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Evolutionary Approach to Investigations of Cognitive Systems

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Abstract. Evolutionary approach to investigations of cognitive systems is analyzed. Modeling of cognitive evolution (a study of evolution of animal cognitive features) is considered. Backgrounds of models of cognitive evolution that are developed in the area of research "Adaptive behavior" are outlined. Our initial models of cognitive evolution investigations are described. The sketch program for future modeling of cognitive evolution is proposed.

Keywords. Cognitive evolution; modeling; adaptive behavior; animal cognitive abilities

Introduction

Studies of cognitive evolution are related to a profound epistemological problem: why *human* mind is applicable to cognition of *nature*? Investigating models of cognitive evolution, we can analyze, why and how did animal and human cognitive features emerge, and how did applicability of human mind to cognition of nature origin. So, this modeling is related to foundation of science, cognitive science and epistemological studies. Fortunately, there is a direction of research "Adaptive Behavior" [1] that is in close relation to the modeling of cognitive evolution.

The starting point of our consideration is the mentioned epistemological problem. Approaches to analyze this problem by means of modeling of cognitive evolution are described in the next section. Then we outline the area of research "Adaptive Behavior" and models of adaptive behavior that are directly related to cognitive evolution. The sketch program for future modeling of cognitive evolution is also proposed. Models that correspond to initial steps of the sketch program are described.

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1. Epistemological Problem

There is the epistemological problem: why *human* thinking is applicable to cognition of *nature*? To characterize the problem, let us consider physics. The power of physics is due to effective use of mathematics. However, why mathematical deductions are applicable to studies of real physical phenomena? Indeed, a mathematician makes logical inferences, proves theorems, working with abstractions in his mind, independently from the physical world. Why results of his work are applicable to real nature?

Similar questions were interesting for scientists and philosophers for a long time. In the 1780s, Immanuel Kant investigated human thinking and human cognition [2, 3]. According to Kant, there is a system of categories, concepts, logic rules, and inference methods which humans use in cognition of nature. This system of "pure reason" is of *a priory* character; it exists in our minds before any experience. As the pure reason is of a priory character, our reason prescribes its laws to nature [3]:

"…it seems at first strange, but is not the less certain, to say: *the understanding does not derive its laws (a priori) from, but prescribes them to, nature.*"

After appearance of Darwinian theory, the concept of a priory pure reason had to be revised. Such revision was clearly expressed by Konrad Lorenz [4]. According to Lorenz, human mind emerged in the course of evolution as a result of numerous interactions with the external world. In an evolutionary context, "pure reason" is not of a priory character, it has obvious evolutionary empirical roots.

Actually, Kant and Lorenz demonstrated that without analysis of evolutionary origin of human mind, we can't answer the question of applicability of human thinking to cognition of nature.

In order to analyze evolutionary roots of human mind, we can follow evolutionary roots of animal and human cognitive abilities. Can we really proceed in this way? Our answer is: yes, we can. To justify this answer, we can use the following analogy.

Let us consider the elementary logic rule that is used by a mathematician in deductive inferences, namely, *modus ponens*: "if *A* is present and *B* is a consequence of *A*, then *B* is present", or

$$\frac{A, A \to B}{B} \tag{1}$$

Let us go from the mathematician to a dog that is subjected to the experiment of classical conditioning. A neutral conditioned stimulus (CS) precedes a biologically significant unconditioned stimulus (US). After a number of presentations of the pair (CS, US), the causal relation CS → US is stored in the dog's memory. Using this relation at a new presentation of the CS, the dog is able to do the elementary "inference":

$$\frac{\mathrm{CS}, \mathrm{CS} \to \mathrm{US}}{\mathrm{US}} \tag{2}$$

Thus, after the presentation of the CS, the dog expects the US.

Of course, the use of the rule *modus ponens* (purely deductive) by the mathematician and the inductive "inference" of the dog are obviously different.

However, can we think about evolutionary roots of logical rules that are used in mathematics? Yes, we certainly can. The logical conclusion of the mathematician and the inductive "inference" of the dog are similar.

Is there a background for modeling of cognitive evolution? Fortunately, there is the area of research "Adaptive Behavior" that includes some steps towards modeling of cognitive evolution. This research field is outlined in the next section.

