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ALife approach for body-behavior predator-prey coevolution: body first or behavior first?

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Abstract: We present the results of morphology-behavior predator-prey coevolution in a 3D physically simulated environment. The morphology and behaviors of virtual creature predators and prey are evolved using a genetic algorithm and random one-on-one encounters in a shared environment. We analyze the evolutionary dynamics on the basis of quantitative characterization of morphology and behavior. Specifically, we pose and answer the question: Which precede the other, morphology or behavior, during the evolutionary acquisition of predator and prey strategies?

Keywords: Coevolution, Predator-prey, 3D physical simulation, Artificial life

1 INTRODUCTION

Prey-predator interactions are the key element of ecological systems [1]. Predation pressures in food chains shape diversity and functions of organisms [2]. Many predators employ various strategies capturing their prey and at the same time, many prey employ various protective mechanisms against their predators. These strategies arose through the coevolution between predators and prey. Furthermore, in the coevolution, morphology and behavior have been tightly coupled in each species. Therefore, the process can be regarded as double coevolution of morphology-behavior and predator-prey couplings (Fig. 1).

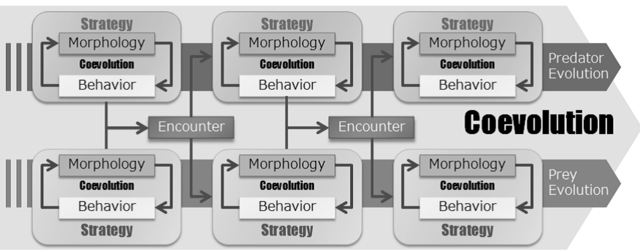

Fig. 1. Double coevolution of morphology-behavior and predator-prey.

The purpose of this study is to understand the process and dynamics of strategy emergence in the context of this double coevolution. We performed double coevolution of morphology-behavior and predator-prey by using a simple predator-prey scenario in a 3D physically simulated environment. Predator-prey coevolution has been studied mainly in mathematical biology using mathematical methods typically to analyze the change in population size of each species [4]. However, these studies have not focused or have not been able to focus attention on coevolution of morphology and behavior of individual virtual creatures. On the other hand, virtual creature models in Artificial Life, following the pioneering study [5], allow us to analyze the morphology and behavior coevolution.

In our previous study as a first step, we observed the emergence of various morphological and behavioral prey defensive strategies. This paper focuses on the morphology-behavior coevolution in terms of the evolution of strategies. Specifically, we pose a question: *Which preceded the other, morphology or behavior, during the evolutionary acquisition of new strategies?* We attempt to answer it by analyzing two example cases of evolutionary experiments: acquiring a new strategy as the first move or the countermove against the new strategy of the other species.

2 MODEL

We used the Morphid Academy open-source simulation system [6] to evolve virtual creatures in a 3D physically simulated environment (Fig. 2). The presented coevolution of predators and prey provides the example of simulating several agents in a shared environment of Morphid Academy in a coevolutionary context.

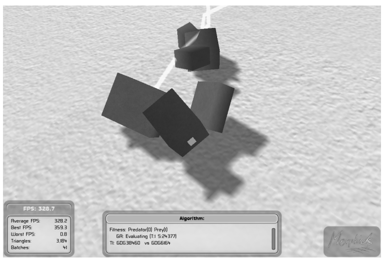

Fig. 2. Virtual creatures in Morphid Academy.

The agents are virtual creatures comprised of several 3D rectangular solid body parts connected with simple hinge joints. Their physical phenotype is developed from a directed graph (Fig. 3). The nodes represent body parts and the links represent joints. The genotype graph undergoes evolution based on a genetic algorithm, and the phenotype tree represents the connected body parts. We termed the root body part as the *torso*, and all the other parts as *limbs*.

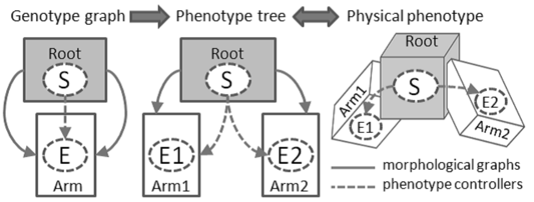

Fig. 3. The development from genotype to phenotype.

