

A Tag-mediated N-person Prisoner's Dilemma Game on Networks with Different Topologies

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Keywords: N-person Prisoner's Dilemma game, tag, parochial cooperation, evolutionary stability, social network

Abstract

In tag-based Prisoner's Dilemma games, agents learn tolerance, copy traits from more successful neighbors, cooperate with in-group alters, and otherwise defect. Current research concludes that cooperation can emerge and be sustained, tolerance decreases, and agents become homogeneous. Such emergent societies are vulnerable to invasion by mutants with the same traits as those of cooperators but who defect. However, one question that has yet to be answered is whether these results can vary from one network structure to another. We investigate tag-based parochial cooperation not only on grid but also on local, small-world, and random network. We find that cooperation can be institutionalized at lower benefit-to-cost ratios than the average degree given tag-based identities, which would not otherwise happen. The average tolerance is positively influenced by the benefit-to-cost ratio, the number of identity dimensions, and heterogeneity. None of societies holds evolutionarily stable parochial cooperation since the selection pressure for homogenization is strong in a small population. Nonetheless, there are distinctive patterns in the emergence of cooperation, its diffusion, and invasion by mutants across societies. We propose future directions discussing how persistent heterogeneity and the dynamics of clustering and bridging are critical for the evolutionary stability of parochial cooperation in more tolerant societies.

1. INTRODUCTION

Recent studies on tag-based Prisoner's Dilemma games contend that tag-based in-group favoritism or ethnocentrism is a necessary condition for cooperation among people with minimal cognitive abilities. [Holland 1995] laid out theoretical underpinnings on 'tagging' which is a pervasive mechanism for aggregation and boundary formation in complex adaptive systems. [Riolo 1997] and [Riolo et al. 2001] did pioneering research on the evolution of parochial cooperation to be followed by [Hales 2004], [Hammond and Axelrod 2006], and [Choi et al. 2006]. Studies on the co-evolution of ethnic markers and altruism in the cultural

transmission process [Nettle and Dunbar 1997; McElreath et al. 2003] are in line with those tag-based models.

It is generally agreed that: when people learn tolerance, copy traits from more successful local alters, and use the discriminating strategy of cooperating with in-group members and defecting out-group members, such a tag-mediated cooperation can emerge; this parochial cooperation can sustain because tolerance decreases rapidly along with increasing homogeneity; given a small amount of mutation, altruistic groups are so vulnerable to invasion by mutants who satisfy two conditions. First, mutants can be regarded as in-group by altruistic groups since mutants have the same or very similar traits with those of altruists. Second, mutants have lower levels of tolerance than those of altruists so that they are more likely to defect others.

Given two major findings in existing studies that the decrease in tolerance, the increase in homogeneity, and the evolutionary instability of parochial cooperation, we examine these dynamics not only on a grid structure but also a regular network, a small-world network, and a random network. The main questions are: (1) there can be any other levels of tolerance and dissimilarity – more tolerant and heterogeneously diverse; and (2) parochial cooperation can be more significantly robust in the presence of cultural perturbation. After discussing key findings and their implications, we suggest two directions of future works focusing on why and how persistent heterogeneity and the dynamics of clustering and bridging matters in the evolutionary stability of parochial cooperation in more tolerant societies.

2. THEORETICAL BACKGROUND

How to explain the frequent occurrence of cooperation among self-interested people and its regularization? Several approaches have been proposed, but it is hard to explain the evolution of cooperation in society with 'genetically unrelated N-person' with the kinship hypothesis [Hamilton 1964] – the probability of cooperation is determined by how much 'genes' we share – or 'direct' reciprocity [Trivers 1971; Axelrod 1984] – if 'dyadic' interactions are repeated enough, strictly saying infinite, retaliation triggers reciprocal altruism. This study owes to two complementary perspectives. Recall that cooperation can evolve if a certain

mechanism makes it possible that altruists are allowed to interact with each other preferentially so that they receive a disproportionate share of the benefits of altruism.

