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Neighborhood Diversity Promotes Cooperation in Social Dilemmas

JIAHU QIN[1], (Member, IEEE), YAMING CHEN[1], WEIMING FU[1], YU KANG[1], (Senior Member, IEEE), AND MATJAŽ PERC[2,3]

[1]Department of Automation, University of Science and Technology of China, Hefei 230027, China
[2]Faculty of Natural Sciences and Mathematics, University of Maribor, SI-2000 Maribor, Slovenia
[3]Center for Applied Mathematics and Theoretical Physics, University of Maribor, SI-2000 Maribor, Slovenia

Corresponding author: Matjaž Perc (matjazperc@gmail.com)

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ABSTRACT How and why cooperation is able to prevail in social dilemma situations is an intensely investigated subject with much relevance for the well-being of human societies. Many mechanisms that promote cooperation have been identified within the theoretical framework of evolutionary game theory. Here, we advance the subject by relaxing the simplified assumption that each player in the population has the same number of interaction neighbors. This assumption indeed contradicts actual conditions, and it is, thus, important to understand what consequences this has for the evolution of cooperation. We therefore take into consideration that replacement and interaction neighbors can differ, and moreover, that each player can randomly select the number of interaction neighbors. The results of Monte Carlo simulations reveal that the introduction of neighborhood diversity elevates the level of cooperation in various types of social dilemmas, including the prisoner's dilemma and the snowdrift game. We also show that the same mechanism of cooperation promotion remains valid in evolutionary multigames. Taken together, our results strongly support the assertion that diversity, in general, is a strong facilitator of cooperation even under the most testing conditions and they provide a rationale for engineering better social systems.

INDEX TERMS Complexity theory, evolutionary computation, social engineering, cooperative systems.

I. INTRODUCTION

Cooperative phenomenon occurs in many natural and social systems, from microbial communities to intricate human societies [1]. However, it is not optimal for each player to act as a cooperator in accordance with Darwin's theory of evolution. Therefore, how to illustrate the occurrence and sustentation of cooperative behavior has become a challenging issue for scientific researchers. The evolutionary game theory [2]–[6] is the most commonly adopted theoretical framework to study cooperation in social dilemmas, where social conflicts are similar to the competition or coordination for finite resources. Specifically, two game-theoretical models, the prisoner's dilemma game and the snowdrift game, have received a lot of attention and have been studied extensively [7]–[13]. In the traditional pairwise model, two players need to make a decision about choice of strategy at the same time, and they can only choose between defection and cooperation. If both players choose to cooperate (or defect), they will obtain the reward R (or punishment P). But if a defector encounters a cooperator, the defector gains the temptation T while the cooperator gets the sucker's payoff S. The payoff ranking of the prisoner's dilemma game meets $T > R > P > S$, while the ranking order of payoff for the snowdrift game is $T > R > S > P$. It is evident that defection is the most suitable strategy for rational players, though they realize that mutual cooperation could produce higher collective payoff. Thus, the existence of cooperative behavior is very difficult. Many researchers devoted efforts to study the promotion of cooperation among selfish and unrelated individuals.

In order to solve the adverse consequences of social dilemmas, substantial attention has been paid to the mechanisms for promoting cooperation over the past decades [14]–[19]. All of these mechanisms can virtually be reduced to five mechanisms for elevating the level of cooperation: kin selection, direct reciprocity, indirect reciprocity, network reciprocity, as well as group selection [20]. In the seminal work [21], each player was located on the regular lattice and acquired payoff through playing games with its nearest neighbors.

The authors have discovered that cooperators could form compact clusters so as to reduce the exploitation of defectors and spread their cooperative strategy. With this remarkable breakthrough, network reciprocity as an important mechanism for promoting cooperative behavior has been studied wildly [22], [23]. Moreover, a large number of work has been done in the domain of complex networks [9], [24], which are more attached to the real-world systems. In addition, co-evolution, including the common evolution of strategy and network structure or other properties, provides more inspiration in this area [25]–[27]. Besides, a series of mechanisms promoting cooperation have been introduced, such as punishment and reward [28]–[33], reputation [34], multilayer networks [35] and inhomogeneous activity [36], to name but a few. Recently, heterogeneous interaction neighbors have received attention, which is a common phenomenon in real life. An understandable example of heterogeneous interaction neighbors is that influential people who are rich in social skills tend to have a greater range of communication than people with weak social skills. In [18], the authors have introduced two types of players, having four or eight interaction neighbors, respectively. The research showed that middle heterogeneous neighbors can yield the best level of cooperation.

