Population and Evolutionary Dynamics based on Predator-Prey Relationships in a 3D Physical Simulation

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Abstract

Population dynamics + Evolutionary dynamics → 3D physical simulation
Introduction
What is the Population Dynamics?

- **Population dynamics**
  - The branch of life sciences that studies the size and age composition of populations as dynamical systems
  - The biological and environmental processes driving them

Recent Study Problem

- **Evolutionary changes** usually occur over **long time scales**

- **Population dynamics** are affected in the **short term**

- Therefore, **most ecological models ignore evolutionary changes** from time scales between population and evolutionary dynamics

- This assumption has been challenged by recent studies on **rapid evolution** in nature
Related Work

Rapid Evolution

- “The newest synthesis: Understanding the interplay of evolutionary and ecological dynamics” [Schoener T. W. (California Univ.) / Science 2011]
- “Rapid evolution drives ecological dynamics in a predator-prey system” [Yoshida T. (Cornell Univ.) et al. / Nature 2003]
- “Rapid evolution and the convergence of ecological and evolutionary time” [Hairston Jr. (Cornell Univ.) et al. / Ecology Letters 2005]
Related Work

Feedback between Ecology and Evolution

• “The milker-killer dilemma in spatially structured predator-prey interactions”
  [van Baalen M. and Sabelis M. W. (Amsterdam Univ.) / Oikos 1995]

• “The ecogenetic link between demography and evolution: Can we bridge the gap between theory and data?”

• “Evolutionary feedback mediated through population density, illustrated with viruses in chemostats”
  [Bull J. J. (Texas Univ.) et al. / American Naturalist 2006]

• “Form of an evolutionary tradeoff affects eco-evolutionary dynamics in a predator-prey system”
  [Kasada M. (Tokyo Univ.) et al. / PNAS 2014]
Related Work

Artificial Life in 3D Physical Simulation

• Artificial life approach based on 3D physically simulated environments will provide valuable insights

  ▪ “Recent developments in the evolution of morphologies and controllers for physically simulated creatures”
    [Taylor T. and Massey C. (Abertay Univ.) et al. / Artificial life 2000]

  ▪ “Analysing co-evolution among artificial 3D creatures”
    [Miconi T. and Channon A (Birmingham Univ.) / Artificial Evolution 2006]

  ▪ “Evolving virtual creatures and catapults”
    [Chaumont N (Sherbrooke Univ.) et al. / Artificial life 2007]

  ▪ “Creature Academy: A system for virtual creature evolution”
    [Pilat M. L. and Jacob C. (Calgary Univ.) / IEEE CEC 2008]
The Eco-evolutionary Feedback based on the Predator-prey Relationship

Evolutionary Dynamics

- Predator Strategy
  - Morphology
  - Behavior
  - Double Coevolution
    - Predator-Prey / Morphology-Behavior
- Prey Strategy

Population Dynamics

- Predator Population
  - Interaction between
    - Inter / Intraspecies
- Prey Population

Figure 1. The eco-evolutionary feedback based on the predator-prey relationship.

- Evolve virtual creatures for predators and prey with change in their population sizes
- Analyze the relationship between population size and trait evolution
- Show their two different behaviors depending on the time scale
Model
Model

- Use Morphid Academy, which is an open-source simulation
Agent

• Virtual creatures that composed of several **3D rectangular solid body parts** connected with simple hinge joints

• Genotype graph undergoes evolution through a genetic algorithm

Figure 3. The development from genotype to phenotype.
Controller

• Recurrent **neural network** embedded in body parts
  ▪ Three types of neurons: input, calculation, output

• Input
  ▪ Sensory information from the environment,

• Calculation
  ▪ The computational neurons process the input
  ▪ Results are fed into other computational or output neurons

• Output
  ▪ Joint effectors power the joints, making the creature move
Sensor

• **Detect the nearest living creature** belonging to the other species within a **sensing range** $s$
  ▪ Two measures are calculated by the sensor: angle, distance

• **Angle**
  ▪ To the sensed creature with respect to the main orientation axis of the creature

• **Distance**
  ▪ To the sensed creature

• It is important for this experiment to **use a small sensing range** $s$
Evaluation (1/3)

• Predators and prey are randomly positioned within a radius $C$ from the origin of the simulation space in each generation.