2. Area of Investigations "Adaptive Behavior"

In the early 1990s, the area of investigations "Adaptive Behavior" was initiated [1]. These researches are focused on designing and investigation of artificial (in the form of a computer program or a robot) "organisms" that are capable to adapt to a variable environment. These organisms are often called "animats" or agents, autonomous agents. The term "animat" originates from two words: animal + robot = animat. The main goal of this field of research is [5]:

"…designing animats, i.e., simulated animals or real robots whose rules of behavior are inspired by those of animals. The proximate goal of this approach is to discover architectures or working principles that allow an animal or a robot to exhibit an adaptive behavior and, thus, to survive or fulfill its mission even in a changing environment. The ultimate goal of this approach is to embed human intelligence within an evolutionary perspective and to seek how the highest cognitive abilities of man can be related to the simplest adaptive behaviors of animals."

This ultimate goal of the animat approach is similar to the goals of modeling of cognitive evolution.

Applications of these researches are artificial intelligence, robotics, and models of adaptive behavior in social and economic systems.

Certain models of cognitive abilities of animals are already investigated in the framework of "Adaptive behavior." Some such models are characterized below.

Models of conditioned reflexes were investigated in early works [6, 7].

Researches of an anticipatory behavior, at which animals predict future situations and actively use these predictions for the organization of the behavior, are conducted currently [8].

Interesting works are devoted to the formalization of rules of decision making. For example, Mark Witkowski [9] proposed a theory of decision making rules that correspond to different levels of biological evolution. These rules take into account an associative memory, conditioned reflexes, and predictions of action results. Schemes of learning and decision making that are based on these rules are developed; certain computer simulations confirm efficiency of proposed rules.

Tony Prescott [10] analyzed an evolution of neural structures that have the important role at the action selection ensuring adaptive behavior.

Thus, certain models of cognitive features of animal adaptive behavior are designed and investigated already. However, these investigations are preliminary in many aspects. The next section proposes key steps for future modeling of cognitive evolution.

3. Sketch Program for Further Researches of Cognitive Evolution

The sketch program for further researches of cognitive evolution consists of following steps.

A) Modeling of adaptive behavior of animats that have several natural needs: food, reproduction, safety.

Such modeling can be simulations of a natural behavior of simple modeled organisms. Modeling in this direction is already initiated (see below).

B) Investigation of the transition from the physical level of information processing in nervous system of animals to the level of generalized "notions".

Such transition can be considered as emergence of "notions" in animal minds. The generalized "notions" are mental analogues of our words, which are not said by animals, but really used by them. Usage of notions leads to essential reduction both the needed memory and the time of information processing, therefore it should be evolutionary advantageous.

C) Investigations of processes of generating causal relations in animal memory.

Storing relationships between the cause and the effect and the adequate use of these relationships is one of key properties of active cognition of regularities of the external world by animals. This allows to predict events in the external world and to use adequately these predictions.

The next logically natural step is the transition from memorizing separate causal relations to systems of logic conclusions.

D) Investigations of "logic conclusions" in animal minds.

Actually, at classical conditioning, animals do a "logic conclusion": "If the conditioned stimulus takes place, and the conditioned stimulus results in the unconditioned one, then the unconditioned stimulus is expected". Such conclusions are similar to logical conclusions in mathematical deductions (see above). It is important to understand, how systems of these conclusions operate, to what extent this "animal logic" is similar to our human logic.

The listed items outline steps of possible investigations from simplest forms of adaptive behavior to logical rules that are used in mathematical deductions. Following these steps, we began corresponding modeling [11]. Simple initial models are described in the next section.

4. Initial Models

The formal model of the simple agents which have needs of 1) food, 2) reproduction, and 3) safety (Step A of the sketch program) has been designed and analyzed [11]. According to computer simulations, the model demonstrated a natural behavior of agents. Also the important role of reproduction during evolutionary optimization of agent control systems has been revealed. More detailed model of autonomous agents that have motivations corresponding to these three needs is described below.

Another model [11] demonstrated the formation of several generalized heuristics by the self-learning agent that searches for food in the two-dimensional cellular environment. These heuristics result in generating chains of actions by the agent.

Additionally, the formation of internal generalized “notions” by the autonomous agent (Step B) was observed in this model.

4.1. Model of autonomous agents with natural needs and motivations

The main assumptions of the model are as follows. There is a population of agents. Each agent has its resource $R(t)$, t is discrete time. There is a predator in vicinity of the agent; the activity of the predator changes periodically. The active predator reduces resource of the neighboring agent.