First, assortative local interactions ‘alone’ can facilitate the evolution of cooperation and its sustainment [Nowak and May 1993; Grim et al. 2006]: people play the Prisoner’s Dilemma game with local adjacent neighbors and copy a more successful strategy either locally or globally and; once small cluster(s) of cooperators form and they can benefit from interactions with their own kind while avoiding interactions with defectors, the proportion of cooperation in the population increases. This viscosity effect is impossible to observe under ‘random matching,’ but it cannot be enough when the ratio of benefit to cost in the PD game is not high enough.

The second approaches are interested in different types of ‘cues’ which increases the chance of assortative interactions among people. Repeated interactions are not necessarily needed. The associative co-evolution of cues and cooperation is critical for ‘indirect’ reciprocity to continue. In a broad sense, image scores, communication tokens, or tags can be used as those cues through which people can know who is who. For examples, although people encounter with each other randomly in a one-shot PD game, reputation can facilitate cooperation among N-persons [Nowak and Sigmund 1998], and outbreaks of cooperation can occur through exclusive signaling among cooperators [Miller et al. 2002].

Both reputation-based models and communication-based models are concerned with partner identification, but agents there are required to have high cognitive capacities. Given the shortcomings of those two approaches, how to explain the evolution of cooperation among agents with ‘minimal’ cognitive capacities at ‘relatively low’ benefit-cost ratios, then? Recent studies on tag-mediated parochialism [Riolo 1997; Riolo et al. 2001; Hammond and Axelrod 2006; Choi et al. 2006], which is definitely in line with research on the co-evolution of ethnic markers and altruism in the cultural transmission process [Nettle and Dunbar 1997; McElreath et al. 2003], provide an alternative approach.

Since [Dawkins 1976] proposed the concept of memes – pieces of information in human brain – to understand the evolution of culture, there has been a growing scholarly concern with meme as another replicator in the cultural transmission process. Like the kinship hypothesis that the probability of altruism is proportional to how much genes people share, so the chance of cooperation among two persons depends on how much memes they share. In the term by [Heylighen and Campbell 1995], people form “memetic kin.” Tags are observable markers as the phenotype of memes. People have their own tags, compare the degree of dissimilarity to others to their tolerance levels, and make a distinction between in-group and out-group. In this way, ‘tagging’ is a pervasive mechanism which

facilitates selective interactions through aggregation and boundary formation in complex adaptive systems [Holland 1995].

It should be noted, however, that: tags are unchangeable in [Hammond and Axelrod 2006], but not in [Riolo 1997], [Riolo et al. 2001], and [Choi et al. 2006]. In [Hammond and Axelrod 2006], one of four colors is assigned to agents whereby their group membership is determined. Those ethnic markers can change only through ‘genetic’ mutation. In contrast, traits such as linguistic codes, attitudes, and opinions are changeable in ‘cultural’ transmission. For this reason, evolutionary theorizing of cultural transmission needs to be stimulated by social psychological studies on categorization processes [Tajfel 1974] and social identities [Hoggs 2007]. In this study, sociological concepts such as identities, doing distinction, identity-imitating, and cultural perturbation are preferred to genetic concepts such as traits, tagging, trait-copying, and mutation. For example, the Hamming Distance commonly used in existing research indicates that people count the presence or absence of identities across a certain number of identity dimensions to perceive dissimilarity in such a dichotomized way.

It is generally agreed in existing studies on changeable-tag-based parochial cooperation [Riolo 1997; Riolo et al. 2001; Choi et al. 2006]: people learn tolerance, copy identities from more successful ones, and use the discriminating strategy of cooperating with others if perceived dissimilarity is less than their tolerance levels and defect otherwise. Suffice to say here that people have a conditional strategy, not any preset plans of actions, but this does not mean that people copy strategies of successful others directly. It is rather cultural traits composed of tolerance and arbitrary markers that are diffused in the same generation across the space and transmitted from one generation to another; given which, cooperation could emerge even if the benefit to cost ratio were relatively low; this parochial cooperation can sustain because tolerance decreases rapidly but homogeneity increases; if there is a small amount of mutation, altruistic groups are vulnerable to invasion by mutants with the ‘similar’ traits as those of the majority of altruists but who are more likely to defect. Once mutants have higher payoff and turn out to be more successful than others, people begin to learn their lower tolerance and traits.

