Physica A 395 (2014) 218–227

Contents lists available at ScienceDirect

Physica A

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

Memory does not necessarily promote cooperation in dilemma games

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HIGHLIGHTS

- Memory increases cooperation in the prisoner's dilemma.
- Memory inhibits cooperation in the snowdrift and stag hunt games when the cost/benefit ratio is small.
- Cooperation is analyzed in terms of R, ST, and P reciprocity.
- Cooperation is analyzed for 16 strategies.

ARTICLE INFO

Article history:
Received 14 October 2012
Received in revised form 23 August 2013
Available online 15 October 2013

Keywords:
Updating rules
Tit for tat
Win-stay, lose-shift
Synchronous mode

ABSTRACT

Evolutionary games can model dilemmas for which cooperation can exist in rational populations. According to intuition, memory of the history can help individuals to overcome the dilemma and increase cooperation. However, here we show that no such general predictions can be made for dilemma games with memory. Agents play repeated prisoner's dilemma, snowdrift, or stag hunt games in well-mixed populations or on a lattice. We compare the cooperation ratio and fitness for systems with or without memory. An interesting result is that cooperation is demoted in snowdrift and stag hunt games with memory when cost-to-benefit ratio is low, while system fitness still increases with memory in the snowdrift game. To illustrate this interesting phenomenon, two further experiments were performed to study R, ST, and P reciprocity and investigate 16 agent strategies for one-step memory. The results show that memory plays different roles in different dilemma games.

1. Introduction

Cooperation is needed for the evolution of new levels of organization. Genomes, organisms, social insects, and human society are all based on cooperation [1]. Thus, understanding the emergence and persistence of cooperative behavior among rational individuals is important. Evolutionary game theory provides a suitable theoretical framework for addressing the subtleties of cooperation in dilemmas [2–4].

Seminal work by Martin and Nowak in 1992 showed that cooperation can exist on a lattice in the prisoner's dilemma game [5]. However, the Nash equilibrium position for the prisoner's dilemma is defection, and cooperation cannot exist in a well-mixed population. Since then, a large number of studies have searched for mechanisms that promote cooperative behavior [6–8]. There are three types of two-strategy, two-player dilemma game: the prisoner's dilemma (PD) game, the snowdrift (SD) game, and the stag hunt (SH) game. All these games can model the dilemma of how cooperation can be maintained by rational individuals.

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0378-4371/$ – see front matter
http://dx.doi.org/10.1016/j.physa.2013.10.014

Table 1
Coding examples for strategies for $m = 1$.

Game history for two player	Payoff for the first player	Next step for the first player			
		ALLC	ALLD	TFT	WSLS
00 (defect, defect)	P	1	0	0	1
01 (defect, cooperate)	T	1	0	1	0
10 (cooperate, defect)	S	1	0	0	0
11 (cooperate, cooperate)	R	1	0	1	1

Landmark work by Axelrod and Hamilton in the 1980s involved computer tournaments to find the best strategy in a population PD game [9,10]. A tit-for-tat (TFT) strategy was identified as the best.

In 1987, Axelrod coded game history and strategy using binary strings and applied a genetic algorithm to study the PD game when agents have memory for more than one step [11]. He found that some patterns in the strategy code are similar to TFT. However, in 1993 Nowak demonstrated that a win-stay, lose-shift (WSLS) strategy outperforms TFT and WSLS evolved as the dominant strategy in simulations [12]. Both TFT and WSLS are based on memory. Several groups have studied PD games with memory for different network structures [13–16]. Strategy selection has also been widely investigated [17–23].

Some other memory mechanisms have also been evaluated. Studies of the PD game with accumulated payoffs revealed that memory can boost cooperation [24–27]. Wang et al. investigated the SD game with accumulated strategies (cooperation or defection) and found some non-monotonic phenomena [28].

Although many researchers have studied memory and cooperation, challenges still remain. Most research has focused on comparing different strategies or studying cooperation in a structured network with different memory mechanisms. Few studies have considered cooperation in a completely connected network with memory. It has been widely shown that network structure has an impact on cooperation [6–8]. However, the effect of memory for PD, SD, and SH games in well-mixed population is still unclear. Here we investigate evolutionary dilemma games with a memory mechanism, whereby agents base their decisions on the game history, in a completely connected network.

In two-person, two-strategy game, there are three types of reciprocity, as indicated by the payoff matrix $\begin{bmatrix} R & S \\ T & P \end{bmatrix}$. For R reciprocity, the two players cooperate and obtain payoff R. For ST reciprocity, one player cooperates and the other defects; the cooperator obtain S and the defector gets T. For P reciprocity, both players defect and obtain payoff P. The cooperation ratio for a population thus comprises two parts: all the R reciprocity and half of the ST reciprocity. Reciprocity has been studied by various researchers and can help in understanding cooperation [29–31].

When agents make decisions according to history, the strategies they apply (such as TFT or WSLS) determine the cooperation ratio for the system [9–12]. Thus, the strategy distribution for a population can be used to explain how cooperation arises and is maintained.

The remainder of the paper is organized as follows. Section 2 describes our model of an evolutionary game with a memory mechanism. Section 3 presents our simulations and analysis. First, we investigate the cooperation ratio and average fitness for PD, SD, and SH games with differing memory length in a well-mixed population or on a lattice network. To exclude the effect of the network, subsequent work focuses on a well-mixed population (completely connected network). Second, we show the ratio of R reciprocity, P reciprocity, and ST reciprocity, and observe the strategy selection by agents, which affects the cooperation ratio. Section 4 concludes.

2. The model

2.1. Game matrix

The payoff matrix for a two-strategy, two-player game is $\begin{bmatrix} R & S \\ T & P \end{bmatrix}$, where both players obtain R if they cooperate with each other, both players obtain P if they both defect, and the cooperator obtains S and the defector T in a cooperator–defector pair. For a dilemma game there are two indicators [20]: $T - R > 0$ and $P - S > 0$. There are three 2×2 dilemma games: the PD game ($T - R > 0$, $P - S > 0$), the SD game (chicken or hawk–dove; $T - R > 0$), and the SH game ($P - S > 0$). Without loss of generality, we reduce the four parameters to one: the cost/benefit ratio r. Thus, the payoff matrix for the PD game is $\begin{bmatrix} 1 & 0 \\ 1+r & 0.1 \end{bmatrix}$ $(1 > r > 0)$ (this is a strict PD game and the result is similar to matrix $\begin{bmatrix} 1 & 0 \\ b & 0 \end{bmatrix}$ $(2 > b > 1)$ [5]). The matrix for the SD game is $\begin{bmatrix} 1 & 1-r \\ 1+r & 0 \end{bmatrix}$ $(1 > r > 0)$ [28]. The matrix for the SH game is $\begin{bmatrix} 1 & -r \\ r & 0 \end{bmatrix}$ $(1 > r > 0)$ [32].

2.2. The memory device

Following previous work [11,12,29], we design a memory mechanism to code the game history and strategies. One-step memory means that agents can remember the history for the last game. Cooperation is coded as "1" and defection as "0". Thus, there are four possible historical interactions for one-step memory (Table 1): 00 (the focused player defects and the