Evolution of Strategies in Spatial IPD Games with Structured Demes

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Abstract

The aim of this paper is to examine the effect of neighborhood structures on the evolution of cooperative behavior in a spatial IPD (Iterated Prisoner's Dilemma) game where every player is located in a cell of a two-dimensional grid-world. In our spatial IPD game, a player in each cell plays against players in its neighboring cells. A game strategy of each player is represented by a binary string, which determines the next action based on a finite history of previous rounds of the IPD game. A new strategy for a player is generated by genetic operations from a pair of parent strategies, which are selected from its neighbors. We use two neighborhood structures: One is for the interaction among players (i.e., IPD game) and the other is for the genetic operations. Simulation results show that the evolution of cooperative behavior is facilitated by small neighborhood structures for the genetic operations as well as for the IPD game. We also examine a variant of our spatial IPD game where an opponent of a player is randomly selected from its neighbors at every round of the IPD game. This means that the IPD game is not iterated against the same opponent.

1. INTRODUCTION

The evolution of cooperative behavior in the IPD game has been discussed in many studies (for example, see Axelrod, 1987, Lindgren, 1991, Fogel, 1993, and the special issue of *Biosystems* on IPD, vol.37, no.1-2, 1996). Every player usually plays the IPD game against all players in a population. A game strategy of a player, which was represented by a binary string, was evolved by genetic operations such as selection, crossover, and mutation. A fitness value of a strategy was calculated as the average payoff obtained from the IPD game. It is well-known that a simple reciprocal strategy called "tit for tat (TFT)" works very well in the IPD game.

Dugatkin & Mesterton-Gibbons (1996) discusses three categories of cooperation among unrelated individuals: reciprocal altruism, by-product mutualism, and group selection (i.e., structured demes). The evolution of reciprocal strategies such as the TFT in the above-mentioned studies is related to the reciprocal altruism where the choice of an action by a player is conditioned on the previous actions of its opponent.

Some studies (Wilson et al., 1992, Nowak & May, 1992, Huberman & Glance, 1993, Oliphant, 1994, and Vega-Redondo, 1996) focused on the evolution of cooperative behavior in spatial IPD games where every player was located in a cell of single-dimensional or two-dimensional grid-worlds. Every player plays the prisoner's dilemma game only against its neighbors. That is, the interaction among players is restricted by neighborhood structures. These studies can be viewed as computer simulations of the evolution of cooperative behavior in structured demes (Wilson, 1977). In these studies, only two strategies (i.e., ALLC: always cooperate, and ALLD: always defect) were considered. Thus the evolution of cooperative behavior is not based on the reciprocal altruism but the group selection among the three categories of Dugatkin et al. (1996).

In some studies (Nowak & Sigmund, 1992, and Grim, 1996), strategies are not deterministic but stochastic. The choice of an action of a player was stochastically determined based on the previous action of its opponent. It was shown that a stochastically reciprocal strategy called "generous TFT" finally triumphed in computer simulations with stochastic errors. The generous TFT is almost the same as the deterministic TFT except that it forgives the opponent's defection with a positive probability. Grim (1996) showed that the probability of forgiving in the final population was 1/3 in the non-spatial case and 2/3 in the spatial case. That is, more generous strategies were favorable in spatial IPD games.

In this paper, we examine the evolution of cooperative behavior in a spatial IPD game by computer simulations in a two-dimensional grid-world. A deterministic strategy with stochastic errors is represented by a binary string that determines the next action of a player based on a finite history of previous rounds of the IPD game. Thus the evolution of cooperative behavior in our computer simulations is related to both the reciprocal altruism and the group selection while usually one of these two cooperative mechanisms was examined in the literature. The main characteristic feature of our computer simulations in this paper is that two neighborhood structures are considered. One is for the interaction among players (i.e., IPD game). This neighborhood structure corresponds to trait groups in Wilson's structured demes model (Wilson, 1977). The other is for genetic operations that generate new strategies. This neighborhood structure corresponds to demes in the Wilson's model. Various specifications of these two neighborhood structures are used in our computer simulations for examining their effects on the evolution of cooperative behavior.

