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Impact of probabilistic incentives on the evolution of cooperation in complex topologies

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HIGHLIGHTS

- A mechanism of probabilistic positive or negative reward for the cooperator is proposed.
- The probabilistic positive (negative) extra benefit favors (undermines) cooperation.
- The conclusions are robust for the applied spatial networks and the potential evolutionary games.

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ABSTRACT

Social incentive, as a significant mechanism explaining the evolution of cooperation, has attracted great attention both theoretically and experimentally. In the present paper, we introduce an incentive mechanism in 2-person evolutionary games, in which each cooperative agent has a certain probability to acquire an extra positive or negative benefit. The presented results show that the probabilistic positive incentives promote cooperation, and the probabilistic negative incentives oppose cooperation. The robustness of the conclusions is tested for the prisoner's dilemma game on the Erdös–Rényi random graphs and the Barabási–Albert scale-free networks, which may indicate that the conclusions are generally valid, irrespectively of the underlying interaction networks. In addition, the investigations of the impacts of heterogeneous incentives and varied incentive probabilities on the evolution of cooperation reveal that the essence that influence individual behaviors may be the potential incentive possibilities rather than the incentive itself. Our conclusion may be conducive to interpreting the emergence and maintenance of cooperation within the structured population.

1. Introduction

Cooperation plays an important role in a wide area of nature and society, ranging from biological systems to human society [1–7]. Understanding the emergence of cooperative behaviors among unrelated individuals is a meaningful and challenging subject as it contradicts Darwinian selection [8–13]. Scientific researchers from different fields and disciplines often resort to evolutionary game theory as a common mathematical framework [14–19]. In this context, different games have been developed as metaphors of real biological and economic behaviors. Among them, the prisoner's dilemma game (PDG) and the snowdrift game (SDG) have attracted a great deal of attention both in theoretical and experimental fields [20–24].

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The PDG, as a classical and paradigmatic model of evolutionary games, seizes the characteristics of conflict between altruistic and self-interested behaviors. In the basic version, the equivalent players have two choices (cooperation (C) or defection (D)). Each of the two encountering cooperators (defectors) gets a payoff R (P), a defector confronting a cooperator acquires payoff T (the temptation to defect), while the cooperator gains S (the sucker's payoff) [25,26]. As a standard practice, the payoff ranking is $T > R > P \geq S$, which makes defectors unbeatable and cooperators be doomed to extinction in fully mixed populations. In the SDG, players interact with each other in a similar way, but the payoff ranking is $T > R > S > P$. This slight variation induces a major change in the game dynamics with the creation of a second Nash equilibrium where both strategies coexist [27–29].

Since defection is the dominating strategy for the PDG, the cooperators will die out, which is opposite to observations in the real world [30–36]. Therefore, a variety of mechanisms are proposed to understand the maintenance of cooperation. These mechanisms include personal reputation [37–41], memory effect [42,43], different update rules [44,45], punishment and reward [46–51], to name a few. In 2006, Nowak reviewed five rules for these attempts to resolve the conundrum of co-operation named kin selection, direct reciprocity, indirect reciprocity, network reciprocity, and group selection [52]. Among these promoters, the network reciprocity has aroused great concern and become the focus of considerable research interest. In particular, Nowak and May sparked interest in the role of the spatial structure in the evolution of cooperation [53]. Studies of evolutionary games on networks of square lattice, scale-free, small-world, and many other topologies are springing up [54–56].

Though many intriguing fruits have been obtained in understanding the emergence of cooperation in the spatial PDG [57–61], it would also be interesting to explore more possible mechanisms for enhancing cooperation. Different forms of punishment and reward mechanisms are often considered as common means to solve the dilemma [62–65]. Here punishment is generally defined as incurring a cost (a negative incentive) to a selfish agent. And reward often means a positive incentive for the altruistic individual. If we relax the assumptions by incurring a cost to the cooperator (punishing the cooperator), the effect of anti-social punishment is introduced [66,67]. Actually, as mentioned above, there are numerous works about reward and punishment [68–72]. In vast majority of existing works, the authors focus on their attentions either on the impact of reward or on the impact of punishment and the game models are almost limited to public goods games [73–76]. In the present work, a new 'incentive' mechanism is introduced in 2-person evolutionary games. This is the case of probabilistic incentive mechanism for the spatial evolutionary prisoner's dilemma game, in which the cooperator could receive a fixed or random positive or negative bonus with a certain probability. Actually, this setting is reasonable because altruistic behavior does not always obtain an altruistic response and sometimes even acquires an opposite result in the real world (e.g., a negative incentive) [77]. The positive benefit corresponds to the effect of social reward, and the additional negative income represents the effect of the so-called anti-social punishment, which has been investigated rarely in pairwise games. Numerical simulations suggest that the mechanism is generally valid for the social reward in favoring the evolution of cooperation even if the temptation to defect is large. Nevertheless, the effects of anti-social punishment in deterring cooperation are also corroborated for the discussed evolutionary games.

The remainder of this work is structured as follows. In Section 2, we describe the game model in detail. And then, numerous simulation results are presented in Section 3 to discuss the effect of probabilistic incentives in the evolution of cooperation. Finally, we summarize our conclusions in Section 4.

2. Evolution game model and dynamics

We firstly consider an evolutionary PDG that entails cooperation and defection as the two competing strategies. Following a common parametrization in most of the literature, the PDG is characterized with the temptation to defect $T = b$ ($1 < b \leq 2$), the reward for mutual cooperation $R = 1$, the punishment for mutual defection P along with the sucker's payoff S equaling 0. The PDG's payoffs satisfy a proper payoff ranking ($T > R > P \geq S$) and capture the essential social dilemma between common and individual interests. For the SDG, a similar scheme with $T = 1 + r$, $R = 1$, $P = 0$ and $S = 1 - r$, where $0 \leq r \leq 1$ represents the cost-to-benefit ratio ensuring the ranking $T > R > S > P$, is chosen.

In this work, we introduce a special incentive mechanism in the 2-person evolutionary games. In the model, every cooperator has a fifty-percent probability to obtain an incentive β, which is changed from -0.1 to 0.5. When β takes a negative value (-0.1), cooperators may be punished (i.e., anti-social punishment). Particularly, the model returns to the traditional PDG or SDG where no additional incentive is applied to the agent when $\beta = 0$. While for $\beta > 0$, it introduces a possible positive additional benefit to each cooperator (i.e., social reward). We extend the scope of evolutionary games on complex networks. The evolutionary games on the square lattice (100×100) with periodic boundary conditions is firstly considered. And then, the robustness of the simulation results is tested on the Erdös–Rényi (ER) random graphs and the Barabási–Albert (BA) scale-free (SF) networks.

We implement the evolutionary dynamics in the following elementary steps. At the initial stage, each vertex of the whole network is occupied by a cooperator or defector randomly. Then, player i in the network plays the game with its nearest neighbors at each time step, and obtains a payoff P_i by adding the earnings gained in each game. It is worth noting that the payoff P_i includes the possible additional benefit β if the individual i is a cooperator. Next, all the agents synchronously update their strategies by choosing one of their neighbors at random, say j, and compare the respective payoffs P_i and P_j. Finally, player i will copy j's strategy with a probability proportional to the payoff difference:

$$W_{j \longrightarrow i} = \frac{P_j - P_i}{max\{k_i, k_j\} \Delta}, \tag{1}$$