Our motivation in this paper comes mainly from the fact that different people have different social scope in the real world [37]–[39]. Meanwhile, we wish to expand the scope of influence of diversity on the evolution of cooperation by means of introducing neighbor diversity in evolutionary games. In this letter, we explore the role of diversity of neighborhoods in the evolution of cooperative behavior. Specifically, we place players on the regular network with periodic boundary conditions, and three typical evolutionary games are discussed: prisoner's dilemma game, snowdrift game and multigame. This multigame model is produced by the combination of prisoner's dilemma game and snowdrift game. Here, the diversity of neighborhoods means that the player's interactive neighbors is no longer like the four or eight fixed neighbors in the previous literature. Instead, each player can randomly select the number of interactive neighbors to play evolutionary games. According to the outcomes of the simulation experiment, one find that the diversity of neighborhoods is a good way to improve the fraction of cooperative individuals with the entire parameter range in prisoner's dilemma game, regardless of whether it is compared with von Neumann neighborhood or Moore neighborhood model. To further understand the influence of diversity of neighborhoods on cooperative evolution, we also compare the proportion of cooperators of heterogeneous neighbors model with the homogeneous neighbors case in the snowdrift game and the multigames. However, the promotion of cooperation has been slightly weakened, and the introduction of the diversity of neighborhoods increases the level of cooperation within a certain range of parameters.

The rest of this paper is arranged as follows. We first present the prisoner's dilemma game, snowdrift game and evolutionary multigame in square lattice and the neighbor diversity decided by selecting randomly the number of interaction neighbors. Secondly, we reveal the outcomes of Monte Carlo simulations, and finally show relevant conclusions in this work.

II. MATHEMATICAL MODEL

We study the evolutionary prisoner's dilemma game, snowdrift game and multigames in this work. For the prisoner's dilemma game (*PDG*), it is characterized with the reward $R = 1$ for mutual cooperation and the punishment $P = 0$ for mutual defection. Meanwhile, if one cooperator competes with one defector, the cooperator gains the sucker's payoff $S = 0$ while the defector receives the defection temptation $T = b$. Theoretically speaking, payoff ranking of traditional prisoner's dilemma game is $T > R > P > S$. So we can know that the punishment P should be larger than the sucker's payoff S. It is interested to mention that we employ the weak prisoner's dilemma game (namely, $S = 0$), but the results are robust and could be observed in the full parameterized space. For the evolutionary snowdrift game (*SDG*), we introduce the so-called cost-to-benefit ratio r ($0 < r < 1$). Therefore, we have the reward $R = 1$ for mutual cooperation, the punishment $P = 0$ for mutual defection, the temptation to defection $T = 1 + r$ and sucker's payoff $S = 1 - r$. Then, the ranking of payoffs satisfy $T > R > S > P$. The payoff matrices for two games are showed respectively as

$$PDG = \begin{pmatrix} 1 & 0 \\ b & 0 \end{pmatrix}, \tag{1}$$

$$SDG = \begin{pmatrix} 1 & 1-r \\ 1+r & 0 \end{pmatrix}. \tag{2}$$

We also consider the evolutionary multigames [19], where different S values indicate different perceptions of the same social dilemma. Specifically, one half of the entire stochastically chosen population uses $S = +\Theta$ and the other half uses $S = -\Theta$, where $0 < \Theta < 1$. That is to say, one part of the individuals plays the snowdrift game when the other part of the individuals plays the traditional prisoner's dilemma. Due to the equal distribution of negative and positive S values among the total interaction network, average all payoff matrices return the weak prisoner's dilemma game. Primarily, we consider multigames where, once assigned at the beginning of an episode, players do not change their payoff matrices.

Initially, we employ a $L \times L$ two dimensional regular lattice with periodic boundary conditions as interaction network. Each player occupies the node of square lattice network and chooses to be a cooperator or defector with equal probability. We normally make total the size of network $N = L \times L$ to make sure that every intersection only be placed by one player.

Previously, most studies assumed that each agent can only play the evolutionary game with four or eight neighbors. It means that players have the same number of interaction neighbors. Here, we assume that the replacement neighbor is inconsistent with the interaction neighbor, and every player can randomly select interaction neighbors. We consider von

Neumann neighborhood and Moore neighborhood, where each player could randomly choose the number of interaction neighbors from the collection {1, 2, 3, 4 } or the collection {1, 2, 3, 4, 5, 6, 7, 8 }. We consider that the interaction neighbors of every player are fixed in the first place and no longer change. One thing to emphasize is that all players have four replacement neighbors whatever the number of interaction neighbors are. The situation that different player has different interaction neighbors is more reasonable in nature and human society. Therefore, this paper principally explores how the number of interaction neighbors influences the evolution of cooperative behavior.