Each time moment, the agent can execute one of the following actions: 1) resting, 2) searching for food, 3) eating food, 4) preparing for reproduction, 5) reproduction, 6) defending from predator.

The agent resource $R(t)$ is increased at eating of food and is decreased at execution of actions by the agent. At reproduction, certain resource is transferred from the agent-parent to the agent-child.

Each agent has the following needs 1) food, 2) safety, 3) reproduction. Agent motivations M_F , M_S , M_R correspond to these needs. The following hierarchy is introduced between motivations: M_F is preferable as compared with M_S and M_R , M_S is preferable as compared with M_R . Also, factors corresponding to needs F_F , F_S and F_R are introduced. At determining the leading motivation, these factors are compared with thresholds T_F , T_S and T_R , and hierarchy of motivations is taken into account.

The agent control system is a set of rules $\boldsymbol{S}_k \rightarrow A_k$, where $\boldsymbol{S}_k$ is the situation, A_k is the agent action in this situation. The components of the vector $\boldsymbol{S}_k$ are 1) the activity of the predator in the vicinity of the agent, 2) the index of the action that was executed by the agent in the previous time step, 3) the leading motivation of the agent. Each rule has its weight W_k ; these weights are adjusted by means of reinforcement learning and evolutionary optimization. At action selection, rules having large weights are used.

The model was investigated by means of computer simulations. The results of simulations are illustrated by Figures 1, 2.

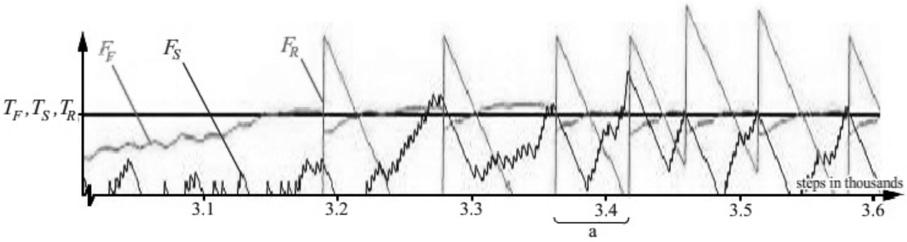

Figure 1. Dynamics of agent factors F_F , F_S and F_R .

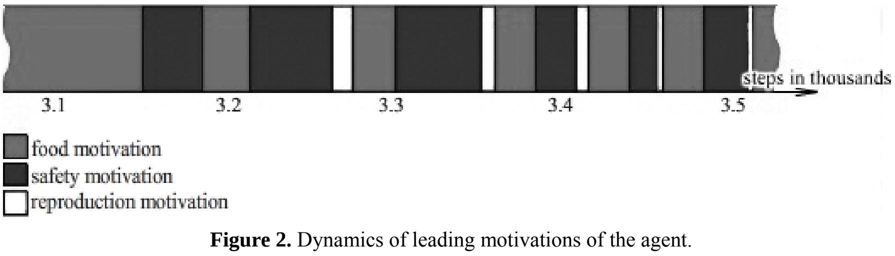

Figure 2. Dynamics of leading motivations of the agent.

The simulation results show that stable chains of actions are formed at agent leaning. In addition, a cyclical behavior of the agent is formed. The cycle is the period between moments of reproductions (the duration of the cycle is approximately equal to 40 time steps); typical cycle is shown by line “a” in Figure 1. In this cycle, the agent firstly increases its resource $R(t)$ by eating of food, then its actions are aimed at maximizing safety, and when both needs (food and safety) are satisfied, the agent reproduces itself.

Returning to general consideration of initial models, we can compare steps of the sketch program with our models and other investigations [6-10] and conclude that there are only some small elements corresponding to each step of the program yet. In other words, we can see some small fragments of a picture of cognitive evolution now, but we do not see the whole picture yet. Nevertheless, investigations of cognitive evolution are interesting and important.

5. Conclusion

Thus, approaches to modeling of cognitive evolution have been proposed and discussed. This modeling is related to foundations of science and to foundations of mathematics. Initial steps towards modeling of cognitive evolution have been already taken in the research area “Adaptive Behavior”. The sketch program for further modeling of cognitive evolution is proposed. The program includes research steps that are aimed for investigations from simple animal cognitive abilities to mathematical deductions.

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