• Once the agents become stable, resting on the ground surface, the encounter phase for the evaluation 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.

• The captured creature is disabled and cannot be sensed until the end of simulation.
Evaluation(2/3)

• The evaluation value of each predator is defined by

\[ EV_{\text{predator}} = \alpha_1 \times (S_p + s_d) \]

\[ s_d = \begin{cases} 
1 - \frac{d_n}{d_0} & (\frac{d_n}{d_0} < 1) \\
0 & (\frac{d_n}{d_0} \geq 1) 
\end{cases} \]

- \( \alpha_1 \): Coefficient adjusting the number of predator offspring
- \( S_p \): Number of successful predations by the focal predator
- \( s_d \): Success degree of the last (unsuccessful) event calculated
- \( d_n \): Distance between the focal prey and the predator (final simulation step)
- \( d_0 \): Distance between them when the predator detected the prey in this encounter event
Evaluation(3/3)

- The evaluation value of each prey is defined by

\[ EV_{\text{prey}} = \begin{cases} 
  \alpha_2 \times \left(1 - \frac{\nu}{\beta}\right) & (\nu < \beta \text{ and escaped}) \\
  0 & (\nu \geq \beta \text{ or was caught}) 
\end{cases} \]

- \( \alpha_2 \): Coefficient adjusting the number of prey offspring
- \( \nu \): Body volume
- \( \beta \): Coefficient for the maintenance cost of the larger volume
Both population sizes $P_1$ and $P_2$ are changed simultaneously with the reproduction of the next generation.

Each individual has an opportunity to produce some children by mating with another individual selected randomly.

The expected value of the number of offspring $n$ ($0 \leq n \leq M$) for the mating event.

Mating event
- fitness based on the evaluation values of both parents
- $Fitness = \frac{\text{Sum of the parents’ evaluation value}}{D = \text{the difficulty of reproduction}}$
The parents produce \( n \) children through either of the two genetic operators: crossover, grafting.

- **Crossover** with probability \( R_c \)
  - Exchanges parts of the genotype tree at the node level

- **Grafting** with \( R_g \)
  - Graft a randomly chosen subgraph from one parent onto another

- **Mutation** with \( R_m \)
  - Applied to the resulting child individual
  - Apply small changes to the whole genome with probability 0.05 per gene

- The children of all individuals replace the population
  - Population size is changed according to the fitness of creatures
Results
Experimental Setting as a First Step

- The prey population evolved while the predator did not evolve
  - In order to understand the basic dynamics caused by evolution of one species
  - Pre-evolved the predators in preliminary experiments
  - Some successfully evolved predators were used to seed the initial population of predators

<table>
<thead>
<tr>
<th>Predator</th>
<th>Prey</th>
</tr>
</thead>
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<tr>
<td>$R_c$</td>
<td>0.0</td>
</tr>
<tr>
<td>$R_g$</td>
<td>0.0</td>
</tr>
<tr>
<td>$R_m$</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**Simulation**

<table>
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<th>g</th>
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<th>C</th>
<th>1,500</th>
<th>$P_{1, \text{min}}$</th>
<th>5</th>
<th>$P_{1, \text{max}}$</th>
<th>50</th>
<th>$P_{1_0}, P_{2_0}$</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>100,000</td>
<td>$D_{\text{predator}}$</td>
<td>6,000</td>
<td>$P_{2, \text{min}}$</td>
<td>5</td>
<td>$P_{2, \text{max}}$</td>
<td>50</td>
<td>$M$</td>
<td>3</td>
</tr>
<tr>
<td>s</td>
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<td>$D_{\text{prey}}$</td>
<td>6,000</td>
<td>$\alpha_1$</td>
<td>10,000</td>
<td>$\alpha_2$</td>
<td>10,000</td>
<td>$\beta$</td>
<td>50</td>
</tr>
</tbody>
</table>
Basic Behavior

- Perform 10 trials of evolutionary experiments

Figure 4. Population of the predators (red) and prey (blue).

