

Effects of spatial distribution and information transmission over cooperation dynamics

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Abstract. An Agent Based Model was used to explore the effects of spatial distribution and horizontal information transmission over cooperation when groups provide protection against predation. This exploration was done by observing three probabilities for the effectivity of information diffusion of the majority's opinion.

Our results show that spatial structures affect the cooperation dynamics under horizontal information transmission and in some structures, particularly Small World Networks, cooperation is more sensible to information transmission.

1 Introduction

Biologists, economists, computer scientists and physicists have all worked to further our understanding of human and animal cooperation. Yet different premises underlay these efforts. The main difference among them is the assumption that social behavior arrived through biological evolution among animals, and that culture and rational decision making is a principal driver of the evolution of cooperation and sociality among humans [16]. Human cooperation seems to be molded by both, cultural and biological forces [9].

There exist important differences between the dynamics of cultural evolution [3],[16] and biological evolution [13]. Although both processes are often mixed up and lumped together when studying the evolution of cooperation, as done in [14].

One important feature differentiating systems driven by biological (BE) and cultural evolution (CE) is the direction of information's transmission. The transmission of information in BE is vertical (heredity), and that in CE is horizontal (imitation of behavior). This feature affects the pattern and the speed of information transmission, and is sufficient to explain important differences in the dynamics between both types of evolution [8].

Several mechanisms have been proposed to explain the emergence and maintenance of cooperation in biological terms. Hamilton [5] explains cooperation between relatives through "kin selection"; in which donor and recipient of a cooperative action are genetic relatives. Between the mechanism that have been

proposed to explain cooperation between unrelated individuals we have: Direct reciprocity [17], indirect reciprocity [12].

The study of the effects of spatiality over cooperation was introduced by Nowak and May [11]. They showed how cooperation could emerge in a population of strategies without memory when individual's relations conform a spatial structure. After Nowak and May's work, cooperation by individuals occupying spatial positions in lattices or networks that interact with their neighbors have been studied for the prisoner dilemma by several authors [7],[15]. They showed that structured populations help cooperation to evolve and maintain under certain conditions.

In this work we want to explore the effects of spatiality and the intensity of the horizontal information transmission over cooperation dynamics. To do so, we modify a one-dimensional spatial model [2] to study the differences between the dynamics of cooperative, group-forming individuals subject to a selective pressure (in this case predation). We based our model on the well known "selfish herd" concept [6] and assume that cultural and biological dynamics are driven by natural selection of the phenotypes.

2 The Model

We construct an agent-based model for the study of cooperation dynamics based on Hamilton's "selfish herd" [6]. The model simulates a population of interacting individuals with different social roles and different information transmission directions in environments with different spatial structure. This model was initially proposed by Cipriani and Jaffe [2] using a cellular automata. In this formulation, the "selfish herd" is implemented by means of the importance of group formation. In particular, group formation provides protection against predation.

Spatial structures (that represent spatial relations or contact between individuals) are modeled using undirected graphs. The vertexes of these graphs can be occupied by individuals of any species or be empty. The neighbors of an individual in the graph form the group of this individual. These graphs are initially empty and are created at the beginning of the simulations as shown in Algorithm 1. The structure of the graph remains fixed throughout the simulation execution.

Algorithm 1 Main simulation cycle

```
1: createWorld(worldSize)
2: populateWorld()
3: for  $t = 0$  to numIterations do
4:   for each agent do
5:     agentStep()
6:   end for
7:   reapDeadAgents()
8:   repopulateWorld()
9: end for
```

The majority rule is implemented here to simulate the horizontal information transmission (H). It assumes that individuals had a given probability pT of imitating the behavior of their neighbors. Each agent executes this rule each time step, this is done by the *agentStep* algorithm, Algorithm 2. In this scenario repopulation (3) is done using the initial proportion of each individual's kind.