We also examine a variant of our spatial IPD game where an opponent of a player is randomly selected from its neighbors at every round of the IPD game. This means that a different opponent may be selected at every round. Thus the current action of an opponent affects the choice of the next action by the player against a different opponent. For example, if a player adopts the TFT strategy, the defection of its opponent in the current round of the IPD game causes the player's defection against a different opponent in the next round. In this situation, the evolution of cooperative behavior is very difficult (also see Crowley et al.(1996)). By computer simulations, we show that only a very small neighborhood structure for the IPD game facilitates the evolution of reciprocal strategies.

2. SPATIAL IPD GAME

In this paper, we use a typical payoff matrix in the IPD game. When both players cooperate, the payoff of each player is 3. On the contrary, when both players defect, each player's payoff is 1. The highest payoff 5 is obtained by defecting when the opponent cooperates. In this case, the opponent receives the lowest payoff 0.

A strategy of a player is denoted by a binary string. Every strategy determines the next action based on a finite history of previous rounds of the IPD game. We show an example of such a strategy in Fig. 1. This figure illustrates how a binary string "00001" determines the next action based on the memory of the previous single round of the IPD game. This strategy defects at the first round of the IPD game. Afterwards, this strategy cooperates only when both the player and its opponent cooperated in the previous round. Every single-round-memory strategy is denoted by a binary string of the length 5 in the same manner as in Fig. 1.

Player's move is to defect on the first play: 0		
Moves on the preceding play		Suggested move on the next play
Player's move	Opponent's move	
Defect	Defect	Defect: 0
Cooperate	Defect	Defect: 0
Defect	Cooperate	Defect: 0
Cooperate	Cooperate	Cooperate: 1

Figure 1: Illustration of the strategy $s_i = 00001$.

A single-round-memory strategy can be extended to a two-round-memory strategy that determines the next action based on the memory of the previous two rounds of the IPD game. Every two-round-memory strategy is denoted by a binary string of the length 18 as in Fig. 2. A player with the strategy in Fig. 2 cooperates at the first and second rounds of the IPD game. The action of the player for the *t*-th round ($t \geq 3$) is determined by a kind of a decision tree in Fig. 2 based on the memory of the previous two rounds.

In our spatial IPD game, we assume that every player is located in a cell of a two-dimensional 31×31 grid-world (we do not use the torus structure). In this grid-world, every player plays the IPD game only against its neighbors defined by a neighborhood structure. Let $N_{IPD}(i)$ be the set of the neighboring players of Player *i*.

We can view $N_{IPD}(i)$ as the neighborhood structure for the interaction among players (i.e., IPD game). We examine several specifications of $N_{IPD}(i)$ in computer simulations. Some examples are shown in Fig. 3.

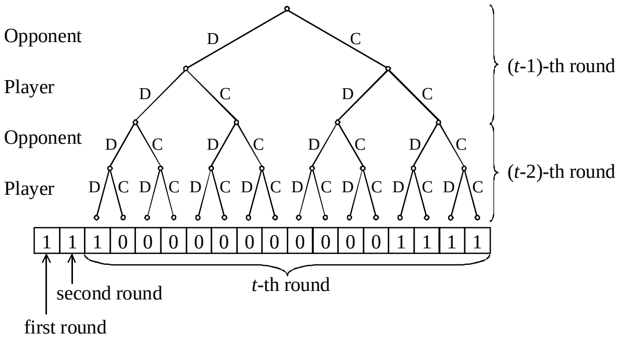
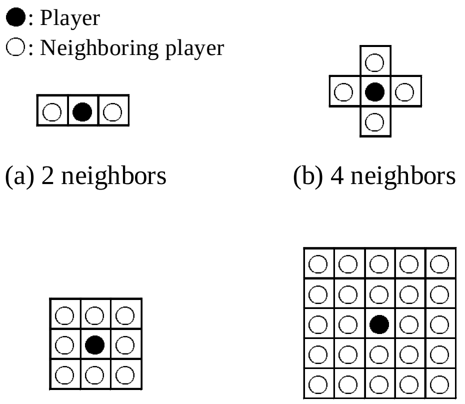


Figure 2: Illustration of a two-round-memory strategy denoted by $s_i = 111000000000001111$.