After each round of evolutionary game, the player will receive matching benefit on the basis of the normalized form [21]. We assume that the payoff of all players is simultaneously accumulated through playing the evolutionary game with their interaction neighbors. After a whole iteration cycle of evolutionary game, total players will synchronously update the current strategy. According to the Fermi-like rule [40], the agent i stochastically chooses one neighbor j from four closest replacement neighbors, and then the agent i learns the strategy S_j from the agent j with the probability depend on their payoff difference:

$$W(s_i \leftarrow s_j) = \frac{1}{1 + \exp[(\Pi_i - \Pi_j)/K]}, \quad (3)$$

where K represents the uncertainty of the strategy selection process.

We simulate the evolutionary game in accordance with the Monte Carlo simulation process, and on average every participate has a chance to imitate the strategy from interaction neighbors during a complete Monte Carlo step. Most simulation results are acquired from the regular lattice networks with $N = 100 \times 100$ participants. In fact, we also make simulation experiment on larger network to ensure the accuracy of the conclusions. The proportion of cooperators f_c across the entire network is used for evaluating the level of cooperation of the system. And then, we gain the proportion of cooperators in the stationary state through computing the average value over the last 2000 time steps after total 20000 iteration cycles of evolutionary games. In order to ensure higher accuracy, the eventual data is obtained by averaging over 20 independent realizations.

III. RESULTS

Now, we study the impact of neighbor diversity on the emergence of cooperation through Monte Carlo simulation method for the aforementioned three evolutionary games. A lot of preceding studies [19], [41]–[43] have shown that defectors could coexist with cooperator in a network because of the existence of network reciprocity. Meanwhile, the setup of asymmetric network structure plays an important role in the promotion of cooperative behavior [44]. Further speaking, we explore the neighbor diversity of players that each player has a random number of interaction neighbors from either the von Neumann neighborhood or the Moore neighborhood.

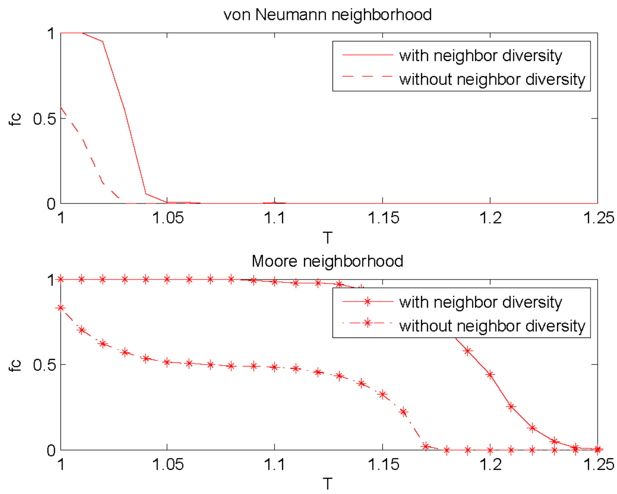

FIGURE 1. (Colour online) Proportion of cooperators f_c on the square lattice changes with temptation to defect T in the prisoner's dilemma game, as acquired with and without neighbor diversity for von Neumann neighborhood (top) and Moore neighborhood (bottom). Presented results are obtained for $K = 0.1$.

As is known, cooperative players are extinct when the temptation to defect receives a very small threshold (i.e. 1.0375) in the spatial prisoner's dilemma game. Therefore, it is quite necessary to propose a new mechanism to ensure the maintenance of cooperation in the same environment. Above all, Fig. 1 describes the proportion of cooperators f_c at the equilibrium state in dependence on the temptation of defector T in the prisoner's dilemma game. The results of top and bottom plane show the von Neumann neighborhood and Moore neighborhood models respectively. We can observe that, irrespective of the number of interaction neighbors, the larger the temptation to defect T, the smaller the density of cooperators f_c. In the top plane, we consider two kinds of cases: the interaction neighbor is the von Neumann neighborhood or selected randomly from four nearest neighbors. When the focal player plays the evolutionary game with four nearest neighbors, the model turns to classical prisoner's dilemma game and the evolution of cooperative strategy entirely rely on the spatial reciprocity. In this situation, the level of cooperation is extremely low and declines quickly. When the diversity of neighborhoods is considered, the initial proportion of cooperative agents is quite large and it slowly reduces with temptation to defect. Meanwhile, the critical value of cooperators die out is greater than the traditional condition. Likewise, the bottom plane presents every player has Moore neighborhood or chooses the interaction neighbors from eight neighbors. The cooperative behaviour at the stationary state is also substantially improved compared to the standard condition (eight interaction neighbors) when the neighbor diversity game model is included. All in all, the introduction of neighbor diversity provides a better survival environment for cooperators and promotes the level of cooperation.