[Riolo et al. 2001] inquired whether tag-based parochial cooperation is an ‘evolutionary stable strategy,’ but it was difficult to put its robustness to mutation to ‘strict’ test given ‘random matching’ in their model. In other words, if people interact with each other ‘locally,’ it is expected that both the emergence of parochial cooperation and the drift from a cooperation-dominant society to a defection-dominant society happen ‘more drastically.’ [Choi et al. 2006] implemented local interactions on a large torus to report similar results: parochial cooperation increases up to

‘universal’ cooperation in a ‘completely homogeneous’ society; meanwhile, tolerance ‘always’ converges towards ‘1,’ which indicates that people want to cooperate only if local neighbors have the ‘exactly same’ traits with theirs; and in the presence of a small amount of mutation, the endless cycle occurs between ‘universal’ cooperation and ‘universal’ defection. It seems that that ‘cue-based cooperation’ in general is not evolutionarily stable because of ‘learning the secret handshake’ [Robson 1990] named. In [Miller et al. 2002], for instance, cooperators cannot survive immediately after the emergence of those who use the same token – which was exclusively shared among cooperators once – but defect.

Two major results in sum are: the society has to experience the overall decrease in tolerance and increase in homogeneity when parochial cooperation emerges and prospers; and it cannot continue in the long run given a small amount of mutation. However, none of existing studies take into account how people are connected to each other. Our study asks whether those phenomena are inevitable on fixed networks with different topologies such as regular network, small-world network, and random network. The importance of the dynamics of tag-based cooperation on fixed networks is two-fold. First, ‘network heterogeneity’ can be treated. People on a lattice and a regular network have the equally same number of adjacent neighbors (i.e., homogeneous), but they have different positions and connectivities on a small-world network and a random network. Second, the dynamics between ‘clustering’ (i.e., making new ties to neighbors’ neighbors to form closed triads) and ‘bridging’ (i.e., breaking ties from local neighbors and then making new ties to others in different clusters) is centered on the evolutionary dynamics of cooperation. In other words, the emergence of cooperation, its diffusion, and invasion by mutants are expected to differ across spaces in which both the average clustering coefficient and the average path length vary.

3. THE MODEL

3.1. Setup

(1) 49 persons on a torus (TO) with the Moore Neighborhood, and 50 on a regular network (RG), small-world network (SW), or random network (RD). The regular network has exactly 8 local adjacent neighbors, but the average degree is controlled as 8 in both the small-world network and the random network. Therefore, 0.16 of Erdős-Rényi probability is used to build random networks. Small-world networks are generated from their equivalent regular networks after some amount of rewiring to satisfy one-tailed tests at the alpha level of 0.05 on both the average clustering coefficient (ACC) difference and the average path length (APL) difference between those two networks. Our method is the same with another approach to construct small-world networks within a certain range of the rewiring probability

(rp), regular networks at $rp=0$, and random networks at $rp=1$ (Watts, 1999); and (2) both (0 or 1 in L) for tag list and (0, 1, ..., $L+1$) for tolerance are distributed randomly.

3.2. Go

(1) If L is 0, no dissimilarity perception; otherwise, tagging based on the Hamming distance ($Min=0, Max=L$); (2) local interactions with adjacent alters. If perceived dissimilarity is less than my tolerance level, cooperate; otherwise, defect; (3) payoff calculation based on Table 1 in which if cooperate, pay cost (c) to produce benefit (b), but if defect, take benefit without c . As it well known, two conditions should be met – $T>R>P>S$ and $2R>T+S$. Here, Temptation to defect, Reward for mutual cooperation, Punishment for mutual defection, and Sucker’s payoff; (4) cultural transmission through payoff-biased local learning: Given one neighbor randomly chosen, if her score is higher than mine, I copy both her tag and tolerance. In the presence of cultural mutation, my tag and tolerance to be replaced by a new set of traits randomly; and (5) longitudinal data of the proportion of cooperation, the distribution of tolerance, the Index of Qualitative Variation (IQV) of tolerance, and the distribution of the average perceived dissimilarity.

