Physica A 390 (2011) 1615–1622

Contents lists available at ScienceDirect

Physica A

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

Evolution of cooperation among mobile agents

Zhuo Chen [a,*], Jianxi Gao [a], Yunze Cai [a], Xiaoming Xu [b,c]

[a] *Department of Automation, Shanghai Jiao Tong University, Shanghai, China*
[b] *University of Shanghai for Science and Technology, Shanghai, China*
[c] *Shanghai Academy of Systems Science, Shanghai, China*

ARTICLE INFO

Article history:
Received 15 May 2010
Received in revised form 29 December 2010
Available online 12 January 2011

Keywords:
Cooperation
Flocks
Evolutionary games
Prisoner's dilemma
Snowdrift game

ABSTRACT

We study the effects of mobility on the evolution of cooperation among mobile players, which imitate collective motion of biological flocks and interact with neighbors within a prescribed radius R. Adopting the the prisoner's dilemma game and the snowdrift game as metaphors, we find that cooperation can be maintained and even enhanced for low velocities and small payoff parameters, when compared with the case that all agents do not move. But such enhancement of cooperation is largely determined by the value of R, and for modest values of R, there is an optimal value of velocity to induce the maximum cooperation level. Besides, we find that intermediate values of R or initial population densities are most favorable for cooperation, when the velocity is fixed. Depending on the payoff parameters, the system can reach an absorbing state of cooperation when the snowdrift game is played. Our findings may help understanding the relations between individual mobility and cooperative behavior in social systems.

1. Introduction

Cooperation is commonly observed throughout biological systems, animal kingdoms and human societies. But from a Darwinian viewpoint, cooperators are at a disadvantage in natural selection, because they increase the fitness of others at the cost of their own survival and reproduction [1]. In a broad range of disciplines, understanding the emergence of cooperation is a fundamental problem, which is often studied within the framework of evolutionary game theory.

The prisoner's dilemma (PD) game and the snowdrift (SD) game are commonly used two person games with two strategies, cooperation (C) and defection (D). Mutual cooperation pays each a reward R, while mutual defection brings each a punishment P. When one defector meets one cooperator, the former gains the temptation T while the latter obtains the sucker's payoff S. The PD is defined by the payoffs, if $T > R > P > S$ and $2R > S + T$. In a single round of the PD, though the individual interest can be maximized by defection, the collective payoff achieves the maximum only when both players cooperate. Hence the dilemma arises. As an alternative model to study cooperative behavior, the SD is produced when $T > R > S > P$. In contrast with the PD, the best strategy of the SD depends on the co-player: to defect if the opponent cooperates, but to cooperate if the opponent defects. Under replicator dynamics in well-mixed populations, defection is the only evolutionarily stable strategy in the PD, while cooperators may coexist with defectors in the SD. Note in the SD, the average population payoff at evolutionary equilibrium is smaller than that when everyone plays C [2]. Thus SD is still a social dilemma.

One of possible mechanisms accounting for the establishment of cooperation is the so-called network reciprocity [3]. Discarding the well-mixed assumption for populations, this theory focuses on how spatial structure affects the evolution of

* Corresponding author.
E-mail address: jeffchen_ch@yahoo.com.cn (Z. Chen).

0378-4371/$ – see front matter
doi:10.1016/j.physa.2011.01.004

cooperation. Axelrod first suggested to locate individuals on the two-dimensional array, where interactions only happened within local neighborhoods. Nowak and May developed this idea later, showing that unconditional cooperators could survive by forming clusters [4]. These pioneering studies have triggered an intensive investigation of spatial games, yielding enormous combinations of evolutionary rules, graphs and game models. In Ref. [5], the effect of noise is incorporated in the strategy adoption, and Darwinian selection of the noise level favors a specific parameter value that induces the highest level of cooperation [6,7]. Diversity is another role facilitating cooperation, which takes various forms as heterogeneous graphs [8], preferential imitations [9], reproduction probabilities [10], individual rationality [11], fitness [12] or behavioral preferences [13]. Since connectivity structures in the real world are far more than regular lattices, there are many interests in the impact of complex topologies on cooperative behavior [14–19]. The co-evolution of strategies and individual traits, such as teaching activities [20,21], learning rules [22,23] and social ties [24–28], constitutes a key mechanism for the sustainability of cooperation. Interestingly, cooperators can benefit from the continuous supply of new players [29,30], and the strategy-independent evolution of networks can evoke powerful mechanisms to promote cooperation [31,32]. More details about spatial evolutionary games can be found in Refs. [2,3,33,34] and references therein.

