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Evolution of cooperation in the spatial public goods game with adaptive reputation assortment

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ABSTRACT

We present a new spatial public goods game model, which takes the individual reputation and behavior diversity into account at the same time, to investigate the evolution of cooperation. Initially, each player x will be endowed with an integer R_x between 1 and R_{max} to characterize his reputation value, which will be adaptively varied according to the strategy action at each time step. Then, the agents play the game and the system proceeds in accordance with a Fermi-like rule, in which a multiplicative factor (w_y) to denote the individual difference to perform the strategy transfer will be placed before the traditional Fermi probability. For influential participants, w_y is set to be 1.0, but be a smaller value w ($0 < w < 1$) for non-influential ones. Large quantities of simulations demonstrate that the cooperation behavior will be obviously influenced by the reputation threshold (R_C), and the greater the threshold, the higher the fraction of cooperators. The origin of promotion of cooperation will be attributed to the fact that the larger reputation threshold renders the higher heterogeneity in the fraction of two types of players and strategy spreading capability. Our work is conducive to a better understanding of the emergence of cooperation within many real-world systems.

1. Introduction

Although the cooperation is not a dominant strategy from the theoretical viewpoints or individual perspectives [1], but it is still a widespread phenomenon within real-world systems ranging from cellular organisms, vertebrates, even to human beings and societies [2]. Thus, understanding the universality of cooperation has become an inter-disciplinary topic which attracts a lot of concerns in the scientific communities [3], including life science, engineering and technology, natural and social sciences. Among them, evolutionary game theory provides a fruitful platform to address the origin of cooperation, and even the so-called social dilemmas [4,5]. In this field, over the past decades, a couple of mechanisms have been proposed to shed light on the persistence and emergence of cooperation inside the population, and five main schemes to promote the collective cooperation, as suggested in Ref. [6], including kin selection [7], direct [8] and indirect reciprocity [9,10], group selection [11] and spatial reciprocity [12], have been identified. In particular, more concerned is the network reciprocity in the recent years [13], a mechanism that has attracted a huge realm of interest inspired by the growing relevance in the field of network science [14,15], and which fosters the survival of cooperators by limiting the number of interactions of playing the game and multiplexing the individual payoff [16–25]. Along this research line, a great myriad of works [26–40] explored the impact of game mechanisms or interaction topology on the cooperative behaviors and uncovered the evolving patterns of cooperation hidden behind the real population, to some extent (see Refs. [41–44] for comprehensive reviews).

As evidenced by some researches, modern society is built on the individual or collective credit system, which is accumulated and guaranteed by past acts or behaviors [45]. Any individual lacking the credit or holding the lower reputation will incur the cost of losing the cooperation or coordination since most of people are not willing to cooperate with such an agent. Thus, it is of utmost importance to deeply investigate the role of individual reputation in the evolution of cooperation. In a previous work regarding indirect reciprocity [9], the choice of strategy will be correlated with the individual image score during the game playing, which can be generally considered as a type of the individual reputation to sustain the level of cooperation. Additionally, Milinski et al. [46] utilized

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the human experiments to demonstrate that, through alternating game rounds of public goods or indirect reciprocity, the collective cooperation regarding the public goods game can be kept at a surprisingly high level. Cuesta et al. [47] declared that the reputation really fosters the cooperation through experiments conducted within groups of humans playing an iterated prisoner's dilemma on a dynamical network. However, in the above-mentioned works, the individuals playing the game are often looked upon as the game peers whose behavioral properties are considered to be identical, while the diversity in the individual behavior or activity may also play a vital role in the collective cooperation. As an example, it is proven that the social diversity of individual behavior will substantially improve the level of cooperation [48], and the more diverse the individual behavior, the more obvious the elevation of cooperation. Meanwhile, the individual diversity can also be characterized by the difference of strategy transfer capability, in which all players will be divided into influential and non-influential ones according to the strategy spreading behavior, and the results have shown that the cooperation can be greatly promoted in the prisoner's dilemma game [49] or the public goods game [50]. Altogether, provided that we can combine the individual reputation and diversity to discuss the evolution of cooperation, it will be helpful to investigate the cooperation behavior under the more realistic scenarios. In the present work, we propose a model of public goods game (PGG) with adaptive reputation assortment simultaneously taking the individual reputation and strategy transfer difference into account, and extensive simulations demonstrate that the cooperative behaviors will be largely improved after the reputation assortment is introduced.

The remainder of this Letter is organized as follows. In Section 2, the game model with adaptive reputation assortment is firstly described in detail. Then, a wealth of simulation results and discussions are depicted in Section 3. At last, some concluding remarks and conclusions are summarized in Section 4.