3.3. Stop

When no cultural mutation is allowed, Go continues until 1000 steps or it can stop in the middle when the society arrives at universal cooperation or universal defection.

Table 1. Payoff matrix in Prisoner’s Dilemma game

	Cooperate	Defect
Cooperate	$(b/c) - 1$ (R)	-1 (S)
Defect	b/c (T)	0 (P)

3.4. Verification and replication issues

First, tags (t) and tolerance levels (T) are assigned randomly to agents from $U [0, 1]$ in [Riolo et al. 2001]. Given two persons A and B, if $|t_A - t_B| \leq T_A$, then A cooperate; otherwise, defect. [Edmonds and Hales 2003] found that [Riolo et al. 2001] would have had a lower level of cooperation if they had used $|t_A - t_B| < T_A$. [Roberts and Sherratt 2002: 500] brought up the same issue whether cooperation or not when A and B have exactly the same tags and T_A is 0. A will cooperate in [Riolo et al. 2001], but not in the setting that $|t_A - t_B| < T_A$. In our model, A will defect in spite of no difference between two tags as long as T_A is 0 (i.e., “Always defect”). In the same way, C will cooperate as long as T_C is $L+1$ (i.e., “Always cooperate”) because the maximum identity difference is L . Second, [Edmonds and Hales 2003] pointed out that the selected bias method in [Riolo et al. 2001] than the no bias method yielded a higher proportion of cooperation. The no bias method (i.e., “higher than” instead of “higher than or equal to”) is implemented in our model.

4. EXPERIMENTAL DESIGN

In a factorial design, the ratio of benefit to cost (b/c) and the length of tag (L) are expressed in columns and rows, respectively (Table 2). 100 repetitions for each group G_{ij} . 2500 cases for each structure, torus, regular network, small-world network, and random network, controlling for no cultural mutation. The total number of cases is 10000.

Table 2. Summary of experimental design

	b/c				
L	2	4	6	8	10
0	G_{11}	G_{12}	G_{13}	G_{14}	G_{15}
1	G_{21}	G_{22}	G_{23}	G_{24}	G_{25}
5	G_{31}	G_{32}	G_{33}	G_{34}	G_{35}
10	G_{41}	G_{42}	G_{43}	G_{44}	G_{45}
20	G_{51}	G_{52}	G_{53}	G_{54}	G_{55}

5. SUMMARY OF FINDINGS

The number at each cell in Table 3 represents how many times cooperation in the absence of mutation survives out of 100 trials on a torus, regular network, small-world network, and random network from the left to the right. For examples, when $L=1$ and $b/c=4$, the chance of institutionalized cooperation is 3% on a torus, 6% on a regular network, 0% on a small-world network, and 2% on a random network. The effect of local interaction without tagging at $L=0$ is not enough for the evolution of cooperation and its sustainment when the b/c ratio is less than 8 in all four types of social structures. This result is consistent with the rule that cooperation survives if the ratio of benefit to cost (b/c) exceeds the average number of neighbors (k) regardless of whether it is a cycle, lattice, random graph, or scale-free network [Ohtsuki et al. 2006].

However, tag-based local interaction (i.e., tagging effect + local interaction effect) increases the emergence of cooperation and its survival. When people have a single identity item (i.e., $L=1$), cooperation can be institutionalized even at lower benefit-to-cost ratios than the average number of local adjacent neighbors. Overall, the possibility of the institutionalization of cooperation is highest on a regular network; the second highest on a torus; the third highest on a small-world network; and the lowest on a random network. This is congruous with the ranking of the average degree of

clustering. However, when the number of identity dimensions is large enough, parochial cooperation can emerge and maintain with no significant differences among four types of societies.