The controller of a virtual creature is a recurrent neural network embedded in body nodes. There are three types of neurons: input, calculation and output. The input neurons represent sensory information from the environment, the computational neurons process the input and the results are fed into the output neurons as joint effectors that power the joints, making the creature move. The creature sensor detects other living agents nearest to the virtual creature within a sensing range r . This virtual creature model is a simplification of Sims' Blockies model [5] and is fully described in [6]. The simplification in body and neural structure decreases the evolutionary search space and has been demonstrated to perform well for various evolutionary task.

Two populations are concurrently evolved, representing the predators and the prey. A steady-state genetic algorithm is used with tournament selection of size 3. Fitness of each agent is calculated from the result of an encounter between a randomly selected predator-prey pair. For each tournament, one or two individuals with the best fitness can produce a child through one of the genetic operators of copy, crossover or grafting. The child replaces the worst performing of the 3 individuals. Mutation is applied to the resulting child individual and includes: mutation of the morphological node or link parameters, addition of morphological nodes, and the addition or removal of morphological links.

The fitness of each agent is calculated after the encounter through a fitness function. The fitness of a predator is defined by Eq. 1. It gets 5000 if it has captured the prey and gets another maximum of 5000 points proportional to the early capturing. Otherwise, its fitness is proportional to the distance gained towards the prey, based on the initial distance r_0 and the final distance r_n.

$$F_{pred} = \begin{cases} 5000 + 5000 \times \frac{t-t_n}{t} & \text{(caught)} \\ 5000 \times \frac{r_0-r_n}{r_0} & \text{(missed, } r_0 \geq r_n) \\ 0 & \text{(missed, } r_0 < r_n) \end{cases} \quad (1)$$

The fitness of the prey is defined by Eq. 2. If it escaped from its predator without caught in the simulation time steps, it gets 5000 and gets another maximum of 5000 fitness points proportional the distance it moved l_n. Otherwise, the fitness is calculated according to the ratio of the time the prey escaped during t_n over the time limit t.

$$F_{prey} = \begin{cases} 5000 + 5000 \times \frac{l}{l_n} & \text{(escaped, } l_n \leq l) \\ 10000 & \text{(escaped, } 0 \leq l < l_n) \\ 5000 \times \frac{t-t_n}{t} & \text{(being caught)} \end{cases} \quad (2)$$

The random predator and prey are positioned above the simulation plane and allowed to free-fall due to gravity during a stabilization phase. Once they are stable from movement and resting on the ground surface, the evaluation encounter begins and lasts for S simulation time steps. Capturing is defined as the predator touching the torso of the prey with any of the predator's body parts. A captured creature is disabled and cannot be sensed.

We calculated several indices to characterize the morphology or behavior of the creatures quantitatively. As for the morphology, we used these four indices: volume (*VOL*), center of the mass (*COM*), agent body width (*WID*) and number of body parts (*NUM*). Comparing morphology and behavior, it is more difficult to characterize the latter quantitatively because, in general, the behavior heavily depends on the former, and is too complex to know what kind of indices will clearly represent the progress of coevolution in a 3D physical simulation environment. We decided to use these two simple indices: the maximum output of sensory neurons (*SEN*) and the average output of effector neurons (*EFF*), which are intended to approximately represent the sensitivity to the environment and the mobility, respectively. These indices do not depend directly on the morphology of the agents. In order to answer the question posed in Introduction, concerning the evolutionary order of morphology and behavior, we use the idea of cross-correlation methods.

3 RESULTS

We evolved predator and prey populations, each of size $i = 30$ and initially random individuals, for $g = 10000$ tournaments. Each evaluation of an encounter was performed for $S = 100000$ simulation time steps with an initial distance $r = 700$ between the agents. For each tournament, a child was created by asexual copy (probability of 40%), crossover (30%), or grafting (30%). Mutation of the child was performed with prob. of 80% with each mutation able to apply small changes to the whole genome (prob. of 5% per gene). The vision radius of predators was 5000 while the prey were only able to see within 500 distance units. Therefore, the predator can sense the prey much earlier than the prey.

