論 文 の 内 容 の 要 旨
Abstract

論文題目　Mathematical Structure of Coordination between Individual Learning and Populational Evolution and its Applications
（個の学習と集団の進化が協調する数理構造とその応用）

氏　　名　　中島　蒼

Organisms adapts to the environment by two mechanisms: individual learning and populational evolution. In individual learning, an organism actively changes its trait or action by processing information. By contrast, in populational evolution, a population of organisms generating a variety of traits passively adapts to the environment via natural selection: organisms whose trait fit better to the environments reproduce more daughters than others and their offspring gradually dominate in the population. Although these two mechanisms work simultaneously in biological phenomena, the coordination between individual learning and populational evolution have not been understood well. The similar coordination appears also in engineering, for example, in the mathematical optimization. Iterative optimization methods update a single candidate of solution like the individual learning whereas evolutionary algorithms use a population of candidates and its selection for solving optimization problems.

In this thesis, we analyze the common mathematical framework behind the coordination between individual learning and populational evolution in each field and apply it to the problems in biology and informatics.

1) Acceleration of evolutionary process by learning from ancestors' experience

In conventional evolutionary biology, the variety of traits is assumed to be generated by random mutation. However, recent development in epigenetics revealed the possibility that the mutation can depend on the experience of the parent. Such dependency can be considered as a learning from ancestor’ s experience. Although learning from ancestor’ s experience may accelerate evolution, we do not have a mathematical foundation to consider the evolution of learning agents.

In this thesis, we propose a framework to consider the coordination between learning and evolution. We first propose ancestral learning and numerically validate that a population of agents with ancestral learning acquires the optimal survival strategy faster than the conventional evolution. We next theoretically clarify the relationship between ancestral learning and the fitness gradient and characterized ancestral learning as gradient flow associated to populational fitness. This result implies that learning can accelerate the evolutionary process without communication between agents. To quantify the acceleration of evolution by learning, we finally extend Fisher’ s fundamental theorem (FF-thm) of natural selection, which quantifies the speed of the evolutionary process. The extended FF-thm enablesus to understand when and why ancestral learning is beneficial for organisms. FF-thm also reveals a trade-off between a learning rate and learning frequency.

2) A theoretical framework to analyze the evolutionary algorithms with individual learning

Some evolutionary algorithms like memetic algorithms incorporate iterative optimization algorithm as generalized mutation to improve the performance. Although numerical experiments have empirically validated the efficiency of the algorithms, we still do not have satisfactory theoretical tools to analyze the performance of the algorithms.

In this thesis, we propose a tool to analyze evolutionary algorithms by introducing techniques from population dynamics. To focus on the effect of populational evolution, we focus on the memetic algorithm without cross-over, which we call the Branching Algorithm (BA). We first extend FF-thm to the BA, which states that the BA always performs better than the parallel execution of an iterative optimization algorithm.

Although FF-thm gives us a general result, it is difficult to calculate the difference in the performance in concrete examples. To resolve this problem, we introduce a more concise framework than FF-thm by introducing the retrospective process from population dynamics. We demonstrate the usefulness of the retrospective process by calculating the performance of the BA with Stochastic Gradient Descent (SGD). We show that the BA with SGD achieves a faster convergence rate for a class of not strongly convex functions than the usual SGD because of populational evolution.

In summary, the contributions of the thesis are 1-1) the numerical and theoretical validation that learning from experience accelerates the evolutionary process of acquiring an optimal strategy, 1-2) the quantification of the acceleration by the extended FF-thm, and 2) a framework to analyze the memetic algorithms without cross-over by the extended FF-thm and the retrospective process.