Next, we also study the influence of the uncertainty of the strategy selection process K on the level of cooperation.

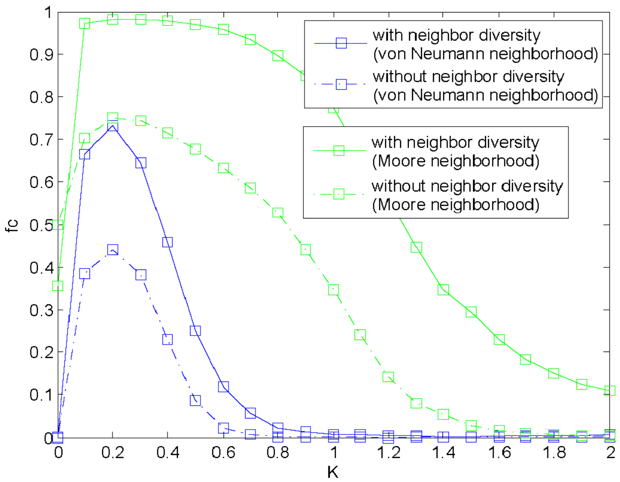

FIGURE 2. **(Colour online) Proportion of cooperators f_c on the square lattice changes with uncertainty of the strategy selection K in the prisoner's dilemma game, as acquired with and without neighbor diversity for von Neumann neighborhood and Moore neighborhood.**

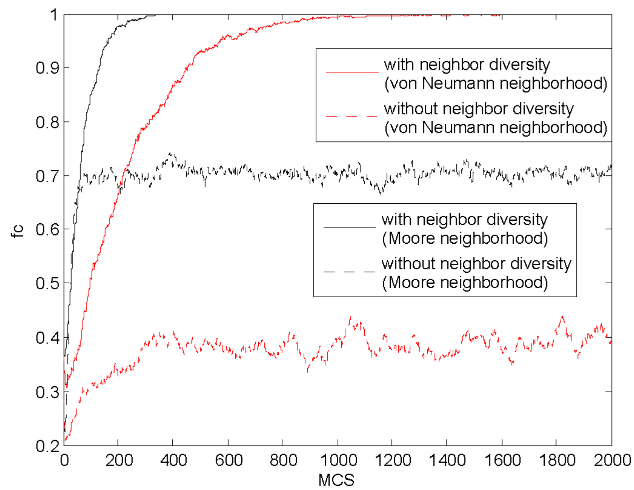

FIGURE 3. **(Colour online) Time courses of the proportion of cooperators f_c in the prisoner's dilemma game on the square lattice, as acquired with and without neighbor diversity for von Neumann neighborhood and Moore neighborhood. Presented results are obtained for $K = 0.1$.**

The research of the relationship between the level of cooperation and K is to further discuss the cooperative behaviour under the diversity of neighborhood. Fig. 2 illustrates the fraction of cooperators varies with temptation to defect for different numbers of interaction neighbors. In particular, we can observe that Fig. 2 shows a classical bell shape under diverse settings. It is clear that the proportion of cooperators gradually reaches the maximum with the increase of K, which means the best level of cooperation in middle K. Nonetheless, if the value of K continues to increase, the density of cooperative agents will decrease with uncertainty of the strategy selection. Obviously, cooperative behaviour is substantially enhanced when diversity of neighborhoods considered. According to the mentioned above, we could conclude that there is an optimal K promoting the level of cooperation.

Since the introduction of heterogeneous neighbors accelerates the level of cooperation, it is meaningful to illustrate the potential cause of this phenomenon. In order to analyze the nature of this enhancement effect, we describe the density of cooperators at every time in Fig. 3. In the early stages of evolution, the defectors have an advantage over the cooperators regardless of the number of interaction neighborhoods. Actually, it can be predicted that defect is more likely to be chosen as the potential strategy than cooperation. With time evolves, cooperators will further weaken till the worst case. With regard to traditional model, cooperative agents could restrain the invasion of defectors due to spatial reciprocity. When the diversity of neighborhoods considered, this mechanism will be strengthened. It is evident that the proportion of cooperators attain a higher standard at the stationary state.