Algorithm 2 agentStep

```

1: neigh ← getMyNeighbours()
2: nNeighCoops ← countCooperators(neigh)
3: dead ← predate(nNeighCoops)
4: if not dead then
5:   naturalMortality()
6: end if
7: if not dead and CT then
8:   applyMajorityRule()
9: end if

```

Algorithm 3 World Repopulate

```

1:  $p_{co}$  ← initial proportion of cooperators
2:  $p_{nCo}$  ← initial proportion of non cooperators
3: for each empty node do
4:   create a new agent on node, cooperator with probability  $p_{co}$  or non cooperator
   with probability  $p_{nCo}$ 
5: end for

```

3 Experiments

We made the implementation of the proposed model in C++. This implementation allows structured environment for populations, in the form of one-dimensional and two-dimensional torus grids. Simulations were done over populations of 10^4 individuals during 10^2 iterations.

At the beginning of simulations the graphs' vertexes were populated by cooperators and non-cooperator, using a probability of 0.5 for each. For non-cooperators and alone cooperators the rates for predation were $pNCo = 0.8$ and $pCo0n = 0.8$. For cooperators in groups the predation rate was $pGCo = 0.2$. The mortality rate, used modeling the cost of cooperation was 0 for non-cooperators and variable (into each experiment series) for cooperators. For all simulations the "fitness differential" was 0.6. The "Fitness differential" is the difference between the predation rate of isolated individuals and that for cooperators being part of a group of cooperators.

For each one of the spatial structures studied (one-dimensional grids, two-dimensional grids, Random Graphs[4], Small-World Networks[18] and Scale Free Networks[1]) we considered three scenarios ($pT \in \{0, 0.5, 1\}$).

In all scenarios production of new agents for was uniform (50/50), and the rate pT determined the probability an agent would imitate the behavior (cooperate or not) of the majority of its neighbors.

Our experiments consisted in 3 series of simulations, corresponding to the described scenarios, over a specific spatial structure. In each series (21 simulations) we varied the cost of cooperation (mortality rate of cooperators) in steps of 0.05, to cover the interval between 0 and 1. Each experiment was run 20 times to get the average of data.

For each network we set its parameters to get the same mean degree. We choose mean degree 4 in order to make a “fair” comparison between networks and with 2-D grids.

Each network structure possess a set of statistical properties that allow explain their behavior. Even though significant properties are still been developed, the most studied are: the mean geodesic path, the clustering coefficient, the degree distribution, the network resilience, the mixing patterns, the degree correlations and the community structure[10].

In table 1 we present the values of some of these properties for studied networks. Degree related values were taken from our networks, while the average path length for complex networks was calculated using equations form [10]. We also checked that degree distributions corresponds to theoretical predictions.

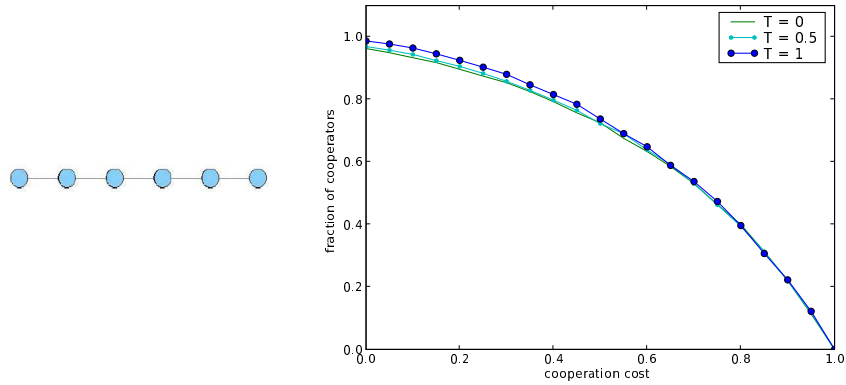
Graph	Parameters	mean degree	degree' SD	average path length
1D Grid	G(10000)	2	0	2499
2D Grid	G(10000)	4	0	50
Random Graph	G(10000,2)	3.99	1.99	6.64
Small World Graph	G(10000,2,0.01)	4	0	1250
Scale Free Network	G(10000, 4)	3.99	6.88	30615

Table 1: Grids and network properties' values.