(a) 2 neighbors (b) 4 neighbors

(c) 8 neighbors (d) 24 neighbors

Figure 3: Examples of neighborhood structures.

The standard non-spatial IPD game can be viewed as the case where its neighborhood structure is the same as the entire grid-world. The IPD game is iterated between a player and its neighbor for a pre-specified number of iterations (e.g., 100 iterations). After the execution of the IPD game is completed against a pre-specified number of its neighbors, the fitness value of the player is calculated as the average payoff obtained from each round of the IPD game. When the neighborhood structure $N_{IPD}(i)$ for the interaction is small, the fitness value of each player is calculated after the execution of the IPD game is completed for all pairs of neighboring players. On the other hand, when $N_{IPD}(i)$ is large, a fixed number of opponents are randomly selected for each player from its neighbors. In our computer simulations, we randomly selected five opponents from $N_{IPD}(i)$ for calculating the fitness value of Player i at every generation when $N_{IPD}(i)$ includes more than five neighbors. This is for preventing the combinatorial increase in the CPU time with the size of $N_{IPD}(i)$.

Let $f(s_i)$ be the fitness value of Player i with the strategy s_i. When a new strategy is to be generated by genetic operations for Player i, a pair of parent strategies are selected from its neighborhood including the player itself. Let $N_{GA}(i)$ be the set of Player i and its neighbors, from which a pair of parent strategies are selected for generating a new strategy for Player i. Thus $N_{GA}(i)$ can be viewed as the neighborhood structure for the genetic operations. It should be noted that the neighborhood structure $N_{GA}(i)$ for the genetic operations is not always the same as $N_{IPD}(i)$ for the IPD game. In our computer simulations of this paper, we examine various specifications of these two neighborhood structures: $N_{IPD}(i)$ and $N_{GA}(i)$.

The selection of a pair of parent strategies for generating a new strategy for Player i is performed in $N_{GA}(i)$. We use the following roulette wheel selection with a linear scaling in this selection:

$$p_i(s_j) = \frac{f(s_j) - f_{\min}(N_{GA}(i))}{\sum_{k \in N_{GA}(i)} \{f(s_k) - f_{\min}(N_{GA}(i))\}} \quad \text{for } j \in N_{GA}(i),$$

where Player j is a neighbor of Player i (or Player i itself), s_j is the strategy of Player j, $p_i(s_j)$ is the selection probability of s_j for generating a new strategy of Player i, $f(s_j)$ is the fitness value of Player j obtained by the strategy s_j, and $f_{\min}(N_{GA}(i))$ is the minimum fitness value among the players in $N_{GA}(i)$.

After a pair of parent strategies are selected, a new strategy is generated from them by genetic operations. We use a standard one-point crossover. When the selected two strategies do not have the same string length, an extension operator in Fig. 4 or a reduction operator in Fig. 5 is employed for generating two strings of the same length (i.e., two strategies based on the same memory length). One string is randomly selected from the two offspring generated by the crossover. A standard bit-change mutation operator is applied to each bit of the selected offspring with a pre-specified mutation probability. If the generated string after the mutation is a single-round-memory strategy, the extension operator in Fig. 4 is employed with a pre-specified extension probability for generating a two-round-memory strategy. The extension operator in Fig. 4 copies the first bit of the single-round-memory strategy to the two-round-memory strategy. The second bit of the two-round-memory strategy is randomly specified. The other bits of the two-round-memory strategy are copies of the single-round-memory strategy as shown in Fig. 4. The correspondence between the single-round-memory strategy and the two-round-memory strategy in Fig. 4 is based on their coding illustrated in Fig. 1 and Fig. 2. On the other hand, if the string generated by the crossover and the bit-change mutation is a two-round-memory strategy, the reduction operator in Fig. 5 is employed with a pre-specified reduction probability for generating a single-round-memory strategy. The reduction operator in Fig. 5 copies the first bit of the two-round-memory strategy to the single-round-memory strategy. The other bits of the single-round-memory strategy are probabilistically specified based on the corresponding bit values in the two-round-memory strategy. For example, the third bit of the single-round-memory strategy in Fig. 5 is specified as "1" with the probability 3/4. Its fourth bit is specified as "1" with the probability 2/4.