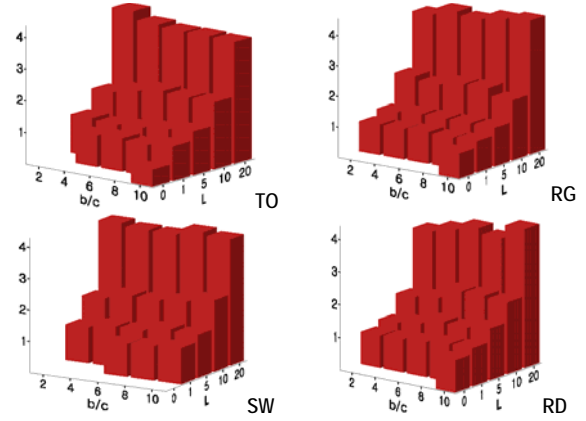


Figure 1. Means of final tolerance

The modes of final tolerance are not shown here, but tolerance dramatically decreases to the level of 1 over time when $L=1$ and $L=5$ in all four societies. This implies that people want to cooperate with others only if they have the exactly same identities. When people are able to make a finer distinction between ‘us’ and ‘them’ with a much larger number of identity dimensions (e.g., $L=10$ or 20), there will be societies with higher levels of tolerance as is shown in Figure 1 about the means of final tolerance in the cases where the proportion of cooperation is not zero. The maximum tolerance is 2 in all four societies at $L=10$, but 6(TO), 6(RG), 6(SW), and 5(RD) at $L=20$. There are no big differences in the average final tolerance across societies with different social structures. The level of tolerance decreases as either the number of closed triads or the average path length increases. However, none of these effects is statistically significant as is presented in Table 4 about the results of robust regression on the average final tolerance given the same cases above. It is rather that the tolerance level is positively influenced by the benefit-cost ratio, the number of identity dimensions, and the degree of heterogeneity measured by the average Hamming Distance in societies.

Table 3. The possibility of institutionalized cooperation

L	b/c				
	2	4	6	8	10
0	0/0/0/0	0/0/0/0	0/0/0/0	0/0/0/0	1/4/0/4
1	0/1/0/1	3/6/0/2	3/8/7/10	8/4/7/9	13/59/14/21
5	94/100/98/92	98/96/91/91	95/97/90/88	96/99/86/92	94/100/89/85
10	100/100/100/100	97/100/99/98	100/100/100/96	100/99/98/99	99/99/96/97
20	100/100/100/100	100/100/100/100	99/100/100/99	99/100/100/99	100/100/100/100

Table 4. Robust regression on final tolerance

Variable	b	SE
b/c=4 (dummy)	.0962**	.0471
b/c=6 (dummy)	.1101**	.0471
b/c=8 (dummy)	.1235***	.0470
b/c=10 (dummy)	.1411***	.0469
L=1 (dummy)	.2095	.3922
L=5 (dummy)	.3957	.3844
L=10 (dummy)	1.0675***	.3844
L=20 (dummy)	2.7510***	.3843
Heterogeneity	1.5266***	.0428
Reverse Ranking in ACC	-.007870	.0222
Reverse Ranking in APL	.006446	.0222
Intercept	.7360	
Probability > F	0.0000	
N	6029	

Parochial cooperation cannot sustain, for example, in the presence of 1% mutation while controlling for $b/c=4.0$ and $L=5$. Once mutants who happen to have the same identities with those of cooperators but defect they are able to earn higher payoffs, the cultural drift from universal cooperation to universal defection can happen rapidly. Figure 2 shows this evolutionary instability of parochial cooperation on the lattice. The degree of color darkness on the lattice is proportional to the number of cooperation with local neighbors. For instances, the darkest represents its maximum (i.e., 8) and the brightest its minimum (i.e., 0). It is expected that the endless cycle between two attractors – universal cooperation and universal defection – will continue.

