A Model of Biological Differentiation in Adaptiogenesis to the Environment

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Abstract

In this paper, we propose a model of biological differentiation based on physical features and behavioral strategies in order to probe the mysteries of biological differentiation. We, then, implement the model, and perform the Alife simulations of birds' evolution in an artificial ecology. The ecology consists of two islands, and the atmospheric temperature in each of the islands fluctuates periodically. As a result of the simulations, we have observed that birds, adapting themselves to a change of temperature in their habitat, branch off in two types of biology: migratory bird and resident bird.

Introduction

This paper proposes a computationary evolution model for biological differentiation. A number of evolutionary models for an ecosystem has been proposed during past decade or so (e.g., (Takashina & Watanabe 1994),(Eiben & van Hemert 1999),(Downing 1998)). In the models, some species acquire behavioral and physical features suitable for a certain environment to which the species is exposed. The ecosystem of a few different species is well simulated by the evolutionary computation based on the models (e.g., (Michalewicz 1996),(Miychell 1996),(Kaneko & Yomo 2000)). Our research group (Moriwaki *et al.* 1996) has presented a computationary evolution model for a pseudo ecosystem including three types of artificial living things: herbivores, carnivores and plants. The model has well simulated food-chain. In the model, an ecological niche of the living things is given as fixed element. On the other hand, natural living things acquire an ecological niche, such as carnivore and herbivore, with the macro-evolution. It is obvious that the emergence of the variation in ecological niche is necessary for the development of an ecosystem. A long-range target of this research is to propose an evolution model for emergence of ecological niche.

In this paper, as a first step of this research, we propose a computationary evolution model of the biological differentiation. Our model is based on the interrelation between physical feature and behavioral strategy. This paper, then, presents a simulated ecology by our model, in which birds are taken. The ecology has two islands where atmospheric temperature fluctuates antithetically. The simulation shows that birds' behavior evolves so as to adapt themselves to the ecology, and then that the biology of the birds becomes to differentiate into two types: a migratory bird and a resident bird. As an interpretation on the results of the simulation experiment, we then discuss the generated differentiation from two points: physical feature and behavioral strategy. Moreover in respect of the two typical behavioral strategies which the migratory and resident birds have acquired, we also discuss their structure.

A Model of Biological Differentiation

Biological differentiation has been generally observed in the nature. It is said that the evolution of physical feature and behavioral strategy, as the one of many factors, causes the biological differentiation. In this paper, we propose a computationary evolution model of the biological differentiation. The following section gives a description of the definitions of an artificial living thing (called *autonomous agent*, or simply *agent*) and its reproductive activity, and also gives a brief description of the common property of reproductive isolation that the living things have.

Agent in the model

At an unit time, an agent chooses one from finite actions, and then, does it. The sensory information which an agent can perceive consists of a self state (internal state) and an environmental situation (external stimuli). An agent has a behavioral strategy for determining an action by the sensory information. Moreover, the relative merit of a behavioral strategy for an agent depends on the agent's body, and we call the body element *physical feature*. Let a_i be an agent (i is identifier), and let b_i and st_i be the physical feature and the behavioral strategy of a_i, respectively. a_i is, then, characterized as follows.

$$a_i(b_i, st_i). \quad (1)$$

The behavioral strategy st_i is represented as a function which determines action. Let ACT be a set of finite actions, and act_i^t be an action in ACT, which is selected by a_i at time t. act_i^t is determined by the value of the function for st_i, as follows.

$$act_i^t = st_i(in_i(t), ex_i(t)), \tag{2}$$

where in_i(t) and ex_i(t) are internal state and external stimuli of a_i at time t, respectively. This equation means that a behavioral strategy of the agent determines an action by agent's sensory information. After the action, the internal state of the agent is updated.

$$\begin{cases} in_i(t) = in_i(t-1) + d_{act_i^{t-1}}(b_i, e_i), \\ in_i(0) = C_0, \end{cases} \tag{3}$$

where $d_{act_i^t}(b_i, e_i)$ is the amount of change of the internal state at t, and C_0 is the initial amount of the internal state. It should be noticed that $d_{act_i^t}(b_i, e_i)$ depends on the action by agent $a_i(b_i, \_)$ under the external stimuli e_i at that time. It should be also noticed that time t means the elapsed time from birth. Agent a_i becomes extinct when fulfilling any of the following conditions

$$in_i(t) \leq C_1, \tag{4}$$

$$t \geq C_2, \tag{5}$$

where C_1 means the lower bound of the internal state to survive, and C_2 means the generation time.