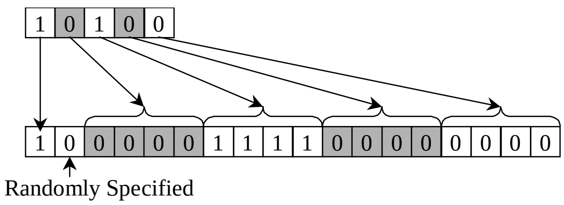


Figure 4: Extension operator.

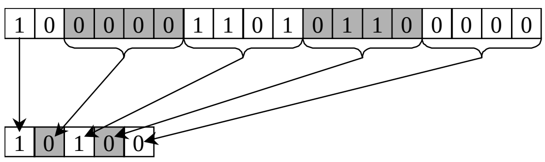


Figure 5: Reduction operator.

After new strategies of all players are generated by the genetic operations, the current population of strategies is updated by the newly generated strategies. The same procedures (i.e., the IPD game among neighboring players and the genetic operations) are applied to the new population again. In this manner, the generation update is iterated until a pre-specified stopping condition is satisfied (e.g., 1000 generations: 1000 population updates).

3. COMPUTER SIMULATIONS

Using various specifications of the two neighborhood structures (i.e., $N_{IPD}(i)$ for the IPD game and $N_{GA}(i)$ for the genetic operations), we examined the evolution of cooperative behavior among spatially fixed 961 players in the two-dimensional 31×31 grid-world. We examined all the 36 combinations of the following specifications of the two neighborhood structures:

The number of players in $N_{IPD}(i)$: 2, 4, 8, 24, 48, 960.
The number of players in $N_{GA}(i)$: 3, 5, 9, 25, 49, 961.

These neighborhood structures are defined as shown in Fig. 3. It should be noted that the spatial IPD game with 960 players in $N_{IPD}(i)$ and 961 players in $N_{GA}(i)$ is actually the same as the standard non-spatial IPD game. It should also be noted that 31 players in each row are evolved independently from other players in different rows of the 31×31 grid-world in the case of $N_{IPD}(i)$ with two players and $N_{GA}(i)$ with three players (see Fig. 3 (a)). In this case, players in different rows do not play the IPD game. Their strategies are not crossed over, either. That is, a strategy of a player has no effect on the evolution of strategies of other players in different rows of the grid-world. When $N_{GA}(i)$ includes more than three players, a strategy of a player can be propagated to any other players in the long run by the genetic operations. On the other hand, when $N_{IPD}(i)$ includes more than two players, a strategy of a player has a direct or indirect effect on the evolution of strategies of any other players through the IPD game among neighboring players.

Our computer simulations were performed with the mistake probability 0.01. The mistake probability is the probability with which each player chooses an action different from the one suggested by its strategy. We used a relatively high mistake probability for intentionally disturbing the mutual cooperation between players. The other parameter values were specified as follows:

Crossover probability: 1.0,
Mutation probability: 0.00002 (for bit-change),
0.00001 (for extension),
0.00001 (for reduction),
Termination of the IPD game: 100 rounds,

Termination of the evolution: 1000 generations.

