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Learning process in public goods games

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HIGHLIGHTS

- The effects of memory and learning in the evolution of cooperation are addressed.
- We investigate two different learning processes: dynamic and static.
- In dynamic learning a transition occurs from non-cooperative to neutral regime.
- In static learning a long memory entails long training time to achieve rationality.

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ABSTRACT

We propose an individual-based model to describe the effects of memory and learning in the evolution of cooperation in a public goods game (PGG) in a well-mixed population. Individuals are endowed with a set of strategies, and in every round of the game they use one strategy out of this set based on their memory and learning process. The payoff of a player using a given strategy depends on the public goods enhancement factor r and the collective action of all players. We investigate the distribution of used strategies as well as the distribution of information patterns. The outcome depends on the learning process, which can be dynamic or static. In the dynamic learning process, the players can switch their strategies along the whole game, and use the strategy providing the highest payoff at current time step. In the static learning process, there is a training period where the players randomly explore different strategies out of their strategy sets. In the rest of the game, players only use the strategy providing the highest payoff during the training period. In the dynamic learning process, we observe a transition from a non-cooperative regime to a regime where the level of cooperation reaches about 50%. As in the standard PGG, in the static learning process there is a transition from the non-cooperative regime to a regime where the level of cooperation can be higher than 50% at $r = N$. In both learning processes the transition becomes smoother as the memory size of individuals increases, which means that the lack of information is a key ingredient causing the defection.

1. Introduction

Social dilemmas arise when actions that ensure or improve individual benefits are in conflict with the collective choice [1]. There is a plethora of examples where individual interests bring severe damage to social development on many

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scales [2]. The tropical rain forests are a common resource that the world population benefits from. In some parts of the world, vast expanses of dense rain forests are devastated due to unregulated logging. The greenhouse gas emissions and air pollutants from fossil fuel both contribute to the global warming [3,4]. Ground water basin usage in agricultural and urban areas, and uncontrolled fishing are also examples of public goods subjected to the conflict between individual and collective interests of the group [5].

These social dilemmas are also known as the tragedy of the commons [6]. Many researchers study the mechanisms which foster cooperation instead of the selfish behavior in such social dilemma [7–11]. A promising approach to address individual interactions in a social context is game theory [12], where individuals make decisions according to the behavior of others. One simplified picture is to classify individuals as cooperators (C) who pay a cost to contribute to the group, and defectors (D) who take advantage of the group without any contribution. The tragedy of the commons is addressed in the context of multi-players, named as the public goods games (PGG) [5,13].

One simplest example of PGG is the case where cooperators contribute an amount (cost) to the public goods, and defectors do not contribute. The total amount of provision is multiplied by a factor r, and then evenly distributed among all members in the group [14]. This is also known as a N-person Prisoners' Dilemma (NPD) in which the public goods is a linear function of individual contributions [15,7,16,17]. In the same situation, defectors get more than cooperators as they do not pay a cost to the public goods. Thus, individuals are tempted to defect instead of cooperating. Not all PGG have the structure of a NPD [18] and a more general example of PGG was discussed in Ref. [19].

The Nash equilibrium in a linear public goods game is to defect, while the Pareto efficiency is reached when all members contribute their entire endowments to the group [20]. PGG with spatial population structures are one of the most explored scenarios shown to promote cooperation [21]. Nowak and May have shown that by forming clusters cooperators minimize the defectors' exploitation in a Prisoners' Dilemma, a two-player PGG [22]. Later it was shown that complex topologies for the interaction network also enhance cooperation [23]. Brandt et al. [24] considered a three-player PGG in a hexagonal lattice. They verified: when the public goods factor r is below a critical value r_c only defectors remain; when it is above an upper value r_u, cooperators dominate; in between, cooperators and defectors coexist. In spatial games the neighborhood size (or group size) displays a key role. Szolnoki et al. [25] showed that in regular graphs larger group sizes can sustain cooperation by lower enhancement factors than small groups. The joint effect of population structure and conditional strategies enhances cooperation for even lower synergy r [26]. Recent studies also demonstrate that coevolutionary rules, which affect how players interact with one another, can also be pivotal in raising cooperation in spatial PGG [23,27].

Besides, other mechanisms like peer punishment, pool punishment and reputation system are also investigated to study the maintenance of cooperation [28–32]. Cooperators react in retaliation against defectors by punishing them [8,10]. However, when punishing defectors is costly, it leads to second order PGG [33,34]. Moreover, defectors may counter-punish in response to a punishment [35]. When players accumulate past information about the others, they may distinguish punishers from nonpunishers and establish a reputation system [24]. The combination of punishment and reputation boosts cooperation [36]. A plausible alternative mechanism to punishment is reward [37,38]. Reward is costly to the individuals, but paid by those who benefit from action of the recipient. In general, all these mechanisms are considered to play an important role in explaining how individuals can form cooperative institutions [39,40].

The PGG in well-mixed populations and under no additional mechanism evolves to the extinction of cooperators [41]. Although the dominant strategy for the finite repeated game is to not contribute at each step, experimental studies show that over-contribution is not rare especially in the initial endowments [42]. Experimental data show that individuals are heterogeneous in several behavioral dimensions, and some of them seem to be not interested in maximizing their outcomes [43]. One may impute the discrepancies in individual strategies in the early rounds of PGG to outside disturbance or inexperience of players, but this is not enough to explain individual behaviors observed in real data [44].

An alternative view is to consider that decision-making is a learning process [45,46]. There are many different approaches to study learning in experiments [42]. One approach is the belief-based model [47,48], where individuals update their anticipation (belief) about their opponents' behavior based on the previous behavior of the others. The players maximize their payoffs by using the best strategy, taking the past history or their anticipation of the others into account [49]. The second approach is the reinforcement learning model, where strategies that have led to higher payoffs in the past are more likely to be repeated in the future [50,51]. In summary, the former approach focuses on opponents' behavior, while the later is based on the performance of the strategies. A more general learning model is to include the reinforcement learning model, and other learning models with belief-based learning as a special case [49,9].

In many game theoretical models, individuals are assumed to be rational. This means that they are supposed to know all possible strategies of themselves and the co-players in a particular situation to find the best strategy that maximizes their own payoffs. This assumption might be suitable to study transactions related to goods with specific attributes in a competitive market but it fails to predict and validate data in many other social dilemmas [52]. Instead of assuming that individuals know all possible strategies, it is necessary to develop a more general formulation in which individuals explore different strategies by learning. This may reveal the mechanisms why individuals can build mutual trust and allow themselves to pay the costs of cooperating and overcoming the social dilemmas [53].

Here we propose a framework for the learning process of individuals in a PGG, which assumes individuals have bounded rationality and finite memory size. The individuals' cognition is modeled by a set of strategies ranked according to the past performance, estimated as a linear payoff function. The strategies consist of looking back into the last m_s events and thereby