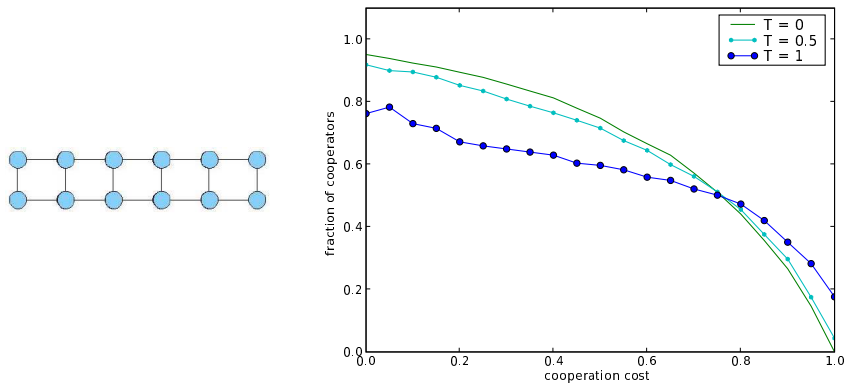
4 Results

The results of our experiments are shown in figure 1, where each sub-figure summarizes the results from simulations of a particular spatial structure: 1-Dimensional Grid (Fig. 1a), Two-Dimensional Grid (Fig. 1b), Random Graphs (Fig. 1c), Small World Networks (Fig. 1d) and Scale Free Networks (figure 1e). These figures show the final proportion of cooperators for each scenario under various cooperation cost. In all the spatial structures and all the scenarios the proportion of cooperators decreases monotonically as cooperation costs (cc)

increment. Also, cooperators are the majority of the population in most circumstances.



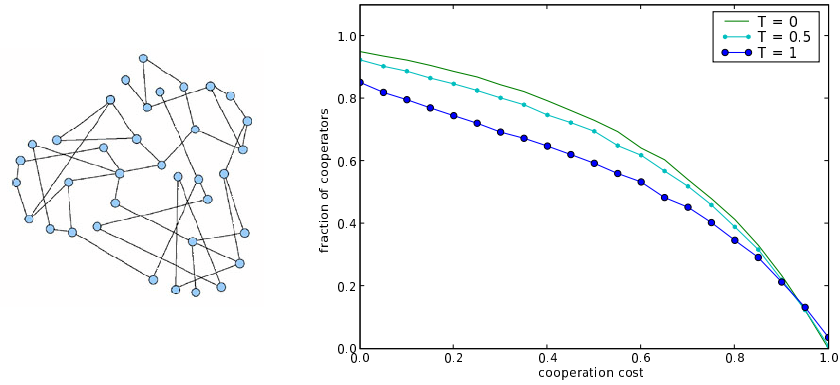
(a) Grid 1D



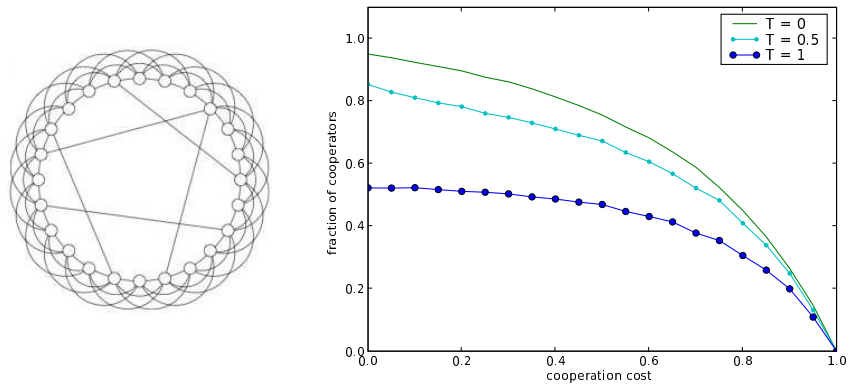
(b) Grid 2D

Fig. 1: Final fraction of cooperators in simulations with different costs for cooperation (x axis) and with different kinds of horizontal transmission of information (pT). On the left side of each subfigure we present a graphical representation of the subjacent spatial structure.

