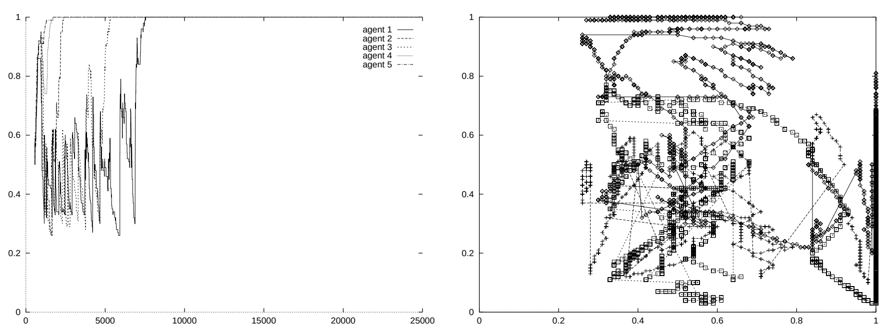

Fig. 1. Left: The evolution over time of the association strength of the word `fi` with each agent's meaning for the first predator (P1). Right: Phase plot for agent 1. Each point represents a pair of association strengths, one between `fi` and the meaning for P1 (always horizontal), and one between `fi` and another meaning (vertical)

This section presents the results of the experiment. In a particular experiment, see figure 1 (left), 4 agents developed strong associations between the word `fi` and the situation where predator 1 is present. For agent 1, this association fluctuated (t = 5000) before it was established (t = 8000). In the phaseplot in figure 1 (right), this final situation is represented by the points at the vertical line to the right (x = 1). The main part of the plot consists of trajectories where the association between `fi` and P1 (P1FI) competed with the other meanings. Of particular interest is the folded curve just right of the middle at the top of the graph. Here, the strength of P1FI repeatedly reaches high values (the horizontal position, around 0.75), but returns to lower values each time. Apparently, the competing meaning (corresponding to the vertical position) was too high to be overcome. As we know from the time series, P1FI did move to 1 later on. This is represented by the series of squares starting just below the line that was mentioned, and describing a curve towards the lower right corner, indicating the meaning gave way to P1FI to become associated. The fact that the system's state never reaches the upper right corner corresponds to the competitive nature of form meaning associations; in the top right corner, a signal would be simultaneously associated with two meanings. It can be deduced from the algorithm that such a state is unlikely to be stable. What analyzing the algorithm doesn't show is *how* the system evolves over time, i.e. through what states it tends to move. That is the result of complex interaction between the association strengths of multiple agents and multiple meanings and words for each of those agents. This is why it can be useful to investigate the phase space of a system, in addition to time series of the relevant data.

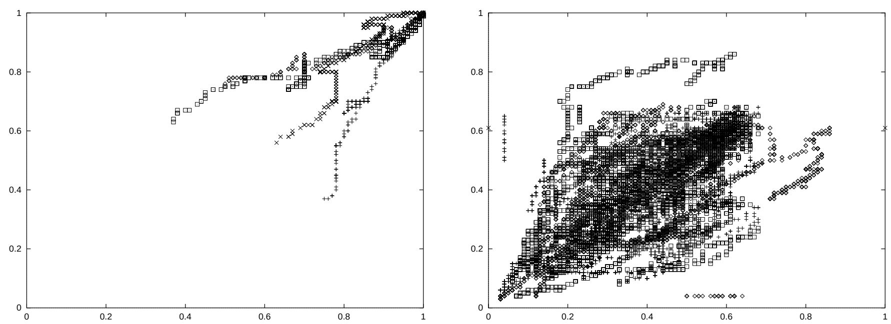

Fig. 2. Left: Phase plot of the association strength of the word `ci` with the first predator for different pairs of agents. Right: Phase plot of the association strength of the word `bo` with the second predator for different pairs of agents

A rather different pattern is seen in figure 2 (left), which shows a phase-plot where the associations between the word `ci` and P1 are plotted for pairs of agents. This word eventually becomes associated to P1 for every agent. What the phaseplot shows us is how the association strengths influence each other. Whereas near the middle of the graph, where association strengths are moderate, variation of the strengths appears rather flexible, this changes when the system reaches the top right corner. In that phase, the association strengths have been observed (also in other graphs) to tend towards each other, resulting in an increased density of points around the diagonal line y = x. This is what one would intuitively expect; once most agents use some word for a certain concept, the rest will follow and adopt the word as their preferred word for that concept.

Figure 2 (right) shows the association strength patterns for a word (BO) and a meaning (P2) that did not become associated. Similar to the previous graph, the association strengths of different agents for a particular combination of form and meaning tend towards each other when extreme values are reached, though this time the values are low instead of high. Qualitatively, this can be understood as a word losing its association with a particular concept. When the word is not used anymore by some critical mass of the population, the rest follows and also discards the word.

3 Conclusions

The main conclusion that can be drawn from the experiments is that the evolution of communication, as it was observed in the experiments presented here, can appropriately be viewed as the behavior of a dynamical system. Interacting elements are the vital part of such a system, and the composition of their behavior soon becomes too complex to analyze. By taking a dynamical systems perspective, different ways of analyzing the system become available. The analysis of experiments based on phase plots revealed relationships that would probably not have been found otherwise. Particularly, a tendency of different agents to converge towards the same association strength, both high (1) and low (0) for certain combinations of meanings and signals was found. Furthermore, the behavior of the competition between one form and several meanings of a single agent could be observed. It may be concluded that investigating the phase space of a learned system of communication gave new insights, and is a promising method. An interesting continuation of the analysis would be to investigate relationships between order and control parameters of the system [Kelso, 1995].

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