Average payoff over ten independent trials for each combination of $N_{IPD}(i)$ and $N_{GA}(i)$ is shown in Table 1. From this table, we can see that combinations of small neighborhood structures $N_{IPD}(i)$ and $N_{GA}(i)$ facilitated the evolution of cooperative behavior. The highest average payoff 2.78 was obtained in the case of $N_{IPD}(i)$ with four players and $N_{GA}(i)$ with five players (see Fig. 3 (b)). We can also see that the smallest neighborhood structure $N_{GA}(i)$ for the genetic operations did not work as well as $N_{GA}(i)$ with five players (see the average results by these two specifications of $N_{GA}(i)$ in the last row of Table 1). In the case of $N_{GA}(i)$ with three players (see Fig. 3 (a)), a strategy of a player can not be propagated to other players in different rows in the two-dimensional grid-world. This limitation of the genetic spread of strategies may have a negative effect on the evolution of cooperative behavior. On the contrary, the smallest neighborhood structure $N_{IPD}(i)$ for the IPD game worked as well as $N_{IPD}(i)$ with four players (see the average results obtained by these two specifications of $N_{IPD}(i)$ in the last column of Table 1). That is, we did not observe a clear negative effect of the very small neighborhood structure $N_{IPD}(i)$ for the IPD game.

Table 1: Average payoff obtained from each combination of the two neighborhood structures.

Size of $N_{IPD}(i)$	Size of $N_{GA}(i)$						Average
	3	5	9	25	49	961	
2	2.45	2.56	2.62	2.33	2.20	2.11	**2.38**
4	2.45	**2.78**	2.49	2.28	2.28	2.08	**2.39**
8	2.30	2.68	2.33	2.10	2.26	1.81	2.25
24	2.22	2.53	2.21	2.19	2.14	1.99	2.21
48	2.24	2.29	2.20	2.25	2.15	2.10	2.21
960	2.14	2.24	1.89	1.93	1.98	2.07	2.04
Average	**2.30**	**2.51**	2.29	2.18	2.17	2.03	2.25

For further examining the evolution of strategies in our computer simulations with various specifications of the two neighborhood structures, we monitored the share of each strategy and the average payoff at every generation in each trial. In Fig. 6 and Fig. 7, we show simulation results obtained by a single trial with no spatial structures (i.e., a spatial IPD game with 960 players in $N_{IPD}(i)$ and 961 players in $N_{GA}(i)$). As shown in these figures, cooperative behavior was rapidly evolved, but rapidly collapsed due to the relatively high mistake probability. At the end of this computer simulation, all players had the same strategy "10001" (see Fig. 6). If the mistake probability is zero, the average payoff "3" is obtained from this strategy. Since the mistake probability was 0.01 in our computer simulations, the average payoff was about 1.9 at the end of Fig. 7.

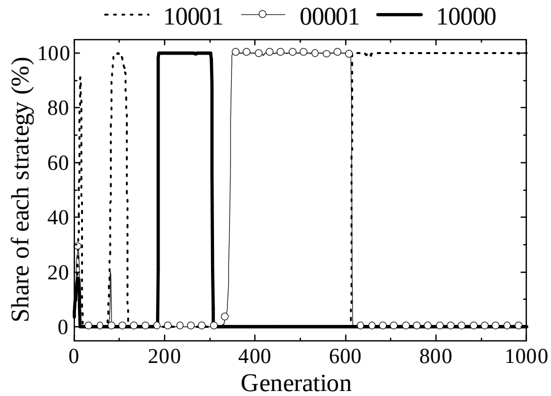


Figure 6: Shares of strategies in a computer simulation with no spatial structures.

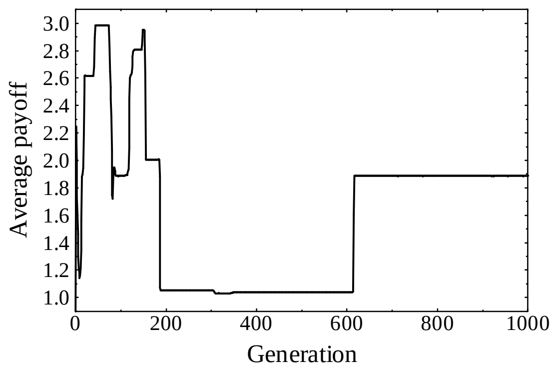


Figure 7: Average payoff obtained by the computer simulation in Figure 6.