Mobility of individuals is responsible for various spatiotemporal dynamics on geographical scales, such as the spread of infectious diseases and wireless viruses [35]. And statistical properties of human motion have attracted much interest in recent years [36–38]. Indeed, the motion of individuals is an important characteristic of social networks [39]. Though it is often neglected, the effects of mobility on the evolution of cooperation vary with movement forms and population structures. Vainstein et al. [40] considered a random diffusive process in a population of agents with pure strategies, where each agent can jump to a nearest empty site with a certain probability. It was found that cooperation can be enhanced by the movement of players, provided that the mobility parameter is kept with a certain range. The weak form of the PD adopted in Ref. [40] was later extended to other games [41,42],and it was found that cooperation in the SD is not so often inhibited as that reported in Ref. [43]. Besides, the movement of players may take an adaptive form for payoffs or neighbors, and contingent mobility is often expected to enhance cooperation. Aktipis [44] proposed a walk-away strategy to avoid repeated interactions with defectors, which outperforms complex strategies under a number of conditions. Helbing and Yu introduced the success-driven migration, in which players determine destinations through fictitious play [45]. Besides, individuals can decide when to move based on the number of neighboring defectors [46].

The synchronised motion of animal groups, such as fish schools and bird flocks, is an intriguing phenomenon, which can be modeled by systems of self-driven agents [47–49]. Recently, the model by Vicsek et al. has gained much attention for minimalism styles and rich dynamics [47]. Here we combine the Vicsek model with evolutionary games, focusing on the effect of mobility on the evolution of cooperation. We reserve well-known elements like direction alignment and circular neighborhoods, ignoring the influence of angular noise on the update of velocity. We also cancel the periodic boundary conditions for simplicity, which can strongly affect the system behavior at the large velocity regime [48]. Thus when players move, the system is split into some disconnected groups, within which agents move toward the same direction. Note in some social systems, individuals do divide into groups according to race, wealth, age, and so on. We think that the aggregation of individuals partly reflects the community structure in social networks. In Ref. [50], we have investigated an evolutionary PD game in a Vicsek-like model, where each agent plays with a constant number of neighbors. We have found that cooperation can be maintained and even enhanced by the motion of players, provided that certain conditions are fulfilled. In the current work, we will check the robustness of our conclusions, when each agent plays the PD game with those individuals within a certain distance. Besides, we will study how mobility affects the outcome of the SD game.

2. The model

We consider a system with N autonomous agents, which have positions $x_i(t)$ and move synchronously with velocities $\overrightarrow{V_i}(t)$ in a two-dimensional plane. The velocity $\overrightarrow{V_i}(t)$ of the agent i is characterized by a fixed absolute velocity v and an angle $\theta_i(t)$ indicating the direction of motion. When $t = 0$, all agents are randomly distributed in an $L \times L$ square without boundary restrictions. Rather than fixed within a periodic domain, individuals can cross the border of the square when $t > 0$, and move in the whole plane. The square only represents the initial distribution of individuals with a density $\rho = N/L^2$. Besides, initial moving directions of agents, $\theta_i(0)$, are uniformly distributed in the interval $[0, 2\pi)$. At each time step, the ith agent updates its position according to

$$x_i(t+1) = x_i(t) + \overrightarrow{V_i}(t)\Delta t. \tag{1}$$

Here Δt is set to 1 between two updates on the positions.

To simulate the process of direction alignment in flocks, the angle $\theta_i(t)$ of the agent i is updated according to the average direction of nearby neighbors [47]. Then we have

$$\theta_i(t+1) = \arctan \frac{\sin\theta_i(t) + \sum\limits_{j\in W_i(t)} \sin\theta_j(t)}{\cos\theta_i(t) + \sum\limits_{j\in W_i(t)} \cos\theta_j(t)}, \tag{2}$$