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Does coevolution setup promote cooperation in spatial prisoner's dilemma game?

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ABSTRACT

Understanding the emergence and maintenance of cooperative behaviors represents one of the most interesting challenges in natural and social science. A great number of studies have investigated this question via spatial reciprocity, namely, players are put on networks and obtain their payoffs by playing the game with their neighbors. It has also been verified that in networked population spatial heterogeneity and coevolution setup promote cooperation theoretically and empirically. Inspired by this well-known fact, we consider a coevolution mechanism: players not only adopts the strategy of his opponent, but also learn his opponent's ability. We find a more interesting and counterintuitive phenomenon: compared with the heterogeneity scenario, this coevolution setup does not promote the cooperation in spatial prisoner's dilemma game. With regard to this observation, we unveil that it is related with the range of distribution of individuals' ability. The coevolution setup finally makes the individual's ability shrink towards a single value. To explore the generality of this finding, we have testified on different types of topology structure.

1. Introduction

Cooperation is ubiquitous in nature and human society, for example, human hunting food collectively in primitive society, in ant colony, the worker giving up their reproductive opportunities and helping the queen to reproduce. In this regard, cooperation means to help others at the cost of one's own consume. Despite of being so universal, it is still a difficult problem to understand the emergence and maintenance of cooperation among the population of selfish individuals [1–3]. Because in Darwin's theory of natural selection, this altruistic behavior will be eliminated in the process of evolution [4,5], which seems inconsistent with the empirical phenomenon.

During the past decades, evolutionary game theory has become a useful tool to study this puzzling dilemma and has received much attention [6,7]. In particular, the prisoner's dilemma game (PDG), as a paradigm illustrating social conflict between individual and common interest, has attracted a lot of interest to study the evolution of cooperation in both theoretical and experimental studies [8–13]. In its basic version, two players are simultaneously asked to make a choice between cooperation (C) and defection (D). They will receive the reward R if both cooperate. Mutual defection yields punishment P to each other. If one player chooses to cooperate while the other decides to defect, the latter can obtain a temptation T, and the former receives a sucker's payoff S. The ranking of these payoffs satisfy $T > R > P > S$ and $2R > T+S$. Obviously, for a rational person, his best choice is defect regardless of the opponent's choice. Hence, two players will inevitably fall into the mutual defection.

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In order to resolve this dilemma and probe the evolution of cooperation, the predecessors have done a lot of works [14–23]. Nowak attributed all these to five mechanisms: kin selection, direct reciprocity, indirect reciprocity, network reciprocity, and group selection [24]. Among these mechanisms, network reciprocity has attracted much interest (for a comprehensive understanding referring to Ref. [25]). In the pioneering work by Nowak and May [26], where the players were located on the vertex of a square lattice, and their payoffs were obtained via interacting with the immediate neighbors. Then players were allowed to adopt the strategy of their neighbors if they had a higher payoffs. By simply taking the interaction structure into consideration, the emergence and sustainment of cooperation could be greatly enhanced. In original PDG, a basic assumption is that human beings are rational, but players are usually affected by different environment factors in realistic cases. Along this idea, the role of these factors have been intensively explored. Examples include environmental noise [27–29], heterogeneous network topology [30–32], heterogeneity in payoffs [35], to name but a few. Due to the discrepancy of people [35], individuals' ability may also be heterogeneity and even adaptively change in the time. With this point, we extend the traditional PDG by introducing individuals' ability into their fitness. Besides, individuals can also learn the ability of their opponents. Inspired by these phenomenon we can propose a coevolution mechanism: if players adopt the strategy of his neighbors as well as learn his neighbor's ability. Does this setup promote cooperation?

To verify this guess, we study the prisoner's dilemma game with the consideration of coevolution that maps to players' fitness. Compared with the works of influence of heterogeneity (player merely adopts a neighbor's strategy with a probability, but does not learn the ability of his neighbors), we demonstrate that this coevolution setup does not promote the cooperation in spatial prisoner's dilemma game, which does not agree with our previous knowledge [36]. In the following, we will first describe our modified model of PDG; later present the simulation results, and summarize our conclusions finally.

2. Model

In our work, each player is initially designed as either a cooperator (C) or defector (D) with equal probability, which can be described as

$$s_x = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \text{ or } s_x = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \tag{1}$$

With regard to the interaction network, we choose the square lattice with four nearest neighbors, the small-world network, or the random regular network of size L^2. For simplicity, but without loss of generality, the element of payoff matrix can be rescaled: $R = 1$, $P = S = 0$, and $T = b$, where $1 < b < 2$ ensures a proper payoff ranking ($T > R > P > S$) and captures the essential social dilemma between individual and common interest [26]. (Also see the payoff matrix A (Eq. 2)).

$$A = \begin{pmatrix} 1 & 0 \\ b & 0 \end{pmatrix}. \tag{2}$$

At each time step, player x first acquires his payoff p_x by interacting with his four nearest neighbors.

$$p_x = \sum_{y \in \Omega_x} s_x^T A s_y, \tag{3}$$

where Ω_x represents the four neighboring participants of x. The payoffs p_y of neighbors of player x can be obtained in the same way. As we all know, people are inevitably affected by external environment, so we use parameter ε_x to reflect the effects of external environment for player x.

$$\varepsilon_x = \eta * \Lambda_x, \ \ \Lambda_x \in [-1, 1], \tag{4}$$

where Λ_x is a uniformly distributed random number in the interval [−1, 1], and the so-called individuals ability. η ($\eta \in [0, 1]$) is used to control the range of random number. Obviously, when $\eta = 0$, it goes back to the traditional version [37,38], while $\eta > 0$ incorporates heterogeneity. Then we can evaluate the fitness of player x according to the following expression

$$U_x = P_x * (1 + \varepsilon_x). \tag{5}$$

The game is iterated forward in accordance with the Monte Carlo simulation composed of the following elementary steps. First, a random selected player x evaluates his fitness. Then it chooses at random one neighbor y, who also gets his fitness in the same way. Finally, player x adopts the strategy s_y from the selected player y with the following probability.

$$w = \frac{1}{1 + \exp([(U_x - U_y)/K])}, \tag{6}$$