All of these results mentioned above indicate that the diversity of neighborhoods is advantageous for the promotion of cooperation. In the process of evolution, when cooperators

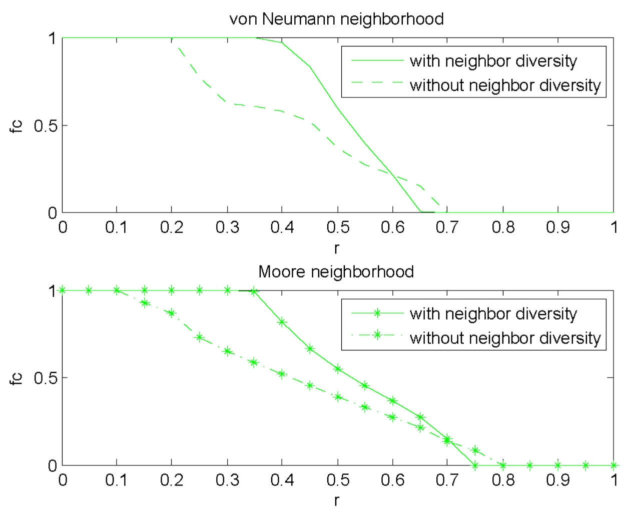

FIGURE 4. **(Colour online) Proportion of cooperators f_c on the square lattice changes with r in the snowdrift game, as acquired with and without neighbor diversity for von Neumann neighborhood (top) and Moore neighborhood (bottom). Presented results are obtained for $K = 0.1$.**

are in key positions, they can spread cooperation strategy and form compact cooperative clusters, which is a practical method to resist the invasion of defectors spatial network. In other word, cooperative agents gather together and survive by generating clusters. However, the defectors do not have the characteristics of clustering, thus they can not spread their strategy rely on the diversity of neighborhoods. Similar to the evolution of cooperation on scale-free networks, and hub nodes determine the fraction of cooperative individuals at stationary state. When cooperators occupy the hub nodes of interaction network, the cooperators get together fast to decrease the invasion of the defectors. The setting of heterogeneous interaction neighbors may result in

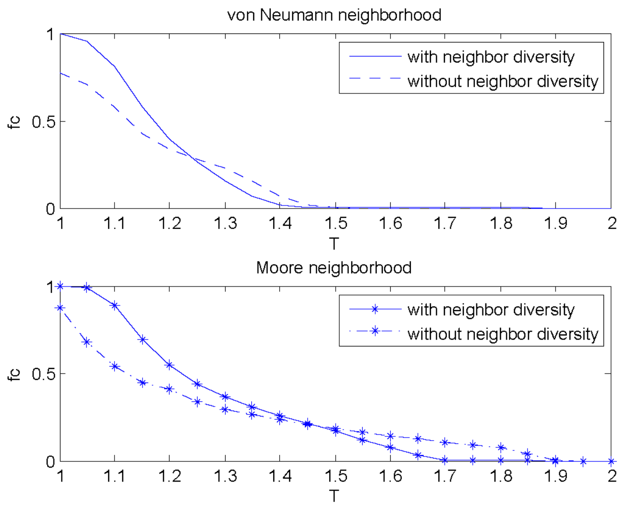

FIGURE 5. **(Colour online) Proportion of cooperators f_c on the square lattice changes with temptation to defect T in the multigames, as acquired with and without neighbor diversity for von Neumann neighborhood (top) and Moore neighborhood (bottom). Presented results are obtained for $K = 0.1$.**

leader-follower-model relationship, which is efficient for the promotion of cooperation.

Lastly, in order to further explore the effect of neighbor diversity on the evolution of cooperation in evolutionary games, we perform simulation experiment with the multi-games and the snowdrift game. The fraction of cooperators f_c in dependence on r with regard to the snowdrift game is shown in Fig. 4. In the top plane, von Neumann neighborhood and heterogeneous neighbors are considered. It is evident that the initial density of cooperation is almost complete dominant, which means that there possesses the penetrating cluster of cooperators. The cooperative level of heterogeneous neighbor model is higher than that of homogeneous neighbor for $r < 0.6$, but be lower than the situation of traditional model for large r. The cases of Moore neighborhood and heterogeneous neighbors models are shown in the bottom plane. For model with neighbor diversity, cooperation reaches the higher level in a wide range of parameters. Fig. 5 features the proportion of cooperators as a function of temptation to defect T in evolutionary multigames. Similar to above results, there exists a range of temptation to defect T insuring the larger proportion of cooperators with setup of neighbor diversity.