Figure 5. The average fitness of the predators (red) and prey (blue).
Population and Evolutionary Dynamics

• Analyze the relationship between the population and evolutionary dynamics of both populations

• As the quantitative index of the evolutionary dynamics
  ▪ Use the average volume of the body
  ▪ Track its evolution
Figure 6. Populations of the predators (red graph) and prey (blue graph) and the average volume of the prey (blue dotted graph) from the 300th to the 400th generation.
Figure 7. Population of the predators (red graph) and prey (blue graph) and the average volume of the prey (blue dotted graph), smoothed by a 30-period simple moving average.
Population and Evolutionary Dynamics

Spectrum Analysis

- Frequency spectra are composed of two parts:
  - The low frequency range from 1 to 25 generation$^{-1}$
  - The high frequency range from 25 to 1000

Figure 8. The frequency spectra of the prey volume (green) and the prey population (red).
Population and Evolutionary Dynamics

Short-Term Trajectory Analysis

(a) Predator population vs Prey population

(b) Prey volume vs Prey population
Population and Evolutionary Dynamics

Long-Term Trajectory Analysis
Influence of Population Dynamics on Evolutionary Dynamics

\[ R_{VC} = \frac{V_c}{V_c + V_p} \]

- \( V_c \): Variance of cost (=volume)
- \( V_c \): Variance of the successful escape from predation

Figure 10. The predator population (red) and the relative variance of the prey’s cost (black).
Discussion
Discussion
Short-Term Dynamics

Figure 11. The interactions between the population and evolutionary changes in the short-term dynamics.
Discussion

Long-Term Dynamics

Figure 12. The interactions between the population and evolutionary changes in the long-term dynamics.
Discussion

• The long-term dynamics observed in our experiments is probably the first demonstration of such eco-evolutionary feedbacks in a 3D artificial creature model
  ▪ “Evolutionary trade-off between defence against grazing and competitive ability in a simple unicellular alga, Chlorella vulgaris” [Yoshida T. (Cornell Univ.) et al. / proceedings of the royal society B-biological sciences 2004]
  ▪ “Feedback between population and evolutionary dynamics determines the fate of social microbial populations” [Sanchez A. and Gore J. (MIT) / PLoS Biology 2013]
Conclusion

• Different interactions between population and evolutionary dynamics on short and long time scales

• Trait evolution of a predator-prey scenario in a 3D physically simulated environment

• Focused on the short-term dynamics,
  ▪ Simple cyclical dynamics of the population of predators and prey
  ▪ Lotka-Volterra population dynamics

• Focused on the long-term dynamics,
  ▪ Complex interactions between the population dynamics of both species and the evolutionary dynamics of the traits of the prey
  ▪ Inverse correlation between the population sizes and the average volume of the prey and their continual fluctuations
Future Work

• We believe that such dynamics can be observed in predator-prey scenarios both in artificial frameworks and in nature

• Evolve the predators simultaneously
  ▪ Show the population and evolutionary dynamics in the predator-prey relationship more clearly

• Add Intraspecies interaction to support group hunting

• Add prey herding behaviors
Appendix
Lotka-Volterra Equation

\[
\begin{align*}
\frac{dx}{dt} &= \alpha x - \beta xy \\
\frac{dy}{dt} &= \delta xy - \gamma y
\end{align*}
\]

- \( x \) : the number of prey
- \( y \) : the number of some predator
- \( \alpha, \beta, \delta, \gamma \) : positive real parameters describing the interaction of the two species