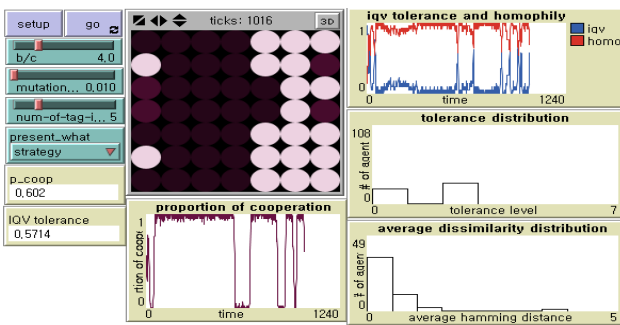


Figure 2. Invasion by mutants on torus

It holds true for three other societies with different network topologies that parochial cooperation cannot be an evolutionary stable strategy. However, its dynamics are quite different from one structure to another depending on both the average local clustering and the average path length (Figure 3 through Figure 5). Recall that the average clustering coefficient is highest in regular network, second-highest in torus, third-highest in small-world network, and

lowest in random network, while the average path is longest in regular network, second-longest in torus, third-longest in random network, and shortest in small-world network. In the examples in Figure 2 through Figure 5, the average clustering coefficients and the average path lengths are: .429 and .333 (TO); .643 and 3.571 (RG); .202 and 2.075 (SW); and .097 and 2.133 (RD). Given three distinctive phases – the emergence of cooperation, its diffusion, and invasion by mutants, higher clustering on average is a plus factor for the formation of altruistic clusters. The shorter average distance, the faster the prolongation of cooperation once it emerges. For example, although parochial cooperation emerges more quickly it takes much longer for localized cooperation to expand to other regions on the regular network in Figure 3. Indeed, the first time of reaching universal cooperation in that regular network is 40 generations, in contrast to 32 on torus (Figure 2), 12 on small-world network (Figure 4), and 14 on random networks (Figure 5). As [Cassar 2007] and [Hanaki et al. 2007] pointed out, the shorter the average distance, the more vulnerable to invasion by defectors, however. This is why intolerant mutants are able to replace existing altruists to spread out more easily on the small-world network (Figure 4) than on the random network (Figure 3) and the random network (Figure 5). The change from universal cooperation to universal defection is sharpest on the small-world network and smoothest on the regular network.