Agent's reproductive activity

The generation of an agent is performed by only crossing. Let a_i and a_j be agents (i, j are identifiers). A child agent a_k is generated from a_i and a_j as its parents by the following crossover function.

$$a_k(b_k, st_k) = cr(a_i(b_i, st_i), a_j(b_j, st_j)). \tag{6}$$

Crossover function cr outputs a new agent as follows.

$$cr(a_i(b_i, st_i), a_j(b_j, st_j)) = a(mb(cb(b_i, b_j)), ms(cs(st_i, st_j))), \tag{7}$$

where cb and cs mean the crossover which crosses two physical features and two behavioral strategies, respectively, and mb and ms mean mutation which mutates a physical feature and a behavioral strategy, respectively.

Behavioral strategy and the evaluation

As our general idea in respect to an evaluation of the behavioral strategy, we are taking our stand on that there is some correlation between the relative merit of a behavioral strategy which an agent has and the physical feature of the agent.

Let st_i be a behavioral strategy (i is an identifier), and let $E(st_i(b))$ be the expectation of gain made by behaviors, based on st_i, of agents whose physical feature is b.

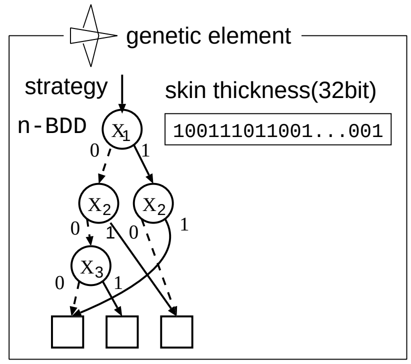

Figure 1: The structure of a bird agent.

For two different behavioral strategies st_l and st_m , we, then, consider the variation of $E(st_l(b))$ and $E(st_m(b))$ when b is changed. As the case may be, we observe a certain amount B of physical feature satisfying the following conditions.

$$E(st_l(B)) = E(st_m(B)), \tag{8}$$

$$E'(st_l(B)) \cdot E'(st_m(B)) < 0. \tag{9}$$

We call such as the amount B *turning point* to the biological differentiation. Generally, living things evolve so as to heighten the expectation of gain made by their behaviors. We, thus, think that the behavioral strategy of agents differentiates into plural strategies, such as st_l and st_m, and physical feature, such as B, gives that occasion.

Reproductive isolation

Reproductive isolation may be one of the important factors for the biological differentiation. It acts as a trigger for biological differentiation, by making a gap in the amount of the physical features. It is said that the limitation of the reproductive range stimulates differentiation. By reproductive isolation, agents a_i and a_j can cross only when satisfying the following condition.

$$gd(a_i(b_i, st_i), a_j(b_j, st_j)) < K, \tag{10}$$

where gd is the function which returns the genetic distance between agents, and K is a constant.

Artificial Ecology

In this paper, we consider two islands where temperature fluctuates in antiphase.

Agent

Two kinds of agent: plants and birds, exist in the islands. Plant agents are living matter without evolution. Plant agents live their simple life cycle depending on the climate in the island. Bird agent a_i is defined as follows by concretization of the agent which defined in Section *"Agent in the model"*:

$$a_i(sk_i, bdd_i), \tag{11}$$

Table 1: Sensory information.

X_1	Is it a full stomach?
X_2	Is it hungry?
X_3	Does a plant exist around there?
X_4	Does a friend exist around there?
X_5	Is it cold?
X_6	Is the temperature up?
X_7	Is the temperature down?