IV. CONCLUSION

In summary, we come up with a new heterogeneous mechanism that concentrates on the impact of the introduction of neighbor diversity on the evolution of cooperation in the evolutionary games. To be specific, we principally compare the level of cooperation of inhomogeneous interaction neighborhoods model with the traditional model. Particularly, the neighbor diversity of individuals can be achieved by randomly selecting interaction neighbor from four or eight neighborhoods. The numerous simulation experiments suggest that cooperative level can be largely enhanced when heterogeneous interaction neighbors incorporated in prisoner's dilemma game. Meanwhile, the time travel of the proportion of cooperators and the relationship between cooperative level and uncertainty of the strategy selection are exhibited as well. The promotion of cooperative strategy is because of the introduction of different interaction neighbors of players, which motivate the occurrence of compact cooperative clusters. And cooperators could flock together and form clusters fast so as to resist the invasion of defective players. Furthermore, with the purpose of further researching the influence of the diversity of neighborhoods on the evolution of cooperation, we present the fraction of cooperators varies with relevant parameters in snowdrift game and multigames. We can observe that cooperative level has been promoted to a certain extent.

With regard to these results, we emphasize the important role of heterogeneous neighbors in the promotion of cooperation. The present mechanism can be extended to other evolutionary games and may effectively promotes level of cooperation. Our conclusions might help us further understand why cooperation could be sustained in many real systems, and we hope they can provide some insight to resolve the social dilemmas. In the future, we will consider interaction neighbors, selected from either the von Neumann neighborhood or the Moore neighborhood, as time-varying rather than fixed over time. Furthermore, there are also open research directions in terms of different interaction network topologies and in terms of considering the multigame environment that is constituted by several different evolutionary games.

REFERENCES

[1] A. M. Colman, *Game Theory and Its Applications in the Social and Biological Sciences*. Oxford, U.K.: Butterworth-Heinemann, 1995.
[2] J. M. Smith, *Evolution and the Theory of Games*. Cambridge, U.K.: Psychology Press, 1982.
[3] J. W. Weibull, *Evolutionary Game Theory*. Cambridge, MA, USA: MIT Press, 1995.
[4] J. Hofbauer and K. Sigmund, *Evolutionary Games and Population Dynamics*. Cambridge, U.K.: Cambridge Univ. Press, 1998.
[5] M. Mesterton-Gibbons, *An Introduction to Game-Theoretic Modelling*, 2nd ed. Providence, RI, USA: AMS, 2001.
[6] M. A. Nowak, *Evolutionary Dynamics*. Cambridge, MA, USA: Harvard Univ. Press, 2006.
[7] D. Fudenberg and E. Maskin, "The folk theorem in repeated games with discounting or with incomplete information," *Econometrica*, vol. 54, no. 3, pp. 533–554, May 1986.
[8] M. Nowak and K. Sigmund, "A strategy of win-stay, lose-shift that outperforms tit-for-tat in the prisoner's dilemma game," *Nature*, vol. 364, no. 1, pp. 56–58, Jul. 1993.
[9] F. C. Santos and J. M. Pacheco, "Scale-free networks provide a unifying framework for the emergence of cooperation," *Phys. Rev. Lett.*, vol. 95, no. 9, pp. 098104-1–098104-4, Aug. 2005.
[10] F. Fu, X. Chen, L. Liu, and L. Wang, "Promotion of cooperation induced by the interplay between structure and game dynamics," *Phys. A, Stat. Mech. Appl.*, vol. 383, no. 2, pp. 651–659, Sep. 2007.
[11] H.-X. Yang and Z. Wang, "Role of mutual punishment in the snowdrift game," *Europhys. Lett.)*, vol. 111, no. 6, p. 60003-p1–60003-p6, Sep. 2015.
[12] M. A. Javarone, "Statistical physics of the spatial prisoner's dilemma with memory-aware agents," *Eur. Phys. J. B*, vol. 89, p. 42, Feb. 2016.
[13] M. Xu, D.-F. Zheng, C. Xu, and P. M. Hui, "Three-strategy N-person snowdrift game incorporating loners," *Phys. A, Stat. Mech. Appl.*, vol. 468, pp. 454–461, Feb. 2017.

