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Robustness of cooperation in memory-based prisoner's dilemma game on a square lattice

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HIGHLIGHTS

- We introduce the accumulative payoff in all time steps.
- Cooperation can be significantly promoted by introducing the accumulative payoff.
- We introduce random defective mutations into cooperative clusters.
- Robustness of cooperation is analyzed in such an invasive noise.

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ABSTRACT

Cooperation in prisoner's dilemma game can be promoted significantly by introducing memory effects. In this work, we assume that the changing probability of strategy is determined by the agents' accumulative payoff in all time steps. We have numerically investigated robustness of cooperation by introducing an attack probability, with which an individual in cooperation clusters becomes a defector. It is found that the density of cooperators at stable states decreases with the attack probability in traditional memoryless models. However, in the memory-based model, the density of cooperators cannot reach a stable state even if the attack probability is very small. The more the increase of the attack probability, the faster the vanishment of the cooperators. Our work could be helpful to understand the emergence of cooperation in systems consisting of selfish individuals. It suggests a new method to study whether cooperation can be maintained in noisy environments.

1. Introduction

Understanding the emergence and maintenance of cooperation in systems consisting of selfish individuals is one of the challenging problems in various fields [1]. Evolutionary game theory has provided a suitable theoretical framework to study this problem [2,3]. The evolutionary prisoner's dilemma game (PDG), being a suitable metaphor for studying the cooperative behaviors, has attracted substantial attention over the past few decades [4]. In this simple two-player and two-strategy game, the players have two options to choose, which are cooperation (C) and defection (D). A cooperator obtains payoffs, which is denoted as R/S, if he interacts with a cooperator/defector. On the other hand, a defector obtains payoffs, denoted as T/P, if he interacts with a cooperator/defector. These payoffs meet $T > R > P > S$ and $T + S < 2R$ for the repeated interactions. So a single defector gets the highest payoff T when he plays against a cooperator, and the total payoff of two

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players 2R is highest for the case of mutual cooperation. It is easy to see that defection is the better choice irrespective of the opponent's attitude. However, if both of two players choose defection, the total payoff 2P is the lowest, thus creating the dilemma. Landmark work by Nowak and May in 1992 showed that cooperators can survive and even thrive on a square lattice in the evolutional PDG [5]. Since then, a large research effort has been devoted to search for the mechanisms of emerging cooperation and the methods of promoting cooperative behavior [6–8].

In the traditional evolutional PDG model, the changing probability of strategy is determined by the individuals' payoff on one time step [5]. Several groups have studied evolutional PDG with the memory effect, in which players can update their strategy by considering previous payoffs [9–12]. It is found that cooperation can be significantly promoted by introducing memory effects.

To study whether cooperation can be maintained in a noise environment is also important. In 1980, Axelrod conducted a famous computer tournament to find the best strategy in a population PDG, and a tit-for-tat (TFT) strategy won [1]. Recently, TFT strategies have been considered in phase diagrams for three-strategy evolutionary prisoner's dilemma games on regular graphs [13]. However, the deterministic TFT has a weakness when playing against itself in a noisy environment. If a player makes an error selection, then two players would choose alternately to defect and to cooperate in opposite phases. This shortcoming is suppressed by Generous TFT. Instead of certain defection, it chooses cooperation against a previously defecting opponent with a nonzero probability [4]. Since then, a large number of studies have discussed the impact of noise in PDG [14–16].

More recently, Perc et al. have researched the impact of payoff variations with different distributions on the evolution of cooperation in the spatial prisoner's dilemma game [17–21]. They have found that noise can sustain cooperation and Gaussian-distributed payoff variations are most successful in promoting cooperation. Assaf et al. have researched cooperation dilemma in finite populations under fluctuating environments [22–24]. They have found that extrinsic noise may help sustain and promote a much higher level of cooperation than static settings. Ichinose et al. have numerically investigated the robustness of cooperation clusters in prisoner's dilemma played on scale-free networks [25]. They have found that cooperation is most robust against random removal and preferential addition of nodes, while cooperation is most vulnerable against targeted attack. Despite all these efforts, the robustness of cooperation in a noisy environment is still an open question.

In this paper, by introducing memory effects into the PDG model, we assume that the changing probability of strategy is determined by the agents' accumulative payoff in all previous time steps. We have numerically investigated robustness of cooperation in a different noisy environment, under which individuals sometimes make errors after they update strategy. We consider an attack against the cooperator clusters that can be expressed as a probability p where the cooperators in cooperator clusters are tempted to become defectors.

The paper is organized as follows. In Section 2, a memory-based PDG model in an invasive noise environment is proposed, where individuals' accumulative payoff in all time steps is considered. Then in Section 3, we have numerically investigated and compared the density of cooperators and the robustness of cooperation for both the memoryless and the memory-based PDG models. Results are qualitatively analyzed by considering the sum of payoffs of all cooperators or defectors. Finally, we conclude the paper in Section 4.

2. The memory-based PDG model in an invasive noise environment

We consider the evolutionary prisoner's dilemma with players located on the vertices of a 4-neighbor or 8-neighbor square lattice with period boundary conditions. In accordance with previous studies [5,10], the parameters in this paper are $T = b > 1$, $R = 1$, and $P = S = 0$, where b represents the temptatious payoff of defectors over cooperators and is typically constrained as $1 < b \leq 2$. We make a comparative study for evolutionary PDG with or without memory in a noise environment. Each time step is divided into three sub-steps: interaction, strategy updating, and mutation.

In the interaction process, each individual plays the game with its all nearest neighbors. For the traditional memoryless PDG model, the total payoff of each individual is the sum of the payoffs in those interactions with neighbors at one time step. For the memory-based PDG model of our work, however, the payoff of each individual is the accumulative payoff in all the time steps, which are different from previous memory-based models [9–12]. In our model, the payoff of individuals can be understood as the wealth of one person in the realistic world. A person's wealth should be the sum of their payoffs in all the past time, no matter he behaves as a cooperator or a defector.

In the strategy updating process, we use two rules concerning preferential selection and random selection, respectively. For the preferential selection rule, all individuals imitate the strategy of the neighbor with the highest payoff [5]. For the random selection rule, an individual i imitates the strategy of a randomly chosen neighbor j with a probability [26]

$$W = \frac{1}{1 + \exp((E(i) - E(j))/\kappa)}, \tag{1}$$

where κ is the noise generated by the players, allowing irrational choices and, $E(i)$ denotes the payoff of individual i. κ is set as 0.1 for all simulations in this work.

In the mutation process, we assume that each cooperator changes into a defector with probability p. This process corresponds to someone betraying his country or friends, which usually happens in a real world.