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Combining evolutionary game theory and network theory to analyze human cooperation patterns

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ABSTRACT

As natural systems continuously evolve, the human cooperation dilemma represents an increasingly more challenging question. Humans cooperate in natural and social systems, but how it happens and what are the mechanisms which rule the emergence of cooperation, represent an open and fascinating issue. In this work, we investigate the evolution of cooperation through the analysis of the evolutionary dynamics of behaviours within the social network, where nodes can choose to cooperate or defect following the classical social dilemmas represented by Prisoner's Dilemma and Snowdrift games. To this aim, we introduce a sociological concept and statistical estimator, "Critical Mass", to detect the minimum initial seed of cooperators able to trigger the diffusion process, and the centrality measure to select within the social network. Selecting different spatial configurations of the Critical Mass nodes, we highlight how the emergence of cooperation can be influenced by this spatial choice of the initial core in the network. Moreover, we target to shed light how the concept of homophily, a social shaping factor for which "birds of a feather flock together", can affect the evolutionary process. Our findings show that homophily allows speeding up the diffusion process and make quicker the convergence towards human cooperation, while centrality measure and thus the Critical Mass selection, play a key role in the evolution showing how the spatial configurations can create some hidden patterns, partially counterbalancing the impact of homophily.

1. Introduction

In such a variety of systems, from biology to social networks, we can observe the emergence and the maintenance of a phenomenon, difficult to investigate and explain: cooperation. Humans cooperate building complex societies as well as predators hunt in groups in order to become stronger. "Cooperate" means to produce a benefit for a group sacrificing (with a cost) that one of the single individuals. Therefore, one of the most difficult challenges is to explain how an individual should choose the group benefit rather than a selfish behavior, which could be a more profitable choice considering his own perspective. Evolutionary Game Theory (EGT) [1,2] constitutes the theoretical framework for investigating the evolution of cooperation in social dilemmas within a population of nodes [3–5]. It combines the notions of game theory and evolutionary dynamics, taking into account the dynamics of strategies of a population of agents, each of them with its own strategy, interacting with each other and earning payoffs [6]. Evolutionary dynamics represents the mathematical tool to formalize the evolutionary process where the strategies change over time, making the higher fitness strategy more common and spreading them over the population. Therefore, EGT allows us to consider a dynamical context, in which the single actions and strategies represent the result of the evolutionary process. The persistent strategies will be the most successful ones in terms of payoff, that is, the strategies which will produce higher payoffs over time. It is more likely that these strategies with a high fitness (in EGT, payoff is translated into fitness, and the frequency of strategies in the population changes over time accordingly) proliferate and they will be imitated by the other players, while strategies who do not reproduce will be driven out through natural selection. The question in social dilemmas is that if, from one hand, the strategy with the highest individual fitness is defection, from the other hand the overall society would benefit more from cooperation. Thus, cooperation should not evolve under these conditions, but in the reality we can observe how the cooperation in nature does exist. This seems in contrast with the Darwin's principle of natural selection, then the

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challenge is to understand how does the cooperation evolve, explaining why and what are the hidden mechanism leading to this evolutionary process. To explore the evolutionary process, we consider the two most common used social dilemmas represented by the Prisoner's Dilemma Game (PDG) and the Snowdrift Game (SG) [7].

Cooperation constitutes a crucial aspect in the study of social evolution, where interactions among individuals influence the success of the community [8–11] . As underlined in [12], the structure of the network, its properties, the dynamics and the interactions among individuals affect the emergence of cooperation and its evolutionary dynamics. Social interactions depend on the structure and properties of the network, thus the structural characterization of the networks where evolutionary process takes place allows shedding light on the mechanisms by which cooperative behavior emerges and eventually overcomes the natural temptation to defect. For this reason, it becomes essential to exploit social network analysis, which is one of the most used paradigms in behavioral sciences [13]. Social relationships and networking are the key components of the human life and they have been historically bound to time and space constraints. These restrictions have been partially removed due to the increase of social connectedness. Users are increasingly keen to interact, cooperate and collaborate, share contents, and to participate through social media. In [14], the authors have formalized the problem of collective action of large groups towards cooperative and defective behaviors. The role of a single actor or a group of people, community or coalition, could contribute to trigger a dynamic action inside population, which could represent a social contagion process [15]. Collective behavior means the spontaneous emergence of different phenomena without a central regulation mechanism, such as "birds of a feather flock together" [16–20]. Centrality measure is a fundamental concept in social network analysis [13,21]. It allows to measure the importance of the various nodes in the social network, so that the more a node is central, the more it is able to influence the other nodes in the network [22–24]. Centrality assumes a key role in the selection of nodes belonging to the Critical Mass (CM), where Critical Mass (in analogy with the physical concept) is defined sociodynamically as the minimum coalition, able to trigger a behavior within a population [14,25,26]. Therefore, centrality measure constitutes a way to weigh the various nodes of the network, measuring their impact on the evolutionary process.