[14] J. Y. Guan, Z. X. Wu, and Y. H. Wang, "Effects of inhomogeneous activity of players and noise on cooperation in spatial public goods games," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 76, no. 5, pp. 056101-1–056101-4, Nov. 2007.
[15] C.-J. Zhu, S.-W. Sun, L. Wang, S. Ding, J. Wang, and C.-Y. Xia, "Promotion of cooperation due to diversity of players in the spatial public goods game with increasing neighborhood size," *Phys. A, Stat. Mech. Appl.*, vol. 406, pp. 145–154, Jul. 2014.
[16] X. Chen, A. Szolnoki, and M. Perc, "Competition and cooperation among different punishing strategies in the spatial public goods game," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 92, no. 1, p. 012819, Jul. 2015.
[17] M. A. Javarone and A. E. Atzeni, "The role of competitiveness in the prisoner's dilemma," *Comput. Social Netw.*, vol. 2, no. 1, p. 15, Jul. 2015.
[18] R. Cressman, A. Gaunersdorfer, and J.-F. Wen, "Evolutionary and dynamic stability in symmetric evolutionary games with two independent decisions," *Int. Game Theory Rev.*, vol. 2, no. 01, pp. 67–81, Mar. 2000.
[19] Z. Wang, A. Szolnoki, and M. Perc, "Different perceptions of social dilemmas: Evolutionary multigames in structured populations," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 90, no. 3, p. 032813, Sep. 2014.
[20] M. A. Nowak, "Five rules for the evolution of cooperation," *Science*, vol. 341, no. 5808, pp. 1560–1563, Dec. 2006.
[21] M. A. Nowak and R. M. May, "Evolutionary games and spatial chaos," *Nature*, vol. 359, no. 6398, pp. 826–829, Oct. 1992.
[22] Z. X. Wu and P. Holme, "Effects of strategy-migration direction and noise in the evolutionary spatial prisoner's dilemma," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 80, no. 2, p. 026108, Aug. 2009.
[23] J. Tanimoto, M. Brede, and A. Yamauchi, "Network reciprocity by coexisting learning and teaching strategies," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 85, no. 3, p. 032101, Mar. 2012.
[24] J. Gomez-Gardeñes, M. Campillo, L. M. Floría, and Y. Moreno, "Dynamical organization of cooperation in complex topologies," *Phys. Rev. Lett.*, vol. 98, no. 10, p. 108103, Mar. 2007.
[25] B. Wang, X. Chen, and L. Wang, "Probabilistic interconnection between interdependent networks promotes cooperation in the public goods game," *J. Stat. Mech., Theory Experim.*, p. P11017, Nov. 2012, doi: https://doi.org/10.1088/1742-5468/2012/11/P11017
[26] J. Tanimoto, "Promotion of cooperation through co-evolution of networks and strategy in a 2×2 game," *Phys. A, Stat. Mech. Appl.*, vol. 388, no. 6, pp. 953–960, Mar. 2009.
[27] J. Tanimoto, "Difference of reciprocity effect in two coevolutionary models of presumed two-player and multiplayer games," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 87, no. 6, p. 062136, Jun. 2013.
[28] A. Szolnoki and M. Perc, "Second-order free-riding on antisocial punishment restores the effectiveness of prosocial punishment," *Phys. Rev.*, vol. 7, p. 041027, Oct. 2017.
[29] A. Szolnoki and M. Perc, "Correlation of positive and negative reciprocity fails to confer an evolutionary advantage: Phase transitions to elementary strategies," *Phys. Rev.*, vol. 3, p. 041021, Nov. 2013.
[30] A. Szolnoki and M. Perc, "Antisocial pool rewarding does not deter public cooperation," *Proc. Roy. Soc. B*, vol. 282, p. 20151975, Oct. 2015.
[31] A. Szolnoki and M. Perc, "Evolutionary advantages of adaptive rewarding," *New J. Phys.*, vol. 14, p. 093016, Sep. 2012.
[32] A. Szolnoki and M. Perc, "Reward and cooperation in the spatial public goods game," *EPL (Europhys. Lett.*, vol. 92, no. 3, p. 38003, Nov. 2010.
[33] Z. Wang, C.-Y. Xia, S. Meloni, C.-S. Zhou, and Y. Moreno, "Impact of social punishment on cooperative behavior in complex networks," *Sci. Rep.*, vol. 3, p. 3055, Oct. 2013.
[34] F. Fu, C. Hauert, M. A. Nowak, and L. Wang, "Reputation-based partner choice promotes cooperation in social networks," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 78, no. 2, p. 026117, Aug. 2008.
[35] Z. Wang, L. Wang, A. Szolnoki, and M. Perc, "Evolutionary games on multilayer networks: A colloquium," *Eur. J. Phys. B*, vol. 88, p. 124, May 2015.
[36] J. Tanimoto, M. Nakata, A. Hagishima, and N. Ikegaya, "Spatially correlated heterogeneous aspirations to enhance network reciprocity," *Phys. A, Stat. Mech. Appl.*, vol. 391, no. 3, pp. 680–685, Feb. 2012.
[37] F. C. Santos, M. D. Santos, and J. M. Pacheco, "Social diversity promotes the emergence of cooperation in public goods games," *Nature*, vol. 454, no. 7201, pp. 213–216, Jul. 2008.
[38] M. Perc and A. Szolnoki, "Social diversity and promotion of cooperation in the spatial prisoner's dilemma game," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 77, p. 011904, Jan. 2008.
[39] A. Szolnoki and M. Perc, "Competition of tolerant strategies in the spatial public goods game," *New. J. Phys.*, vol. 18, p. 083021, Aug. 2016.
[40] G. Szabó and C. Toke, "Evolutionary prisoner's dilemma game on a square lattice," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 58, no. 1, p. 69, Jul. 1998.
[41] M. Perc, J. J. Jordan, D. G. Rand, Z. Wang, S. Boccaletti, and A. Szolnoki, "Statistical physics of human cooperation," *Phys. Rep.*, vol. 687, pp. 1–51, May 2017.
[42] M. Perc and A. Szolnoki, "Coevolutionary games—A mini review," *BioSystems*, vol. 99, no. 2, pp. 109–125, Feb. 2010.
[43] M. Perc and J. Gómez-Gardeñes, A. Szolnoki, L. M. Floría, and Y. Moreno, "Evolutionary dynamics of group interactions on structured populations: A review," *J. Roy. Soc. Interface*, vol. 10, no. 80, p. 20120997, Mar. 2013.
[44] Y. Ma, J. Lu, and L. Shi, "Diversity of neighborhoods promotes cooperation in evolutionary social dilemmas," *Phys. A, Stat. Mech. Appl.*, vol. 468, pp. 212–218, Feb. 2017.