2. Spatial PGG model with adaptive reputation assortment

The model is built on an archetypal spatial public goods game, in which each intersection node of regular lattice with the periodic boundary condition will be occupied by a game player. Initially, each player will be designated as a binary strategy with equal probability: cooperation (C) or defection (D), and endowed with a random integer denoting an individual reputation value R_x which lies between 1 and R_{max}. R_{max} signifies the maximally potential reputation and, without loss of generality, is set to be 100 in our model.

After that, the system proceeds according to the following elementary time steps. First, each player will participate in $G = k + 1$ game groups (here, k is the number of nearest neighbors), where one group is centered upon the focal agent (himself) and other k groups are resolved around his k nearest neighbors, respectively. Inside every PGG group, all players will make an independent decision about whether to put a specific contribution into the public resource pool at the same time, that is, to cooperate (contribute) or defect (not contribute). If a player cooperates, he will put a unit contribution into the pool; Otherwise, he will not invest any contribution for the public resource. Then, we will count the number of cooperators (n_C) within the group as the total contribution, which will be multiplied by a factor $r \geq 1$ and then evenly distributed among the players who are involved in this PGG group. Therefore, after a game interaction, the payoff that a cooperator or a defector will obtain can be written as follows,

$$\begin{cases} P_D = \dfrac{r * n_C}{G} = \dfrac{r * \sum_{x \in g} s_x}{G} \\ P_C = P_D - 1 \end{cases} \tag{1}$$

where r is the synergy factor greater than 1.0 during the game, P_D and P_C denote the payoff of a defector and a cooperator, respectively; s_x represents the strategy value of a player x belonging to group g, and $s_x = 1$ for a cooperator and $s_x = 0$ for a defector. It is evident, from an individual viewpoint, that a defector wins over a cooperator by a unit benefit since the cooperator needs to pay a cost for the group interest, hence the dominant strategy or Nash equilibrium is the defection in the PGG model. However, from the perspective of whole population, the collective benefits are the highest and then individual payoff will also become higher provided that all players take the cooperative strategy. It creates a dilemma for a selfish player, and there is a free-rider problem: why cooperate if one may obtain a greater personal benefit by cheating? Meanwhile, why not cooperate if all players can produce the greatest benefit by coordinating collectively? Consequently, additional mechanisms need to be devised to stimulate the collective cooperation, such as reward or punishment [51,52], reputation effect [53], etc.

Next, each player x will accumulate his payoff Π_x by summing the payoffs from each PGG group in which he participates, namely,

$$\Pi_x = \sum_g P_x^g \tag{2}$$

where P_x^g denotes the payoff collected by player x when he participates in the PGG group g, and $G = 5$ since we here consider the von-Neumann neighborhood (i.e., $k = 4$).

Then, player x will try to update his current strategy from a randomly selected neighbor y who also calculated the payoff same as player x with the following Fermi-like rule,

$$Prob(s_x \leftarrow s_y) = w_y \frac{1}{1 + e^{\frac{(\Pi_x - \Pi_y)}{K}}} \tag{3}$$

where K represents the amplitude of noise or its reverse denotes the so-called strength of strategy selection, w_y is a multiplicative factor that depends on the reputation of player y. Meanwhile, during the strategy update, his reputation value will increase or decrease 1 if he adopts the cooperation or defection strategy. We will set a reputation threshold R_C, which will divide the population into two types of individuals: A-type (influential and high-reputation agents) if an individual reputation R_x is larger than R_C, otherwise B-type (non-influential and low-reputation ones). For these two types of players, we can set his multiplicative factor w_y to be different so that the individual heterogeneity can be characterized. Accordingly, based on the reputation value of player y, w_y in Eq. (3) can be set as follows,

$$w_y = \begin{cases} 1, & if \ t_y = A \\ w, & if \ t_y = B, \ 0 < w < 1 \end{cases} \tag{4}$$

where t_y stands for the individual type determined by whether his reputation value R_y is over R_C, and t_y is equal to A if $R_y \geq R_C$, otherwise $t_y = B$. Since the individual reputation will vary during the time evolution, the individual type may continually change as the reputation evolves. Therefore, R_C becomes an important quantity dominating the type classification of population, and then influences the evolution of cooperation within the population.

After the above-mentioned basic steps are completed, a full Monte Carlo Simulation (MCS) step is finished. Starting from a randomly chosen player, within one MCS step, each player has a chance on average to adopt the strategy of one of his nearest neighbors. After some transient steps ($t_r = 45{,}000$), the system evolves into the stationary state in which the average fraction of cooperators (ρ_C) almost arrives at a constant value. Among them, ρ_C is the quantity of most interest and determined by averaging the fraction of cooperators within another $t_a = 5000$ time steps.