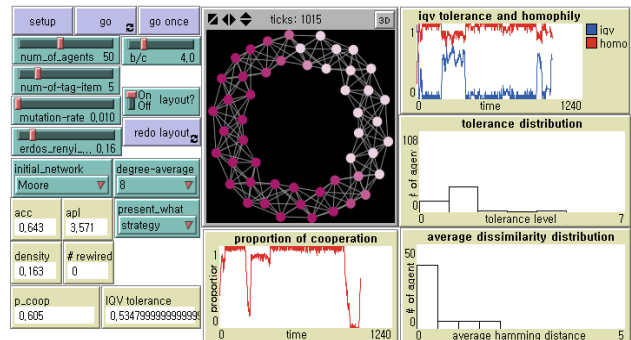


Figure 3. Invasion by mutants on regular network

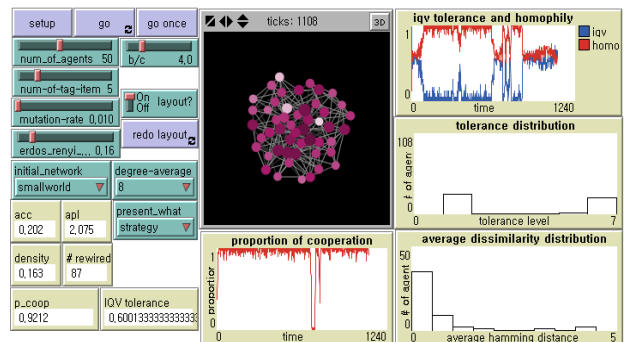


Figure 4. Invasion by mutants on small-world network

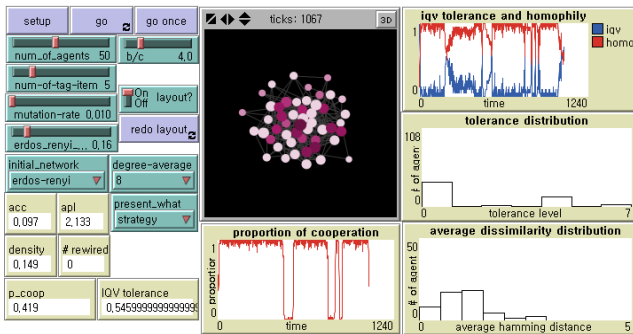


Figure 5. Invasion by mutants on random network

6. DISCUSSION AND CONCLUSIONS

In our study, people have more difficulty keep doing distinction under strong selection pressure for homogenization to become more intolerant. Finally, all altruists in a highly homogeneous society mistakenly accept mutants as in-group members as long as mutants have identical identities. This is why ‘persistent heterogeneity’ is critical to not only preventing tolerance from falling into decline, but also increasing the robustness of parochial cooperation. We find that societies can retain tolerance levels higher than 1 as the benefit-to-cost ratio, the number of identity dimensions, and heterogeneity increases. However, tag-based cooperation is not evolutionarily stable in any of four types of societies because network heterogeneity itself does not lead to the overall increase in heterogeneous diversity. We can consider some sources of persistent heterogeneity in society. First, the increase in the level of mutation brings about the increase in the level of heterogeneity as is in Figure 6 through 8 where the mutation rate is 0.05, 0.10, and 0.20, respectively, controlling for $b/c=4$ and $L=5$, but too much arbitrary noise is a meaningless pursuit in the sense that it destroys cultural transmission.

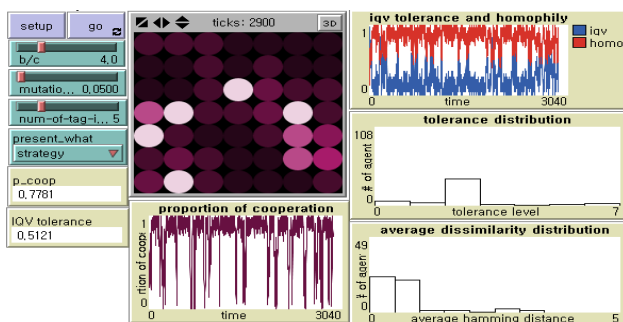


Figure 6. Effect of 5% mutation on cultural drift

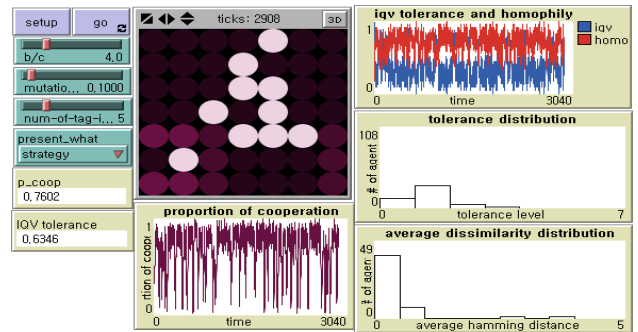


Figure 7. Effect of 10% mutation on cultural drift

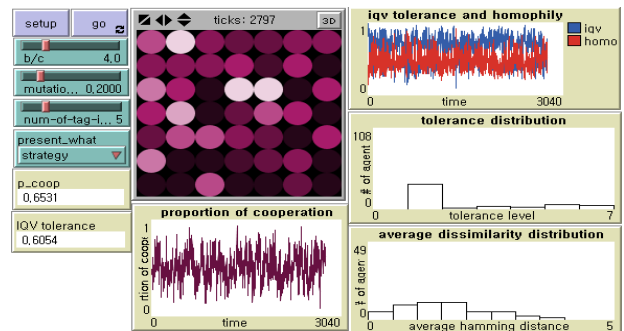


Figure 8. Effect of 20% mutation on cultural drift

We find one big assumption in [Riolo et al. 2001] and [Choi et al. 2006] that traits are so easily changeable that mutants experience no difficulties in having the same traits which were once exclusively shared among cooperators. As is mentioned earlier, “learning the secret handshake [Robson 1990]” is a common issue in models of cue-based cooperation, generally saying. Therefore, it is expected that if people have to pay a portion of their material payoffs and cooperators use costly signals which are not affordable to mutant defectors, the chance of invasion by them will decrease. However, as [Skyrms 2004: 80] pointed out, “what we need to stabilize cooperation are signals with differential costs for differential response types” because “unconditional defectors who pay the same price to send the costly signal do better than the cooperators who send it.”