JIAHU QIN (M'12) received the first Ph.D. degree in control science and engineering from the Harbin Institute of Technology, Harbin, China, and the second Ph.D. degree in systems and control from The Australian National University, Canberra, Australia, in 2012 and 2014, respectively. He is currently a Professor with the Department of Automation, University of Science and Technology of China, Hefei, China. His current research interests include consensus and coordination in multi-agent systems and complex network theory and its application.

YAMING CHEN received the B.E. degree in automation from the Anhui University of Technology, Maanshan, China, in 2015. She is currently pursuing a master's degree at the Department of Automation, University of Science and Technology of China. Her current research interests include evolutionary games of social networks.

WEIMING FU received the B.E. degree in automation from the University of Science and Technology of China, Hefei, China, in 2014, where he is currently pursuing the master's degree. His current research interests include consensus problems in multiagent coordination and synchronization of complex dynamical networks.

YU KANG (M'09–SM'14) received the Dr.Eng. degree in control theory and control engineering from the University of Science and Technology of China, Hefei, China, in 2005. From 2005 to 2007, he was a Post-Doctoral Fellow with the Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing, China. He is currently a Professor with the Department of Automation, University of Science and Technology of China. His current research interests include adaptive/robust control, variable structure control, mobile manipulator, and Markovian jump systems.

MATJAŽ PERC is currently a Professor of physics with the University of Maribor and the Director of the Complex Systems Center Maribor. He is a member of Academia Europaea and the European Academy of Sciences and Arts. He received the Young Scientist Award for Socio- and Econophysics from the German Physical Society in 2015. He became the USERN Laureate in Social Sciences in 2017. His research has been covered by Nature News, New Scientist, MIT Technology Review, Inside Science, The Boston Globe, Fox News, Chemistry World, Phys.org, Physics Today, Science News, and APS Physics. He is among top 1% most cited physicists according to Thomson Reuters Highly Cited Researchers. He is an Outstanding Referee of the *Physical Review* and *Physical Review Letters* journals, and a Distinguished Referee of *Europhysics Letters*.