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Role of aspiration-induced migration in cooperation

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Both cooperation and migration are ubiquitous in human society and animal world. In this Rapid Communication, we propose an aspiration-induced migration in which individuals will migrate to new sites provided that their payoffs are below some aspiration level. It is found that moderate aspiration level can best favor cooperative behavior. In particular, moderate aspiration level enables cooperator clusters to maintain and expand whereas induces defector clusters to disintegrate, thus promoting the diffusion of cooperation among population. Our results provide insights into understanding the role played by migration in the emergence of cooperative behavior.

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Cooperation is fundamental to biological and social systems. Many important mechanisms have been considered for studying the cooperative behavior, such as costly punishment [1,2], reputation [3,4], and social diversity [5–7]. As is well known, migration is a common and essential feature present in animal world and human society. For example, every year millions of animals migrate in the savannas of Africa and every day thousands of people travel among different countries. Recently, the role of migration has received much attention in the study of evolutionary games [8–14].

Migration can be in a random-walk way. Vainstein *et al.* studied the case in which individuals are located on the sites of a two-dimensional regular lattice and each individual makes an attempt to jump to a nearest neighboring empty site chosen randomly with some probability [10]. Meloni *et al.* considered the case in which individuals are situated on a two-dimensional plane and each individual moves to a randomly chosen position with certain velocity [13]. Apart from random-walk way, the direction of migration can be payoff biased, that is, individuals choose the destination of migration according to payoff. Helbing *et al.* proposed a success-driven migration mechanism in which individuals will move to the sites with highest estimated payoffs [11]. Boyd *et al.* divided individuals into different subpopulations and the number of individuals moving from subpopulation i to subpopulation j depends on the payoff difference between two subpopulations [14].

In some real-life situations, individuals will migrate if their current places are not suitable for living. For example, animals will migrate to other places if they cannot find enough food in the current habitats and many islanders have to leave their hometown as the sea level rises. Inspired by such phenomenon, in this Rapid Communication, we introduce an aspiration-induced migration to study the evolution of cooperation. An individual will move to another place if its current payoff is lower than the aspiration level. Here the aspiration level can be understood as the extent of satisfaction of individuals with their environments, for instance, it could be regarded as the minimum living standard. Considering limited information of individuals, we assume that migrants choose new places in a random way.

We use the famous prisoner's dilemma game (PDG) [15] to carry out our researches. In the PDG played by two players, each of whom chooses one of two strategies, cooperation or defection. They both receive payoff R upon mutual cooperation and P upon mutual defection. If one defects while the other cooperates, cooperator receives S while defector gets T. The ranking of the four payoff values is $T>R>P>S$. Following common practice [16], we set $T=b$ (>1), $R=1$, and $P=S=0$, where b represents the temptation to defect. Since the pioneering work of Nowak and May [16], PDG on various networks, such as regular lattices, random graphs [17], small-world networks [18], and scale-free networks [19], has been widely investigated in recent years [20–26].

In this Rapid Communication, we assume that prisoner's dilemma players are situated on a square with periodic boundary conditions and $L\times L$ sites, which are either empty or occupied by one individual. Initially, an equal percentage of strategies (cooperators or defectors) is randomly distributed among the population. Individuals are updated asynchronously in a random sequential order. The randomly selected individual plays against individuals sitting on four neighboring nodes (the von Neumann neighborhood) and collects the payoff from the combats. The individual compares its total payoff with its direct neighbors and changes strategy following the one (including itself) with the highest payoff. Before updating strategy, an individual decides whether to stay at or leave its current site. An individual stays in current site if its payoff reaches or exceeds its aspiration level, otherwise it moves to a randomly chosen empty site within its four neighboring sites. To avoid isolated case, we assume that an isolated individual makes mandatory move.

Following previous study [27], the aspiration level P_{ia} for an individual i is defined as $P_{ia}=k_iA$, where k_i is the number of neighbors of i and A is a control parameter (A is the same

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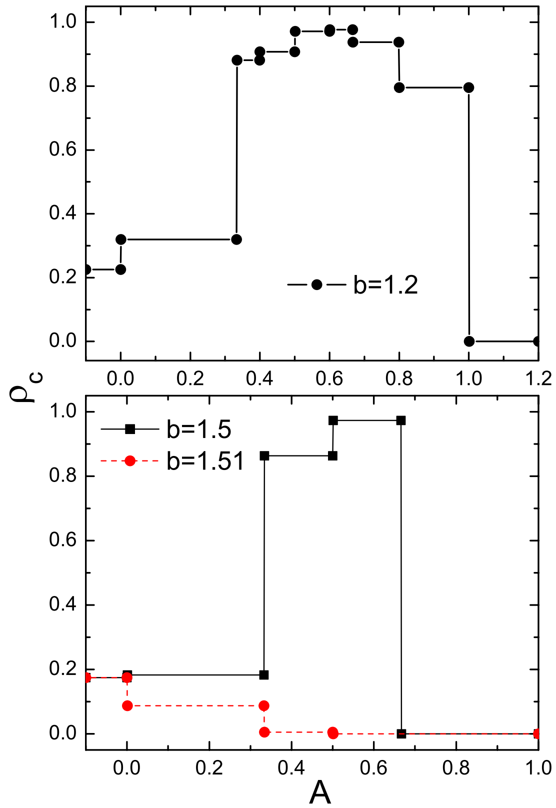

