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Social dilemmas in an online social network: The structure and evolution of cooperation

Feng Fu [a,b], Xiaojie Chen [a,b], Lianghuan Liu [a,b], Long Wang [a,b,*]

[a] *Center for Systems and Control, College of Engineering, Peking University, Beijing 100871, China*
[b] *Department of Industrial Engineering and Management, College of Engineering, Peking University, Beijing 100871, China*

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Abstract

We investigate two paradigms for studying the evolution of cooperation—Prisoner's Dilemma and Snowdrift game in an online friendship network, obtained from a social networking site. By structural analysis, it is revealed that the empirical social network has small-world and scale-free properties. Besides, it exhibits assortative mixing pattern. Then, we study the evolutionary version of the two types of games on it. It is found that cooperation is substantially promoted with small values of game matrix parameters in both games. Whereas the competent cooperators induced by the underlying network of contacts will be dramatically inhibited with increasing values of the game parameters. Further, we explore the role of assortativity in evolution of cooperation by random edge rewiring. We find that increasing amount of assortativity will to a certain extent diminish the cooperation level. We also show that connected large hubs are capable of maintaining cooperation. The evolution of cooperation on empirical networks is influenced by various network effects in a combined manner, compared with that on model networks. Our results can help understand the cooperative behaviors in human groups and society.

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1. Introduction

Cooperative behaviors (mutualism and altruism) are ubiquitous in human society as well as in virtual online community. For instance, people unselfishly and collaboratively recommend commodities such as books, songs, CD/DVDs, etc. to each other. Accordingly, this cooperative behavior (collaborative recommendation) promotes the long tail which is the success foundation of Amazon and eBay [1]. And yet, according to Darwinism, natural selection is based on competition. How can natural selection lead to cooperation among selfish individuals? Fortunately, together with classic game theory, evolutionary game theory provides a systematic framework for investigating the emergence and maintenance of cooperative behavior among unrelated and selfish individuals. Two simple games, namely, Prisoner's Dilemma game (PDG) and Snowdrift game (SG), as metaphors for studying the evolution of cooperation have been extensively adopted by researchers from different background [2–7]. In the original PDG, two players simultaneously decide whether to cooperate (C) or to defect (D). They both receive R upon mutual cooperation and P upon mutual defection. A defector exploiting a C player gets T, and the exploited cooperator receives S, such that $T > R > P > S$ and $2R > T + S$. As a result, it is best to defect regardless of the co-player's decision. Thus, in well-mixed infinite populations, defection is the evolutionarily stable strategy (ESS) [8], even though all individuals would be better off if they cooperated. Thereby this creates the social dilemma, because when every-

* Corresponding author at: Intelligent Control Laboratory, Center for Systems and Control, College of Engineering, Peking University, Beijing 100871, China. Fax: +86 10 62754388.
E-mail addresses: fufeng@pku.edu.cn (F. Fu), longwang@pku.edu.cn (L. Wang).

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body defects, the mean population payoff is lower than that when everybody cooperates. Whereas in the SG, the order of P and S is exchanged, such that $T > R > S > P$. Its essential ingredient is that in contrast to the PDG, cooperation has an advantage when rare, which implies that the replicator dynamics of the SG converges to a mixed stable equilibrium where both C and D strategies are present [8]. It is important to note that in this state the population payoff is smaller than it would be if everyone played C, hence the SG still represents a social dilemma [9]. In addition, the SG is of much applications and interests within biological context. In order to solve these social dilemmas, a variety of suitable extensions on these basic models has been investigated [3,5–7]. Most importantly, it is found that cooperation can be promoted and sustained in the network-structured population substantially [6,10–13]. Indeed, the successful development of network science provides a convenient framework for describing the dynamical interactions of games. The evolution of cooperation on model networks with features such as lattices [14–17], small-world [18–20], scale-free [6], and community structure [21] has been scrutinized. Moreover, the understanding of the effect of network structure on the evolution of cooperation reaches to consensus gradually: the heterogeneity of the network of contacts plays a significant role in the emergence of cooperation. However, the puzzle of cooperation is unanswered yet. What on earth conditions the emergence of cooperation is still a challenging problem [22,23]. Most noteworthy, Nowak summarized five possible rules for the evolution of cooperation corresponding to different situations (see Ref. [24] and references therein). Nevertheless, to our best knowledge, these results are mostly based upon simplified scenario and model. To inspect the evolution of cooperation, further details and characteristics of real world should be considered and integrated.