In previous studies, we classified the evolved prey's defensive strategies into two types, each with an assortment of evolved morphologies and behaviors: *Runaway Strategy* which involves fleeing from the predator and *Guard Strategy* which relies on their morphologies and typically stationary behavior to provide protection from predation [7]. It is easy to detect the emergence of the Guard Strategies as they tend to evolve with a sharp increase in the fitness. Therefore, we investigate the relationship between morphology and behavior evolutions by focusing on the course of the evolution of Guard Strategies. To control the movement of prey and to promote the emergence of Guard Strategies, we used the modified fitness function of the prey (Eq. 2) and the environmental parameter $l = 100$.

We performed 30 trials. Among them, the prey evolved some Guard Strategy to prevent the predator from capturing it in 17 trials and the prey did not evolved any defensive strategies in the other trials. We used 12 results with a sharp increase in fitness for analysis out of the 17 results. Fig. 4 shows a typical evolution in which Guard Strategy emerged. It is shown that firstly, the predator fitness increased, and at the same time, the prey fitness decreased. At some point, the prey increased the fitness sharply by evolving a strong defensive strategy.

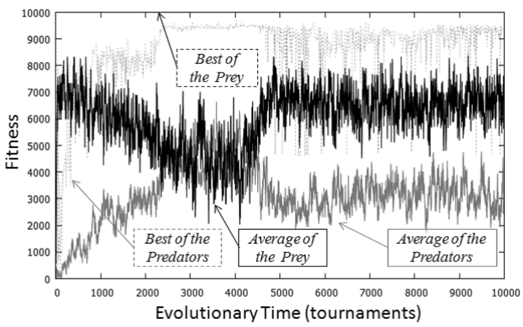

Fig. 4. Fitness change in a typical predator-prey coevolution. The prey evolved strong Guard Strategies at 4500 evolutionary time step.

Fig. 5 shows the changes in a morphological index, VOL, a behavioral index, EFF and the fitness of the prey in the same evolution with the one shown in Fig. 4. We see a certain tendency that when the fitness value increased, the morphological index also increased, but the behavioral index decreased.

3.1 Morphology first or behavior first?

Next, we investigate the evolutionary order relation between morphological and behavioral evolutions by repeatedly calculating the cross-correlation between the evolutionary sequences of index and another index with a changed time-lag. We performed 12 trials and calculated 8 cross-correlation (4 morphological indices $\times$ 2 behavioral indices) per trial and obtained 96 cross-correlation coefficients in total.

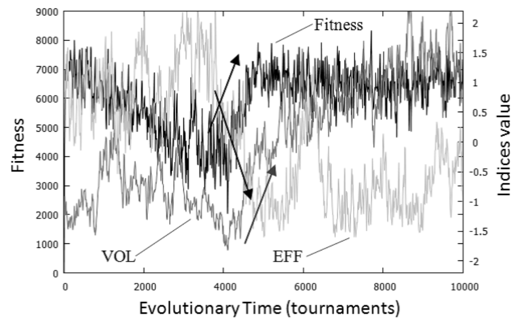

Fig. 5. Fitness and two indices change of the prey in the evolution shown in Fig. 4.

Fig. 6 shows a result of the coefficient between VOL as a morphological index and EFF, SEN as behavioral indices for a typical trial. Note that we used the absolute value of the coefficient in order to calculate the result in Fig. 6. The maximum time-lag was set to 500 evolutionary time steps before and after the emergence of Guard Strategy and focused on in analysis, which was identified by the maximum increase in fitness of the prey. The time-lag maximizing the coefficient can be used to estimate the evolutionary order of the two indices. If it is positive or negative, the behavioral changes precede the morphological changes or vice versa, respectively. In this way, we see from Fig. 6 that EFF change preceded VOL change, and on the other hand, VOL change preceded SEN change, which means that the evolutionary order between morphological and behavioral indices depends on which index was used for calculation even in one trial. We