Table 2: Behavior of a bird agent.

do-nothing	(N)	Do not move
eat	(E)	Move toward a plant and eat
approach	(A)	Approach a friend
crossover	(C)	Approach a friend and cross with it
migrate	(M)	Migrate to another island

Table 3: Parameters setting in the proposed model.

an internal state of an agent

C_0	C_1	C_2
400	0	750

a reproductive isolation

$gd(a_i, a_j)$	$\|sk_i - sk_j\|$	K	$\frac{5}{32}$

genetic operation of an agent: mutation rate

n-BDD	addition	deletion	alteration
	$\frac{1}{5}$	$\frac{1}{20}$	$\frac{1}{20}$
physical feature	invert with the probability of $\frac{1}{16}$ for each bit		

a cycle of temperature change

steps	250

where sk_i and bdd_i are the thickness of the skin and n-BDD, respectively, which work as physical feature and behavioral strategy. Figure 1 shows the structure of a bird agent. The gene of sk_i is expressed by the 32 bit string, and the value of sk_i is from 0 to 1 by proportion of 1 in the bit string. On the other hand, the gene of bdd_i is expressed by n-BDD (n=5) with seven variables. n-BDD is an extension of BDD (Akers 1978), by assigning more than two values to the terminal nodes. We adopt one-point crossover and APPLY crossover (Mutoh *et al.* 1999) for crossover function cb and cs, respectively (see Equation (6) in Section *"Agent's reproductive activity"*).

Internal state consists of energy. A bird agent gains energy by eating a plant agent, and consumes energy by acting. A bird agent can move to one of eight neighborhood cells by an action at one step, and can perceive external stimuli from the circumference.

Sense, behavior, and consumption

Sensory information of bird agent a_i is expressed by the bit string. It is inputted to behavior strategy bdd_i. The output value of bdd_i determines the behavior of a_i. Table 1 shows what each bit of the string means.

The behavior of a bird agent consists of five actions shown in Table 2. A bird agent is going to take the behavior chosen as an output value of n-BDD, and consumes its energy in accordance with the behavior it acts. Energy consumption of the agent also depends on its physical feature and climate in the island it lives.

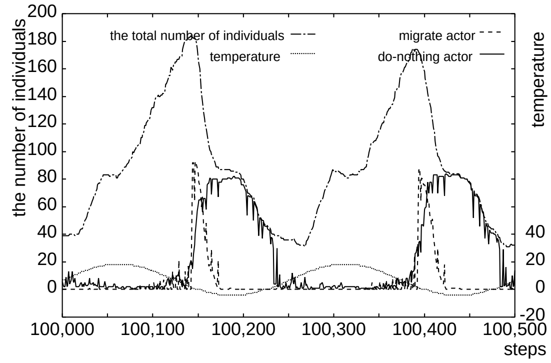

Figure 2: Transition of the number of individuals in an island.

Experiments and Consideration

In this experiment, we consider two islands which consist of 50×50 cells, and take 120 bird agents in each island. At initial state, for all bird agents, $sk_i(i = 1, \ldots, 240) = 0.5$, and $bdd_i(i = 1, \ldots, 240)$ are composed in random, that is, all bird agent have the same physical feature and their behavioral strategy are blind. Table 3 shows a parameter setup for this experiment.

As a experimental results on the above conditions, we observed two characteristic behavioral patterns when simulation was increasing in steps. One is the behavior which migrates periodically between the islands, and another is the behavior which continues remaining in the island. We have investigated the transition of the number of individuals which choose *migrate* or *do-nothing* in an island from $100,000$ steps to $100,500$ steps. Figure 2 shows the results. The results indicate that both *migrate* and *do-nothing* appear periodically in winter season, especially at the beginning of winter for *migrate*. In the season, the results also indicate that most of individuals select either of the two actions. We have, thus, classified individuals in two groups: *migratory birds* and *resident birds*, according to the behavior they select: *migrate* or *do-nothing*. Figure 3 a) shows transition of the total number of individuals and the number of individuals of migratory birds from an initial state to $300,000$ steps (corresponding to $1,200$ cycles of seasons). The figure shows that the balance of the number of migratory birds and resident birds becomes about even stably. Figure 3 b) shows the distribution of the skin thickness of a migratory bird and a resident bird at 300,000 steps. We suppose that the agent whose skin becomes thicker can bear colder climate in winter. Such the agent is considered to specialize in a resident bird. On the other hand, we also suppose that the agent whose skin becomes thinner can migrate at lower cost. Such the agent is considered to specialize in a migratory bird.

