Journal of Theoretical Biology 372 (2015) 118–127

Contents lists available at ScienceDirect

Journal of Theoretical Biology

journal homepage: www.elsevier.com/locate/yjtbi

Neighbourhood reaction in the evolution of cooperation

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HIGHLIGHTS

- An evolutionary strategy–reaction–structure model is proposed.
- The cooperation is promoted by increasing the rewiring strength and reaction strength.
- A shift from softer transition to sharper transition is obtained as the selection strength increases.
- High network density hinders the prosperity of cooperation.

ARTICLE INFO

Article history:
Received 27 November 2014
Received in revised form
26 January 2015
Accepted 20 February 2015
Available online 5 March 2015

Keywords:
Evolutionary games
Adaptive networks
Neighbourhood reaction

ABSTRACT

Combining evolutionary games with adaptive networks, an entangled model between strategy evolution and structure adaptation is researched in this paper. We consider a large population of cooperators *C* and defectors *D* placed in the networks, playing the repeated prisoner's dilemma (PD) games. Because of the conflicts between social welfare and personal rationality, both strategy and structure are allowed to change. In this paper, the dynamics of strategy originates form the partner imitation based on social learning and the dynamics of structure is driven by the active linking and neighbourhood reaction. Notably, the neighbourhood reaction is investigated considering the changes of interfaces between cooperators and defectors, where some neighbours may get away from the interface once the focal agent changes to different strategy. A rich landscape is demonstrated by changing various embedding parameters, which sheds light upon that reacting promptly to the shifted neighbour will promote the prevalence of cooperation. Our model encapsulates the dynamics of strategy, reaction and structure into the evolutionary games, which manifests some intriguing principles in the competition between two groups in natural populations, artificial systems and even human societies.

1. Introduction

When adapting game theory to evolutionary population, the evolutionary game theory (EGT) (Smith and Price, 1973; Smith, 1982) is provided to study the stationary frequency of various interacting populations, who may change their strategies to get more benefits in the competitions. Under a unified framework of strategy, player and payoff as well as the replication and mutation in Darwinian process, EGT can be formalised in a mathematical manner (Nowak, 2006) embedded into the multi-agent systems to explain many fascinating but challenging phenomena in biology, economy and society. The most well-known game—prisoner's dilemma (PD) is intensively researched in the past several decades, where one of the most attractive topics is the evolution of cooperation.

Focusing on this competition between individual benefits and collective interests, Nowak (2006) has made both theoretical and experimental contributions in this complex field. Due to the self-interested behaviour (known as *utilitarianism*), the evolution of cooperation in the prisoner's dilemma will be weakened under natural selection and defecting is always a dominant action regardless of the opponent's action. As a result, the Nash equilibrium (Osborne and Rubinstein, 1994) is not Pareto-efficient. However, it is highlighted that the evolution of cooperation may be influenced by introducing some specific mechanisms, such as direct reciprocity, indirect reciprocity, spatial selection, multi-level selection, kin selection, *etc.* Interestingly, it is the behaviour of *altruism* (*e.g.* indirect reciprocity) (Nowak and Sigmund, 2005) that promotes the prevalence of cooperation within the context of Darwinian process. Considering the bounded structures in real world, the individual can never interact with everyone else in a quite large population society. Therefore, some structured models

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http://dx.doi.org/10.1016/j.jtbi.2015.02.022
0022-5193/

embedded into the evolutionary games are required to explore the prosperities of spatial interactions. Subsequently, evolutionary dynamics on networks (Nowak and May, 1992; Lieberman et al., 2005) were proposed, followed by a large number of studies (shown in Section 2) to investigate the emergence of cooperation within a network of interacting players.

Network topology, interaction games, initial fraction, update rules, *etc.* are explored in a comprehensive picture (Hofmann et al., 2011) to reveal the mysteries in the evolutionary dynamics, where an agent plays the game with all of its neighbours round by round. During the game playing process, the agent's strategy may be updated based on some deterministic or stochastic rules. Interestingly, it was shown that the scale-free network could provide a higher cooperation level than homogeneous network, like regular grid or random network (Santos and Pacheco, 2005). Hereafter, more and more researchers are focusing on the dynamics of network structure evolving from homogeneity to heterogeneity. Numerous researches on evolutionary games within adaptive networks (Gross and Sayama, 2009) are well studied to uncover the latent knowledge in real world.