In Fig. 8 and Fig. 9, we show simulation results obtained by a single trial with the best combination in Table 1: $N_{IPD}(i)$ with four players and $N_{GA}(i)$ with five players. From these figures, we can see that the transition from one strategy to another one (and the change of the average payoff) was relatively gradual in the spatial IPD game if compared with the case of the non-spatial IPD game in Fig. 6 and Fig. 7. This is because the genetic operations for generating a new strategy of each player were locally performed in its neighborhood.

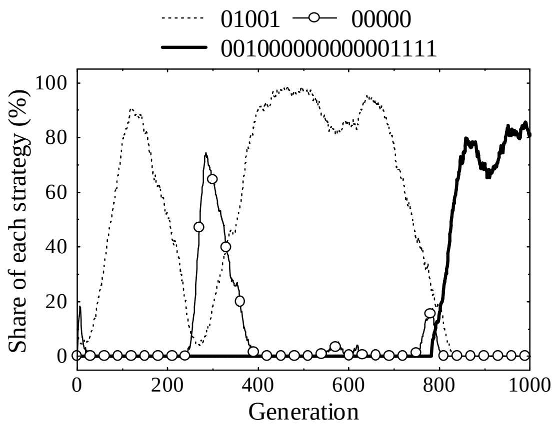


Figure 8: Shares of strategies in a computer simulation with the best combination of the two neighborhood structures.

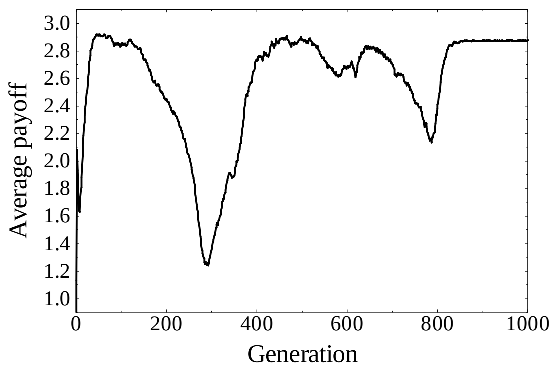


Figure 9: Average payoff obtained by the computer simulation in Figure 8.

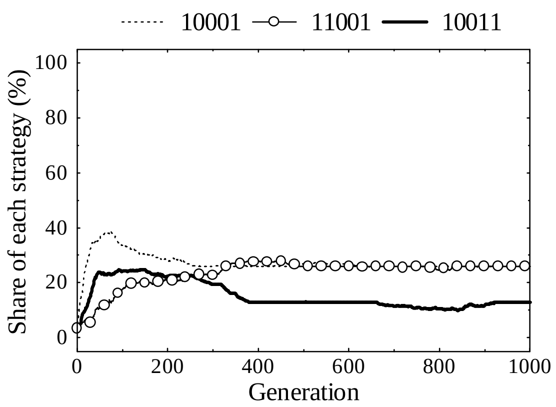


Figure 10: Shares of strategies in a computer simulation with the best $N_{IPD}(i)$ and the smallest $N_{GA}(i)$.

Furthermore, in Fig. 10 and Fig. 11, we show simulation results obtained by a single trial with the combination of the best $N_{IPD}(i)$ and the smallest $N_{GA}(i)$: $N_{IPD}(i)$ with four players and $N_{GA}(i)$ with three players. In this case, strategies of players in each row are not propagated to other players in different rows of the two-dimensional grid-world by the genetic operations. From Fig. 10, we can see that several strategies simultaneously existed at every generation. This is because the spread of strategies by the genetic operations was limited within each row by the smallest neighborhood structure $N_{GA}(i)$ with three players (see Fig. 3 (a)). In Fig. 10, we can also see that the increase or decrease in the share of each strategy is very gradual. Several reciprocal strategies including the TFT "10011" were evolved during the first 200 generations. After that, the change of their shares was very small.

