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Cooperative networks overcoming defectors by social influence

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HIGHLIGHTS

- We present a minimal model for the evolution of cooperation in networks whose individuals have imitation capacity.
- Topology and strategies are decoupled instead a coevolutionary dynamic.
- We present a very robust model whose results are virtually independent of the model's parameters.
- We present a new strategy update rule where the whole information of the neighborhood of the focal player is taken into account.
- The model can be very useful to understand the evolution of human society.

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ABSTRACT

We address the cooperation problem in structured populations by considering the prisoner's dilemma game as a metaphor of the social interactions between individuals with imitation capacity. We present a new strategy update rule called *democratic weighted update* where the individual's behavior is socially influenced by each one of their neighbors. In particular, the capacity of an individual to socially influence other ones is proportional to its accumulated payoff. When in a neighborhood there are cooperators and defectors, the focal player is contradictorily influenced by them and, therefore, the effective social influence is given by the difference of the accumulated payoff of each strategy in its neighborhood. First, by considering the growing process of the network and neglecting mutations, we show the evolution of highly cooperative systems. Then, we broadly show that the social influence allows to overcome the emergence of defectors into highly cooperative systems. In this way, we conclude that in a structured system formed by a growing process, the cooperation evolves if the individuals have an imitation capacity socially influenced by each one of their neighbors. Therefore, here we present a theoretical solution of the cooperation problem among genetically unrelated individuals.

1. Introduction

Cooperation is ubiquitous in every form of life [1–4], ranging from genes to societies such as the human one. The emergence of cooperation is an evolutionary transition that increases the complexity of life by forming new biological organisms from other ones. It is interesting to note that some biological individuals such as human beings and ants have a dual nature, they are part of a more complex organism and an organism more complex than their parts. This self-similar feature shows that cooperation is a fractal property of life. Besides, it is important to note that the cooperation among organisms is temporary, since every form of life dies. In this sense, the cooperative organisms must develop reproductive ability in order to evolve beyond its life. Therefore, understanding the mechanisms that allow formation, persistence

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and reproduction of cooperative systems is essential. The evolution of cooperation has been widely considered [5–10] in literature. In this long and successful tradition, a major effort has been devoted to better understand the evolution of our society. Although several proposed models [11] allow explaining the cooperation of many actual situations, we still cannot solve the problem in a general way. Therefore, we have to keep looking for new theoretical models of our society.

Evolutionary game theory [12,13] has proven to be an appropriate theoretical framework to formally address the cooperation problem. In this theory, the most important prototypical social interactions [14] are represented by a game where each individual adopts a strategy to play against its opponent. In order to consider Darwinian theory, the system evolves favoring the replication of the successful strategies. In particular, the Prisoner's Dilemma has been the most widely studied game as metaphor of the cooperation problem. In this, each player adopts one of the two possible strategies, cooperation or defection. When both individuals cooperate, each receives a payoff R and otherwise P under mutual defection. If one cooperates and the other defects, the former receives S and the second T. The game is completely defined when $T > R > P > S$. Under these conditions and in a one-shot game, it is better to defect no matter the strategy adopted by the opponents. Thus, in fully connected systems defection always has the highest reproduction rate. Therefore, the system evolves decreasing the fraction of cooperators to extinction. However, individuals of actual cooperative systems have local information of the system instead of global. They are placed in a structured population interacting with just some other ones. Taking this into account, several studies have been performed [15–29] considering different properties of actual network interactions. In this way, it has been shown that some features such as locality [17] and degree heterogeneity [19–21] could be [26–28] of great importance for the evolution of cooperation. However, given the high benefit–cost ratio (see next section) required for cooperation to with respect to the one observed in nature, which is particularly evident when the system has a high average number of connections [29], the problem is not completely solved just considering the structure of actual systems. In order to overcome this limitation, some features such as individuals who can distinguish their opponents [30], a rewiring process introduced through coevolutionary dynamics [31] and multiplex networks [32] have been considered showing great importance for the evolution of cooperation.

Recently, in [33,34] a new formulation of the cooperation problem taking into account two general features of actual cooperative systems, *i.e.* the growing process and the possibility of mutations, has been proposed. By considering individuals with imitation capacity and neglecting mutations, it has been shown under very low conditions how to build highly cooperative systems of any size and topology. In particular, the minimal benefit–cost ratio r required for cooperation to evolve approaches the theoretical minimum $r = 1$ when the average number of links of the system increases. Remarkably, the growing process generates locality and degree heterogeneity that, as we previously stated, seem to be important features for the evolution of cooperation. However, from this process other features emerge, drastically improving the required conditions for cooperation to evolve. On the one hand, the system has a high level of cooperation in all stages, instead of half or less of the population normally considered as initial condition in already formed systems [15,16]. On the other hand, defectors inhabit the less linked parts of the system which is the optimal arrangement for the cooperation [35]. In this way, it has been shown that the growing process is essential for the evolution of cooperation when the individuals have imitation capacity. Nevertheless, the emerging cooperative systems require a very high benefit–cost ratio [35] to overcome the emergence of mutant defectors in highly linked individuals of the system. In this way, the new organism is alive just until highly connected mutant defectors appear in the system. In this sense, the longevity and the system size strongly depend of the mutation rate of individuals. However, there are organisms such as in the human society, whose size and longevity cannot be explained completely by the model. Therefore, in order to show theoretically the very existence of this kind of systems by considering our formulation, it is required to introduce new features to the model allowing the system to overcome the emergence of mutant defectors. In this paper, we address this problem performing considerations over the strategy update rule by which individuals adopt their strategy. Obviously, our model did not try to capture completely actual human society, but it just tries to better understand its evolution from simple elements which have not previously been taken into account in the present form. It is important to state that in literature it is possible to find mechanisms [36,37] which allow cooperative systems overcoming the apparition of defectors. Otherwise, as we stated previously, the new formulation of the cooperation problem takes into account the growing process of the system, which has also been considered [31,38] in the context of cooperation as a mechanism to introduce co-evolutionary dynamics. Nevertheless, in the present paper we consider the topological structure and the evolution of strategies decoupled.

Through the evolution of the system, the individuals adopt a strategy by evaluating the information provided by the environment or by mutation. When the problem is considered over structured populations, each individual has information from its neighborhood, *i.e.* itself and its neighbors. Normally, players are considered without memory or prediction ability. Therefore, the information of each individual is restricted to payoffs and strategies from the last round of its neighborhood. Generally, the strategy updates of each individual are performed by comparison of the payoff of the focal player with the one of a neighbor, who can be either the most successful or a randomly selected one. In this way, the individuals with more than one link choose their strategy neglecting part of the available information. However, a strategy update where the whole neighborhood affects simultaneously the behavior of the focal player seems to be more realistic. Taking this as a motivation, a new strategy update rule [39] has been recently proposed where the focal player evaluates its strategy by comparing the average payoff of each strategy in the neighborhood. Studying the new rule over already formed regular lattices, a significant increment in the survivability of cooperators with respect to the one obtained by a pairwise comparison rule has been shown. Although the average payoff of each strategy allows taking into account all the payoffs simultaneously, this strategy update rule is still neglecting part of the available information since the abundance of each strategy in the neighborhood