Nodes interact in the social network in several ways and with a variable rate which depends on various factors. Among these factors, the phenomenon that "birds of a feather flock together", also referred as homophily, is surely one of the most interesting and influential in the formation of social ties, by ruling cooperative interactions in human societies. In fact, humans tend to associate to and cooperate with someone else who has similar characteristics. Some authors have defined homophily as the principle that "similarity breeds connection" [16], used to explain how social ties are forged and cut off over time. Other authors have underlined how homophily is one of the most striking sociological regularities of social life [27,28]. From an "individualistic" point of view, homophily can be explained in terms of similarity of individual and psychological preferences, referred also as "choice homophily". Instead, from a "structuralist" perspective, homophily is also the result of the same shared environments (workplaces, neighborhood, etc.) which create an homogeneity in tastes and behaviors, generating strong patterns of homophily. This kind of homophily is also called "induced homophily" [29]. The concept of homophily is important in the dynamics of collective action and Critical Mass mobilization. Humans tend to interact and create groups with other humans who have similar features or interests [30]. Therefore, homophily represents the similarity between connected nodes, in terms of demographic, behavioral and biological features. Nodes actions will be correlated because of their higher homophily rather than their interactions [19]. The family, the organizations to which we belong and the geographic proximity to our position in the social system, create "contexts" in which homophilic relationships are formed. Homophily can be defined as the principle whereby a contact between persons similar occurs at a high rate compared to that which occurs between different people. The most pervasive and widespread feature of homophily is that the cultural, behavioral and genetic information traveling through the network, will tend to be understood and localized within groups and communities that are shaped by the action of the same homophily. This implies that the distance, in terms of social characteristics, results in a network distance, that is, the number of relationships through which an information must travel to connect two individuals. Thus, from a social network point of view, homophily can be seen as an organizing principle. The analytical strategies used to analyze the homophily can vary widely according to the types of bonds. Homophily could be a bias that leads people to associate more often than one might expect, given a relative number of opportunities [27,31]. Other studies focus on the homogeneity of a network or the similarity of a dyad measured only on some features, without clarifying whether this uniformity is an opportunity created by demographic or by a process of selection in the opportunities [32]. The heterogeneity and similarity dyadic measures are often not highly correlated. By analyzing all these variants we can distinguish between the effects of homophily created by the demographics of potential links, named as the "Baseline Homophily", and homophily measured explicitly regardless of any opportunity sets, referred as "Inbreeding Homophily". Homophily is the result of a wide variety of dimensions regarding age, gender, race and ethnicity, socioeconomic status, and education, etc. This work aims at analyzing how homophily can impact the diffusion of a social behavior within a social network. Homophily, acting through its different dimensions, can produce a change in behaviors, unexpected if considering only the social influence and contagion. Beyond varying the homophily level in the network, our goal is also to choose different spatial configurations of the Critical Mass, that is, the initial seed of adopters (e.g., cooperators) who start the diffusion process. Then, we explore the evolution of cooperation within a social network, using the framework of EGT, identifying the conditions under which a behavior diffuses and becomes persistent in the population. As we will see in the simulation results, these conditions are related to the homophily level in the social network, and to the CM nodes selection depending on the structural properties of the social network.

2. Methods

2.1. Critical mass and centrality

Space, time and infrastructure play a fundamental role in enabling social interactions to form and evolve, and in allowing them to become sustainable from the point of view of energy use and human effort [33]. In [14] Critical Mass is defined as the minimum coalition n, such that if actors organize into coalitions of size n, at least n people will prefer mutual cooperation to unilateral defection, and it is calculated as follows:

$$min(n)\ s.t. \left\{ \sum_{i=1}^{N} H(R_i - T_i) \right\} \geq n \quad (1)$$

where N is the overall population and $min(n)$ is the minimum coalition size. The latter depends on the Heaviside function of the difference between Reward and Temptation payoffs, R_i and T_i respectively. These payoffs are evaluated considering different types of games, in which a player is a randomly selected node from the