Second, tag-based cooperation is expected to be more evolutionarily robust in the ‘larger’ society along with a higher level of tolerance because homogenization becomes relatively slower than heterogenization through mutation as N increases in Figure 9 through Figure 11 where the number of agents is 225, 441, and 961, respectively, holding the mutation rate=1%, $b/c=4.0$, and $L=5$. This is consistent with the point made by [Centola et al. 2007] that the cultural drift does not matter as far as the population size is large enough although their models are not about tag-based cooperation.

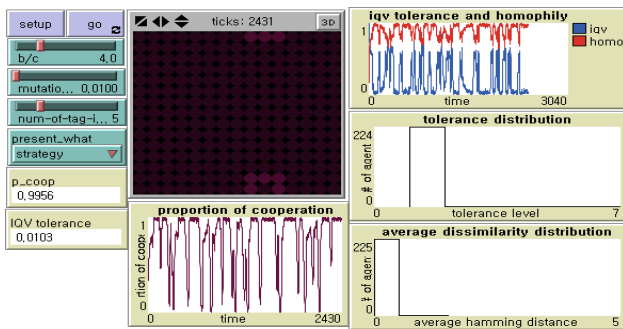


Figure 9. Population size effect on cultural drift (N=225)

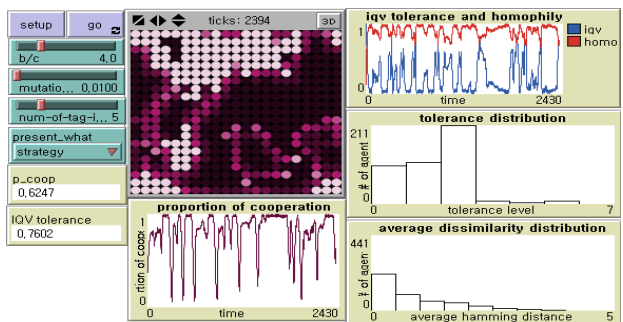


Figure 10. Population size effect on cultural drift (N=441)

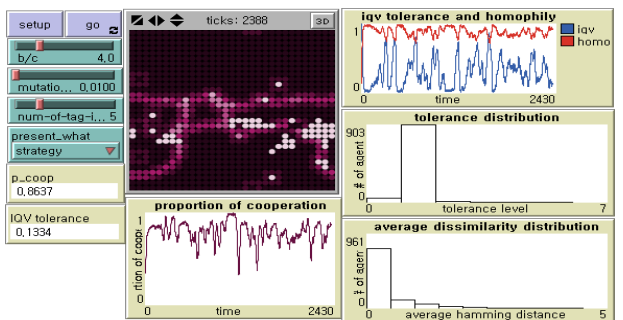


Figure 11. Population size effect on cultural drift (N=961)

It leads to one qualification that it is the evolutionary instability of parochial cooperation in a ‘small’ group that has yet to be solved, but our study indicates the dynamics of tag-based cooperation are significantly different from one network structure to another, given the same small size of population. For this reason, the link between group size and the robustness of parochial cooperation may be spurious: the average path length rather than the size of population matters. We still need to investigate the ‘interplay’ between the dynamics of local reinforcement of homogeneity and global expansion to heterogeneity and tag-based influence and selection. The question here is whether tag-based cooperation can be more stable in any other emergent network structure, for example, with tolerant people at a highly clustered core surrounded by intolerant people at a periphery.

Acknowledgement

I thank Robert A. Hanneman, Peter J. Burke, Jeong-Kyu Choi, and two anonymous reviewers for valuable comments.

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