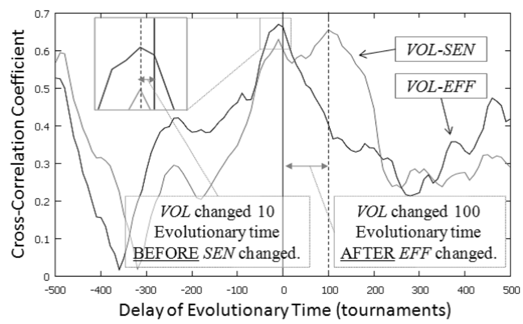

Fig. 6. Cross-correlation coefficients with evolutionary time-lags.

thus classified all 96 cases into the cases in which morphology changes preceded the behavior changes and the reverse cases by checking if the time-lag maximizing the coefficient is positive or negative. Table 1 shows the results. It shows a weak tendency for morphological change to precede behavioral change.

The tendency of morphology evolution to precede the behavior evolution might partly depend on the evolved strate-

Table 1. Frequency of the evolutionary order (precursor).

Morphology	Simultaneous	Behavior
41.6%	17.7%	31.3%

gies. This paper focused on the emergence of Guard Strategies in the prey evolution. They rely heavily on their morphology and do not need specific behavior. Therefore, the increase in fitness during the emergence of these strategies tends to depend on a few mutations which modify the morphology giving a greater fitness. On the other hand, the behavior is less important for these strategies, and therefore, the behavior modification adapting to the new morphology tends to follow the morphological evolution.

It was also shown that the morphological or behavioral indices tended to change in advance of the change in fitness by using the same cross-correlation based method. This result is reasonable because morphology and behavior emergences did not occur simultaneously as shown in the first experiment, and in order to increase the fitness, some morphology might need corresponding behavior or vice versa.

3.2 By morphology or by behavior?

The previous analysis treated evolutionary change in the traits only of the prey. Here, we focus on the evolution of predator strategies responding to the emergence of new prey strategies.

We calculated the cross-correlation coefficient value between the same indices of the predator and of the prey. Fig. 7 shows the frequency of the cases in which the cross-correlation was more than 0.4 in all trials. We see a clear tendency that the cross-correlation coefficient for behavior indices was larger than that for morphological indices. In other word, they tend to respond to new strategies of the opponent by changing behavior and not by changing morphology.

This might be due to the difficulty of morphological change. In general, a morphological change tends to be drastic, and thus non-adaptive without the corresponding change in behavior. By contrast, a behavioral change has a greater tendency to lead to a small improvement for the strategy.

4 CONCLUSION

We presented the results of evolutionary experiments showing morphological and behavioral changes under a predator-prey coevolutionary scenario in a 3D physically simulated environment. We defined the indices to characterize the morphology or behavior of the creatures quantitatively and analyzed their dynamics in order to answer the question: Which preceded the other, morphology or behavior, during the evolutionary acquisition of new strategies? The answer is summarized as follows. Morphology tends to precede behavior in the independent emergence of new strategies and behavior tends to precede morphology in the response to the new strategies of the opponents. This difference might indicate that the former and the latter were driven mainly by big changes and small changes, respectively.

In general, there is an obvious asymmetry between predator and prey at the inter-species level. The results shown in this paper indicate that an asymmetry between morphology and behavior at the intra-species level does produce complex dynamics in the coevolution between predators and prey.

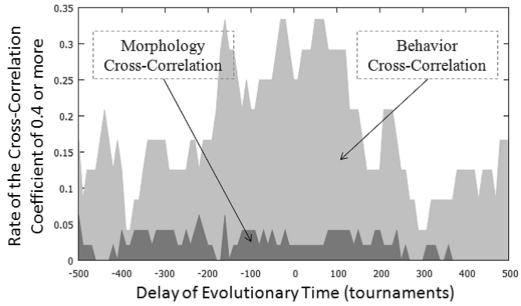

Fig. 7. Frequency of the cases in which the cross-correlation coefficient was more than 0.4 with evolutionary time-lags.

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