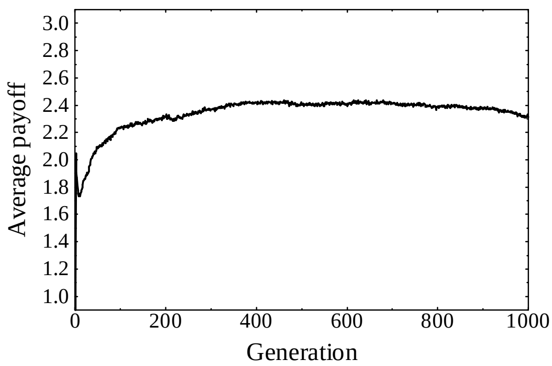


Figure 11: Average payoff obtained by the computer simulation in Figure 10.

4. DIFFERENT MATCHMAKING

In this section, we change the matchmaking scheme in the spatial IPD game for further studying the effect of the neighborhood structures on the evolution of cooperative behavior. In the previous section (and almost all studies on the IPD game in the literature), a player iterated the IPD game with the same opponent for a pre-specified number of iterations (e.g., 100 rounds). We change this matchmaking scheme in the following manner: Every player randomly chooses its opponent at every round of the IPD game from its neighbors.

This matchmaking scheme requires a new implementation of the spatial IPD game, which is totally different from our computer simulations in the previous section because the IPD game is not iterated between the fixed pair of players. In our previous study (Ishibuchi et al., 1999), we tried to implement this situation as a computer program where every player randomly chose its opponent at every round of the IPD game from its neighbors. For calculating the fitness value of Player *i*, our previous computer program iterated the IPD game for a pre-specified number of rounds by selecting an opponent from the neighbors of Player *i* at every round. In this situation, while Player *i* played the IPD game against a different opponent at every round, the neighboring players of Player *i* always played the IPD game against Player *i* when the fitness value of Player *i* was calculated. Thus our previous computer program did not correctly model the situation where an opponent of every player should be randomly selected at every round of the IPD game.

In this paper, we implement the IPD game based on the new matchmaking scheme as the following procedures:

Step 0: Specify *t* as $t=1$ where *t* indexes the number of iterations (i.e., rounds) of the IPD game.
Step 1: Specify *i* as $i=1$ where *i* is the index of player.
Step 2: Randomly select Player *j* from $N_{IPD}(i)$.
Step 3: Player *i* plays a single round of the Prisoner's Dilemma game against Player *j* based on their strategies.
Step 4: Update the memories of Player *i* and Player *j* according to the result of the game in Step 3.
Step 5: If $i<961$ (i.e., if some players have not been selected as Player *i* yet), let $i:=i+1$ and return to Step 2.
Step 6: If $t<T$, let $t:=t+1$ and return to Step 1 where *T* is the pre-specified upper limit of iterations of the IPD game. Otherwise stop the execution of the IPD game.

By these procedures, the fitness values of all players are simultaneously calculated. The next population of strategies is generated by the genetic operations with the neighborhood structure $N_{GA}(i)$ using the calculated fitness values.

Using the same parameter specifications as in the previous computer simulations in Section 3, we examined the evolution of cooperative behavior in the spatial IPD game with the new matchmaking scheme. Because opponents of players are randomly selected from their neighbors at every round of the IPD game (i.e., because the IPD game is not iterated between the fixed pair of players), it seems that the evolution of reciprocal strategies is very difficult. Simulation results in Table 2 show this difficulty. In Table 2, the average payoff, which was calculated over ten independent trials for each combination of the two neighborhood structures, was very small except for some exceptional cases with the smallest neighborhood structure $N_{IPD}(i)$ for the IPD game with only two neighbors (see Fig. 3 (a)). In Table 2, high average payoff was obtained only when $N_{IPD}(i)$ was very small and $N_{GA}(i)$ was appropriate. As shown in the previous section, the smallest neighborhood structure $N_{GA}(i)$ for the genetic operations had a negative effect on the evolution of cooperative behavior. On the contrary, the smallest neighborhood structure $N_{IPD}(i)$ for the IPD game facilitated the evolution of cooperative behavior in our computer simulations with the new matchmaking scheme.