FIG. 1. (Color online) Fraction of cooperators ρ_c as a function of the aspiration level A for different values of the temptation to defect b. The simulations are for 100×100 grids with the fraction of occupied sites $f=0.5$. The equilibrium fraction of cooperators results from averaging over 2000 time steps after a transient period of 20 000 time steps. Each time step consists of on average one strategy-updating event of all the individuals. Results are averaged over 100 different realizations.

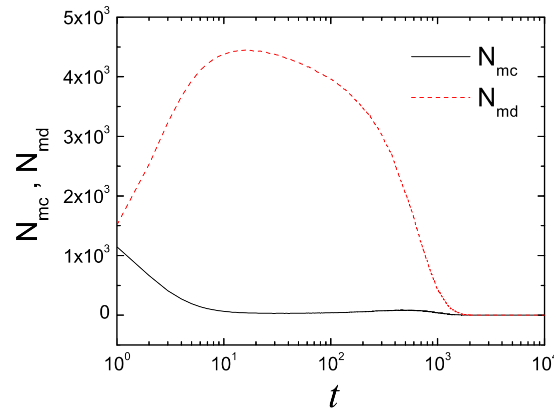

FIG. 2. (Color online) The number of mobile cooperators N_{mc} and mobile defectors N_{md} as a function of time step t on 100×100 grids with 50% empty sites. $b=1.5$ and $A=0.6$. Results are averaged over 100 different realizations.

for all individuals). This definition is based on the following consideration: maintaining a social contact usually is costly [28]. We assume for simplicity that an individual pays A cost to maintain a link with one of its neighbors, and the aspiration level for an individual is defined as the total cost for maintaining social links with all its neighbors.

Figure 1 shows the fraction of cooperators ρ_c as a function of the aspiration level A for different values of the temptation to defect b when the fraction of occupied sites $f=0.5$. One can see that ρ_c exhibits discontinuous phase transition with varying A and ρ_c is the same between two nearby phase transition points. The value of phase transition point can be determined by the average payoff of an individual (total payoff divided by the number of neighbors), which may be 0, 1/2, $b/2$, 1/3, 2/3, $b/3$, $2b/3$, 1, b (here we exclude the isolated case in which individuals make mandatory move and four-neighbor case in which individuals cannot move). Taking $b=1.5$ as example, the phase transition values of A are 0, 1/3, 1/2, 2/3, respectively (here 0.75, 1, and 1.5 are excluded since $\rho_c=0$ for $A>2/3$ when $b=1.5$) [29].

From Fig. 1, one can also find that, for a fixed value of the temptation to defect b, there exists an optimal region of A, leading to the highest cooperation level. For $b=1.2$ and $b=1.5$, the optimal region of A is (0.6, 2/3] and (0.5,2/3] respectively, indicating that moderate aspiration level best favors cooperation. For $b=1.51$, the optimal region of A is $(-\infty, 0]$, in which all individuals do not move. This is because, compared with never-move case, migration makes defectors easily invade cooperator clusters when $b>1.5$ (see the analysis in Ref. [30]).

How to understand moderate aspiration level best promotes cooperation when $b\leq1.5$? It has been known that in spatial games cooperators can survive by forming clusters, in which the benefits of mutual cooperation can outweigh losses against defector [16,31]. For low aspiration level, most individuals do not move. Consequently, cooperator and defector clusters coexist and keep almost unchanged in the stationary state, inhibiting the dispersal of cooperation among population. On the contrary, for high aspiration level, most individuals move. Due to the frequent change in neighbors, cooperators cannot form clusters to resist the invasion of defectors. As a result, cooperators are doomed to extinct, analogous to the situation arising in the well-mixed population.

For moderate aspiration level, on one hand cooperators can form stable clusters since high benefits of mutual cooperation ensure them to stay in cooperator clusters and on the other hand defectors avoid gathering together because the payoffs of mutual defection are low. Figure 2 shows that, during the process of evolution, the number of mobile defectors N_{md} is much larger than mobile cooperators N_{mc} when $b=1.5$, $A=0.6$, indicating moderate aspiration level enables cooperator clusters to be sustained whereas induces defector clusters to be disintegrated. A mobile defector would change to cooperator if it touches cooperator cluster and encounters a cooperator who has the highest payoff among defector and its neighbors (this situation is likely to occur since cooperator clusters usually obtain high payoffs). Hence, for moderate aspiration level, cooperator clusters not only be able to maintain but also expand due to the existence of migration.