Finally, we have investigated the behavioral strategy, which bird agents had acquired by evolution. Figure 4 shows typical n-BDD which migratory bird and resident bird acquired, respectively. This figure shows the com-

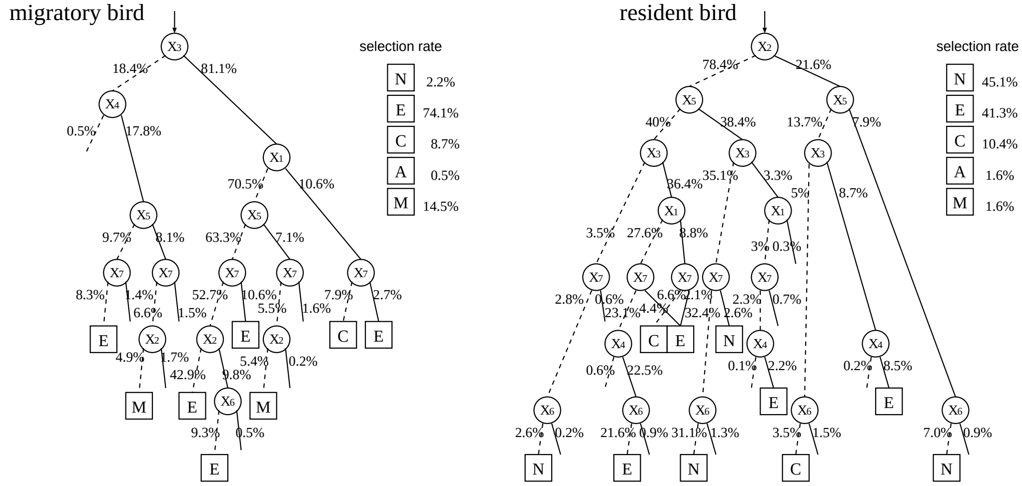

Figure 4: Typical behavioral strategies of bird agents.

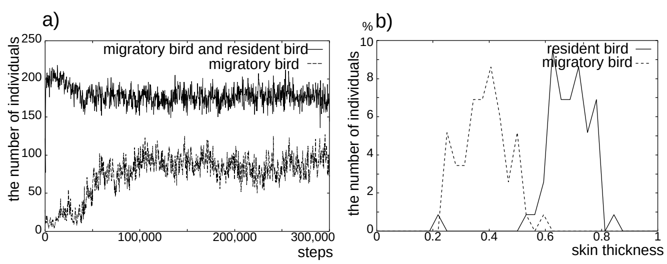

Figure 3: a) the transition of the number of individuals, b) the distribution of skin thickness in the ecology.

mon composition of n-BDD which birds had at 300,000 steps. In the figures, the value labeled with an edge in the n-BDD means the probability (%) that the edge was chosen. The strategy of migratory bird is characterized by *migrate*, and the selection rate in all behaviors is also high. On the other hand, resident bird does not migrate, and it seldom or never move while it is cold.

Conclusion

This paper proposed a computationary evolution model of biological differentiation. The model is based on the interrelation between physical feature and behavioral strategy. We, then, implemented our model in a simulated ecology of birds. The ecology has two islands where atmospheric temperature fluctuates in antiphase. Birds was differentiated into a migratory bird or a resident bird.

A living things' behavioral strategy consists of congenital element and acquired element. In this paper, behavioral strategy is decided only by gene, in other words, it decided by instinct. Learning, an acquired element, will affect acquiring ecological niche, too (e.g., (French & Messinger 1994)). As the future work, we will dedicate to introducing the learning mechanism, such as reinforcement learning, into our evolutionary behavioral model.

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