Combining the evolution of states with the adaptation of networks, adaptive networks mainly focus on the intriguing interplays of the *dynamics on networks* and *dynamics of networks* (Gross and Blasius, 2008), which entangle the state and topology tightly. For the former dynamics, the global phase transition (Gleeson, 2011) is focused; while for the latter dynamics, the emerging heterogeneous structure is concerned. As an important interdisciplinary subject, the related research on adaptive networks receives increasing attentions from the fields like complex networks, statistical physics, game theory, social science, *etc.* From the perspectives of natural populations to artificial systems, and then human societies, many models of adaptive networks are well studied. These studies range from voter model (Holme and Newman, 2006; Durrett et al., 2012), epidemics propagation (Gross et al., 2006; Shaw and Schwartz, 2008), evolutionary populations (Huepe et al., 2011), social games (Pacheco et al. 2006a,b; Zimmermann et al., 2004), *etc.*

To understand the cooperation dilemmas of the self-interested individuals working to benefit the whole society, evolutionary game theory (EGT) should be researched from different aspects. The motivation of this paper is to put evolutionary games into adaptive networks, where the model and analyses for state-topology co-evolution will be explored further to facilitate cooperation. In the multi-agent networks, we assume that the agents are bounded rational, self-interested, and work in a decentralised manner. Under the PD game, cooperators (C) and defectors (D) are placed randomly within the network. The agents will update their strategies based on social learning, namely imitate those neighbours holding a higher payoff. There are three types of links in the network: CD, CC and DD, where CD and DD are the active (unstable) links because both C and D are unsatisfied with D, whereas the CC is the inert (stable) link. As a result, the active links CD and DD are allowed to be reconnected in the network. Notably, the local neighbourhood would like to react to the changes of interfaces and make decisions to leave the flipped neighbours (Szolnoki and Perc, 2009). Hereof, we focus on this point in the following to uncover the rich landscape of the state-topology dynamics by changing some embedding parameters, such as rewiring strength, reacting strength, selection strength, *etc.*

The paper is organised as follows to reveal the influence of dynamical topology on dynamical state. In Section 2, we discuss the related research on the evolution of cooperation. The co-evolutionary model incorporating strategy evolution and structure adaptation is defined in Section 3, followed by a series of simulations and discussions in Section 4. In Section 5, we draw some conclusions.

2. Related work

In the static networks, Nowak and May (1992) demonstrated the games in a grid to show that the cooperation and defection could coexist under the imitate-best-neighbour rule. As for both natural and social societies were grounded in strongly heterogeneous networks, Santos and Pacheco (2005) found a clear promotion of cooperation within a scale-free network, where the diversity of the degree was presented. Ranjbar-Sahraei et al. (2014) studied the evolution in arbitrary complex networks by providing continuous strategies, where they showed that the cooperation level had a positive relation with network size but negative relation with network connectivity. Jiang et al. (2013) proposed a graphical evolutionary game-theoretic view to combine the information diffusion with game theory and derived the closed-form expressions for evolutionarily stable state (ESS). Besides, Hofmann et al. (2011) explored the influences of network structures (*e.g.* scale-free network; regular grid; small-world network; random network, *etc.*) and state update rules (*e.g.* deterministic or stochastic imitate-best-neighbour, imitate-best-strategy, win-stay-lose-shift, imitate-random-neighbour, *etc.*) on the evolution of cooperation, and many interesting findings were presented.

Combining *strategy evolution* with *structure adaptation* (Pacheco et al., 2006b; Yang et al., 2014), the evolution of cooperation presents many amazing phenomena to reveal the complexity of interacting individuals. When it comes to the variable topology (Zimmermann and Eguíluz, 2005), structure adaptation based on preferences enables the individuals to break up some 'bad' links and connect to those 'good' agents, resulting in the big variance in the distribution of benefits, and then the prevalence of cooperation. Wu et al. (2010) modelled the evolution of cooperation within a dynamical network using Markov chains, and they pointed out that the fragile CD links and robust CC links would increase the chances of cooperation. Santos et al. (2012) investigated many factors that could promote the cooperation by improving the diversity, where they highlighted that the evolution-rewiring strength (Santos et al., 2006), responses to neighbours (Van Segbroeck et al., 2009), pre-play signalling (Santos et al., 2011), selection pressure (Van Segbroeck et al., 2011), *etc.* were quite significant in leading to higher level of cooperation. Besides those rule-based rewiring strategies, many researches also explored how to make the agents more intelligent by incorporating individual learning into the decision-making. For instance, Van Segbroeck et al. (2010) encapsulated individual learning into the cooperation dilemma, where the reinforcement learning was used to select future strategies. Fu et al. (2008) proposed a reputation-based partner choice to let the agent reorganise its local structure by switching links from lower-reputation neighbours to higher-reputation ones. In addition, Poncela et al. (2009) investigated the model of evolutionary games in a growing structured population, where they found that the cooperation was improved when the network is growing. Szolnoki and Perc (2008) and Szolnoki et al. (2008) presented a teaching activity mechanism that allowed the successful agents to enhance their influence by making new connections, which would maintain the cooperative behaviour in the population.

3. The model of evolutionary games

This section will introduce the basic background on games on networks, strategy evolution, and structure adaptation, where we provide a co-evolutionary model for the game of cooperation.

3.1. Games on networks

The games studied in game theory are well defined in a mathematical way to show the process of strategic decision