Herein, we consider the two aforementioned social dilemmas over an online friendship network, obtained from a Chinese social networking site (SNS)—Xiaonei [25]. In the age of so-called Web 2.0, SNS as well as blogs provides an extraordinary online laboratory to study dynamic pattern of socio-economic systems. Evidently cooperative (altruistic) behaviors are ubiquitous and robust in natural systems. Actually, people, especially college students, take advantage of online social network services for messaging, sharing information, and keeping in touch with each other. Mutual cooperation thus consolidates the existent basis of this virtual online community. Consequently, it is meaningful and interesting to study the evolution of cooperation on such social network, of which who-meets-whom relationships are abstracted from Xiaonei. In what follows, two metaphors—PDG and SG in the empirical social network will be scrutinized.

In this Letter, we first present a detailed structural analysis of Xiaonei network. It is demonstrated that the network has small-world and scale-free properties. Noticeably, the average connectivity is relatively high. Thus it is shown that cooperation is significantly suppressed in this highly connected network when the values of the game parameters increase, even though the heterogeneity of the underlying network to a certain extent promotes cooperation. In addition, it exhibits assortative mixing pattern. However, we find that increasing degree of assortativity diminishes the cooperation level by random edge rewiring. Furthermore, the appearance of direct links between hubs in a way contributes to the enhancement and sustainment of cooperation. Therefore it is suggested that the evolution of cooperation on realistic social networks is influenced by a variety of network effects in a combined manner, compared to that on model networks. In the rest of this Letter, first, we will analyze the structure of the online social network, then investigate the two social dilemmas (PDG and SG) on this social network by the method analogous to replicator dynamics, exploring the influence of network topological features on cooperation. After that, we discuss the simulation results and make explanations. Finally, we draw the conclusion remarks.

2. The structure of Xiaonei network

In this section, we present our observations into a Chinese social networking site Xiaonei, which is open to college students. It began in late 2005 in select universities, but grew quickly to encompass a very large number of universities. Each registered user has a web page hosted within Xiaonei domain. The user's web page can be visited through a pointer specified by the user id. Users can add others as friends in their own web pages. The friendship is constructed by bilateral agreement. Thus Xiaonei network is bidirectional one (we viewed this network as undirected one). The original Xiaonei network has hundreds of thousands of nodes and millions of edges,[1] which seems too huge to be handled in studying the evolution of cooperation on it due to the limited capacity of our computer resources. Instead, for practical purpose, we focus our eyesight in a connected sub-community of the original large-scale Xiaonei network, and this subnet consists of 9590 vertices and 89873 edges (we view this sub-community as a close world, hence the edges out of this community are omitted. It is referred to as Xiaonei network thereafter). Noteworthy, although this sub-community could not be a good representative of the original one, its size and topological features are still sufficient to study the cooperative dynamics on it.

We perform statistical analysis of the structure of this social network, i.e., the above sub-community network. The quantities including degree distribution, clustering coefficient, average shortest path length, etc. are calculated to capture the topological features. In Fig. 1, we report the cumulative degree distribution $P(> k)$, which gives the probability that randomly selected node has more than k edges. Clearly, except that $P(> k)$ has a flat head, it obeys a power-law form as $\sim k^{-\tau}$ with $\tau = 2.21 \pm 0.01$ for large degrees. One can immediately get the degree distribution $p(k) \sim k^{-\gamma}$ with $\gamma = \tau + 1 = 3.21$. This small-scale Xiaonei network has a degree exponent similar to the web of human sexual contacts, whereas most social networks have the degree exponent falling into the range $2 < \gamma < 3$ [26]. It is apparent that this subnet is deviated from the large-scale one in power law exponent. Actually, the original Xiaonei

[1] The structural analysis of the original one will be presented elsewhere.