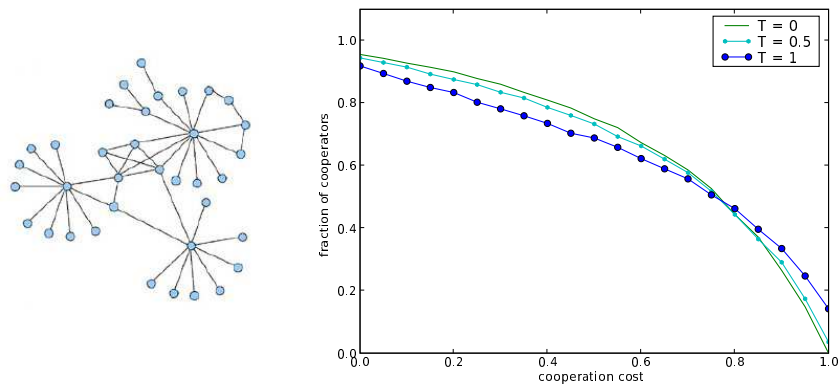
In one-dimensional grids (Fig. 1a) there is no difference in the proportion of cooperators between different pT values.



(c) Random Graph. Erdős-Rényi Model ($G(10000, 0.0002)$); parameters: $size = 10000$, $edge_probability = 0.0002$.



(d) Small World Graph. Newman-Watts model ($G(10000, 2, 0.01)$); parameters: $size = 10000$, $connections_by_direction = 2$, $rewiring_probability = 0.01$.



(e) Scale Free Networks. Barabasi-Albert model ($G(10000,2)$); parameters: $size = 10000$, $m = 2$.

Fig. 1: Final fraction of cooperators in simulations with different costs for cooperation (x axis) and with different kinds of horizontal transmission of information (pT). On the left side of each subfigure we present a graphical representation of the subjacent spatial structure.

For two-dimensional grids (Fig. 1a) curves with different pT differed. From $cc = 0$ to $cc = 0.8$, with $pT = 1$ the proportion of cooperators decreases. For values larger than $cc = 0.75$ this trend reverses.

In Random Graphs (Fig. 1c) curves for $pT = 0.5$ and $pT = 0$ have the same shape that $pT = 0$, but there is a difference of at most 15% between $pT = 0$ and $pT = 1$, being $pT = 1$ below $pT = 0$. The $pT = 0.5$ curve have separation from the $pT = 0$ curve is less than a 3%.

For Small World Graphs (Fig. 1d) all curves also have the same shape, but $pT = 1$ is up to 50% below the $pT = 0$ curve; and the $pT = 0.5$ curve up to 15% below the $pT = 0$ curve. This network shows the biggest differences between the different information transmission rates.

The Scale Free Networks curves follow the same shapes than the 2-D grids, with smaller differences between pT 's values.

Is interesting to note that when $pT = 0$, the curves show no differences between all the spatial structures studied.

5 Discussion

The first feature that strikes us is that horizontal transmission of information has a negative effect on the amount of cooperators that survive the evolutionary dynamics unless the cost for cooperation are very high. This result is due to the fact that the cooperative strategy is more susceptible to invasion by the opposite strategy than the non-cooperative one. A lack of communication or horizontal transmission of information favors groups of cooperators, benefiting from each others neighborhood, who are then less likely to be disrupted by non-cooperators

The results show that some spatial networks but not all affect the effect of information transmission on cooperation dynamics. The largest effect was seen in Small World Graphs which happen to be the networks with the lowest variance in the degree of connectivity of the nodes. The effect on the evolutionary dynamics of Random Graphs and Scale Free Networks was similar. This result makes us wonder what characteristic of Small World Graph produces this difference. As with the result discussed above, a more homogeneous network makes it less likely that isolated groups of cooperators benefit from each other neighborhood. Thus the low variance in connectivity of Small World Graphs makes them less prone to nurture groups of cooperators.

These results obtained confirm that the spatial structure affects the cooperation dynamics under horizontal information transmission.

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