To intuitively understand how moderate aspiration level affects the evolution of cooperation, we plot the distribution of cooperators and defectors on a square lattice at different time steps t for $b=1.5$ and $A=0.6$. Initially ($t=1$), cooperators and defectors are randomly distributed with the same

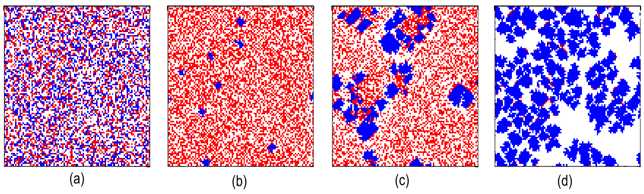

FIG. 3. (Color online) Snapshots of typical distributions of cooperators and defectors at different time steps t for $b=1.5$ and $A=0.6$. The color coding is as follows: red (light gray) represents a defector; blue (dark gray) represents a cooperator; white represents an empty site. The simulations are for 100×100 grids with 50% empty sites. (a) $t=1$, $\rho_c(1)=0.5$, (b) $t=16$, $\rho_c(16)=0.0298$, (c) $t=370$, $\rho_c(370)=0.302$, and (d) $t=3000$, $\rho_c(3000)=0.976$.

probability on the square lattice [see Fig. 3(a)]. From Fig. 3(b), we can see that cooperators and defectors are clustered respectively ($t=16$), and the density of cooperators at this moment is lower than the initial state since cooperators are exposed to much attack of defectors before the formation of steady cooperator clusters. As time step t increases, cooperator clusters expand and defector clusters shrink [see Fig. 3(c)]. Finally, cooperators take over the population and defectors only dispersedly survive nearby cooperator clusters [see Fig. 3(d)], demonstrating that moderate aspiration level can effectively impulse the collapse of defector clusters.

The fraction of occupied sites f also affects the evolution of cooperation. Figure 4 shows the fraction of cooperators ρ_c as a function of the aspiration level A and the fraction of occupied sites f together when the temptation to defect $b=1.5$. From Fig. 4, one can see that, the optimal region of A corresponding to the highest cooperation level changes as f varies. For example, the optimal region of A is (0.5,2/3] and (1/3,0.5] for $f=0.5$ and $f=0.8$, respectively. Besides, one can find that, for a fixed value of A, ρ_c varies as f changes. For $A\leq 1/3$ and $A>2/3$, ρ_c increases as f increases and $f=1$ corresponds to the maximum ρ_c (note that individuals cannot move when $f=1$). For $1/3<A\leq 2/3$, there exists an intermediate value of f, leading to the highest cooperation level.

In summary, we have incorporated an aspiration-induced migration mechanism to the evolutionary prisoner's dilemma game. An individual would migrate if its payoff is lower than the aspiration level. We find that, for individuals locating on square lattice and the temptation to defect $b<1.5$, there exists an optimal range of the aspiration level, leading to the maximum cooperation level. We explain such phenomenon by investigating the evolution of cooperator and defector clusters. Moderate aspiration level induces cooperator clusters to expand and defector clusters to disintegrate, thus promoting the diffusion of cooperation among population. We also study the effect of the fraction of occupied sites f on cooperation. Finally we have checked that our conclusions are robust with respect to using different strategy updating rules, such as Fermi updating rule [32,33] and the finite population analog of the replicator dynamics [20].

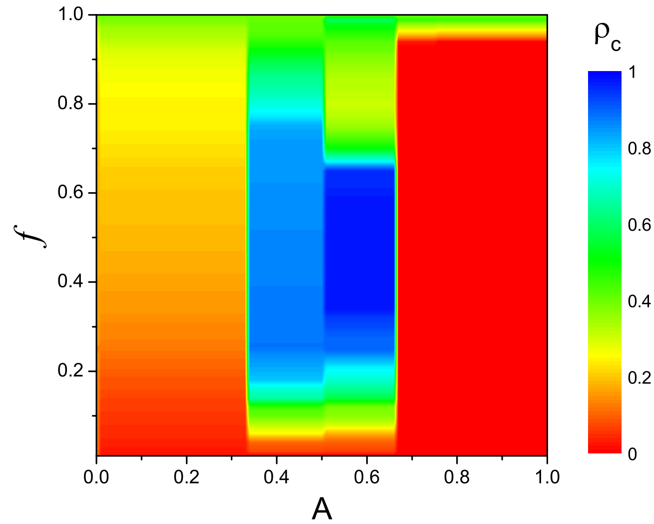

FIG. 4. (Color online) The color code shows the fraction of cooperators ρ_c as a function of the aspiration level A and the fraction of occupied sites f on 100×100 grids. The temptation to defect $b=1.5$. Results are averaged over 100 different realizations.

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