Table 2: Average payoff obtained from the spatial IPD game with the new matchmaking scheme.

Size of $N_{IPD}(i)$	Size of $N_{GA}(i)$						Average
	3	5	9	25	49	961	
2	1.25	**2.55**	**2.42**	1.36	1.36	1.04	1.66
4	1.04	1.04	1.04	1.04	1.04	1.04	1.04
8	1.04	1.04	1.03	1.03	1.04	1.04	1.04
24	1.04	1.03	1.03	1.03	1.03	1.04	1.03
48	1.04	1.03	1.03	1.03	1.03	1.04	1.03
960	1.04	1.03	1.03	1.03	1.03	1.04	1.03
Average	1.08	1.29	1.26	1.09	1.09	1.04	1.14

In Fig. 12 and Fig. 13, we show simulation results obtained by a single trial with the best combination of the two neighborhood structures: $N_{IPD}(i)$ with two players and $N_{GA}(i)$ with five players. From these figures, we can see that reciprocal strategies such as the TFT "10011" were evolved even under the new matchmaking scheme where an opponent of each player was randomly selected from its neighbors. That is, the reciprocal altruism among neighboring players (not between a fixed pair of players) was evolved when the neighboring structure $N_{IPD}(i)$ for the IPD game was very small.

5. CONCLUSIONS

In this paper, we examined the effect of neighborhood structures in spatial IPD games on the evolution of cooperative behavior. We considered two different kinds of neighborhood structures: One is for the interaction among players (i.e., IPD game) and the other is for the genetic operations that generate new strategies. By computer simulations, we showed that the evolution of cooperative behavior was facilitated when both of these two neighborhood structures were small. We also showed that too small neighborhood structures for the genetic operations had a negative effect on the evolution of cooperative behavior. For further examining the effect of neighborhood structures, we implemented a new matchmaking scheme in the IPD game where an opponent of every player was randomly selected from the neighbors of the player at every round of the IPD game. In this situation, the evolution of cooperative behavior is very difficult because each player interacts with a different opponent at every round of the IPD game. By computer simulations, we showed that cooperative behavior was evolved only when we used a very small neighborhood structure for the IPD game and an appropriate neighborhood structure for the genetic operations. Analysis of the observed results with the new matchmaking scheme is left for future work.

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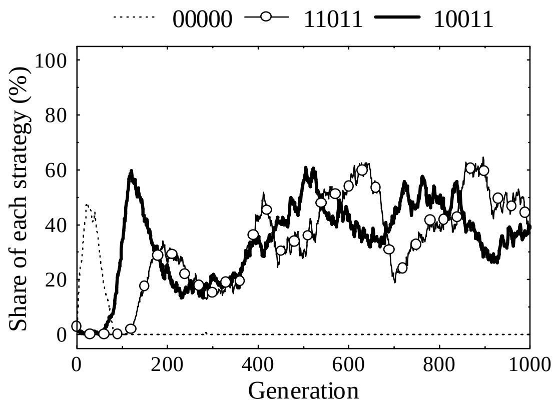

Figure 12: Shares of strategies in a computer simulation with the new matchmaking scheme.

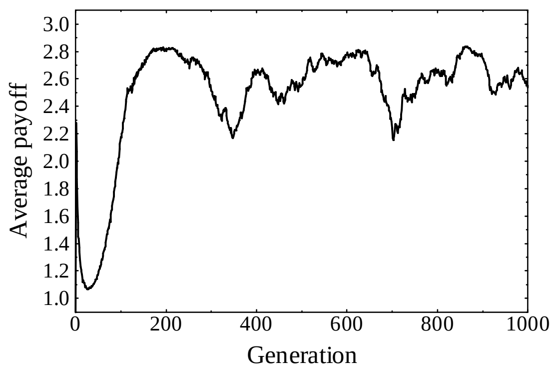

Figure 13: Average payoff obtained by the computer simulation in Figure 12.