Small-world property promotes the evolution of distributive altruism

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Introduction The question of how altruism evolves despite selfish behaviors benefitting agents has for many years been the central theme in the fields such as biology, ecology, sociology, economy and psychology. Several mechanisms promoting the evolution of cooperation have been proposed and can be broadly classified into two categories: direct fitness benefits or indirect fitness benefits (West, 2011). The former covers mutually beneficial cooperation, profiting both the actor and the recipient of the behavior (hence not truly altruistic). Altruistic cooperation is explained by the latter: by helping a close relative reproduce, an individual is still passing copies of its genes on to the next generation, albeit indirectly. Two mechanisms allow related individuals to interact: kin discrimination and limited dispersal.

The prisoner's dilemma game has been commonly used in computational studies on the emergence of altruism. Over the past two decades, many researchers investigated its behavior on networks. The two main properties of the network structure were found to favor survival of cooperators. The first one is clustering coefficient. The success of cooperative behavior is maintained by local interactions within a spatial structure, because cooperators can survive and grow only if they form clusters (Nowak and May, 1992). However, an inverse relationship between the formation of clusters and the success of cooperation has also been reported (Hauert and Szabo, 2005). The second network property is degree heterogeneity. Cooperation has been shown to emerge around the largest hub (Pacheco and Santos, 2005).

While it seems that the riddle of cooperation has been largely elucidated as above, recent empirical research brings a more refined view of cooperation as not just a single, homogeneous trait but several different traits with different costs, benefits and contexts. Warneken and Tomasello (2009) investigated three types of altruism by comparing behaviors of children and chimpanzees. The three types were: helping (when agents help others achieve their goals), sharing (when agents share valuable goods such as food with others) and informing (when agents share with others things the others need or want to know). They found that although chimpanzees help others instrumentally, they are less likely to share resources at their own expense. Also, they do not share information helpful to others. However, both infants and young children were observed to be helpful, generous, and informative. Thus, the authors suggest that sharing and informing are types of altruism specific to humans.

Based on the above, we have proposed the **distribution dilemma game** (DDG) (Ueno and Arita, 2015) that aims to model the altruism in the distribution of resources (material goods or information), but can also capture the emergent properties of resources. Specifically, DDG can describe both how the total value of a resource is changed when it is distributed among agents and how the value is changed synergistically when an agent owns different kinds of resources. Our preliminary study investigated the behavior of an evolutionary model with DDG on a one-dimensional torus and observed the emergence of altruism in certain scenarios. In this paper, we extend the study by investigating the effects of more realistic interaction networks on the emergence of altruism. Specifically, we focus on the behavior of DDG on small-world network topology.

The model Agents are on a network, which is generated using the Watts-Strogatz model. DGG is composed of a repetition of a resource distribution step and a strategy imitation step. In the distribution step, each agent distributes a unit of its unique kind of resource equally among its neighbors and itself. Each agent has its strategy represented by an integer value *S*: the number of nearest neighbors to whom it distributes resource (0 means the agent is selfish). The initial values are randomly set 0 or 1. If *S* is larger than the number of direct neighbors, recipients are selected from the neighbors of neighbors (and further if necessary).

In the imitation step, it will take over the strategy (*S*) of the neighbor who obtained the highest gain in the last distribution step. Mutation changes each *S* by 1 or -1 with a probability of 0.01 during imitation.

The gain of an agent (G_i), i.e. the resultant value of resource each agent owns at the end of a round is calculated using the following equations, with *D* and *K* being model parameters. *D* and *K* express the extent to which the overall value of one's resources is affected by the act of resource distribution.

$$G_i = \left(\sum\nolimits_j F_{ij}\right) * (1 + K * V_i) \ , \tag{1}$$

$$F_{ij} = \left(\frac{1}{1+S}\right)^{D} \ , \tag{2}$$

$$V_i = -\sum\nolimits_{j=1}^{n} P(q_{ij}) \log_2 P(q_{ij}) \ , \tag{3}$$

$$q_{ij} = \frac{F_{ij}}{\sum F_{ij}} \ . \tag{4}$$

Distributing property *D* (see Eq. 2) determines the type of resources being shared. $D = 0$ expresses that the resource is purely informational (each receiver obtains the entire copy),

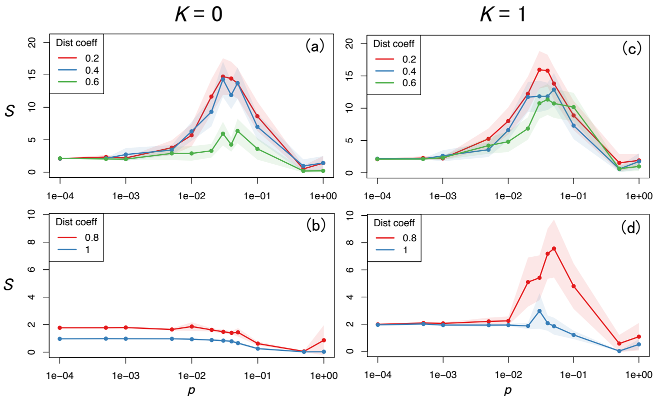

Figure 1: The average number of recipients to whom agents distribute resources (corresponding to their degree of altruism) as a function of W-S network rewiring probability p and for different values of the distributing property coefficient D. The left (a, b) and right (c, d) graphs show the cases with $K = 0$ and $K = 1$, respectively. The upper (a, c) and lower (b, d) graphs show the cases with $D = 0.2$, 0.4, 0.6, and with $D = 0.8$, 1.0, respectively.

whereas $D = 1$ expresses the resource is purely physical (each receiver obtains an equally divided). Furthermore, considering that the resource value can be changed not only by distribution cost but also depending on the number of the people who will share the resource in general, we treat various types of resources in the unified fashion by assuming D is a real number.

Gathering property K allows us to model the synergistic effect of owing different goods by using the idea of entropy. For example, a certain set of knowledge combined together may lead to the creation of a new idea. For values of K larger than 0, the gain coming from received goods is increased beyond the value of its sum.

Results We investigated the behavior of the system by varying the distributing property of resource D between 0 (information) and 1 (material goods) and the gathering property K being either 0 or 1, where $K = 1$ corresponds to a maximum synergistic effect of gathering different resources. The network has $N = 65$ as the population size, an initial node degree 4 and a rewiring probability p ($p = 0$ is the regular network and $p = 1$ is random network). Each game lasted 100000 generations and was replayed 100 times using a different random seed.

For $K = 0$ and resources close to material goods ($D = 0.8$, 1) only a very limited propensity to share emerged only with low values of p ($p < 0.1$, Fig. 1b), in other words, with high spatial locality. For resources having a property closer to the information side ($D = 0.6$, 0.4, 0.2), the most altruistic agents emerged for intermediate values of p. Interestingly, we found that this range of p values corresponds to the networks having the highest small-world-ness coefficient (cf. Fig. 2a), measured using the method of Humphries and Gurney (2008).

In the scenario with synergistic resource effects (gathering property coefficient $K = 1$), the results for resources having a property closer to the information side were similar (Fig. 1c). The agents, however, became on average even more altruistic. The situation was very different for resource closer to material goods. The truly altruistic agents now also emerged in networks having the highest small-world-ness coefficient (Fig. 1d).

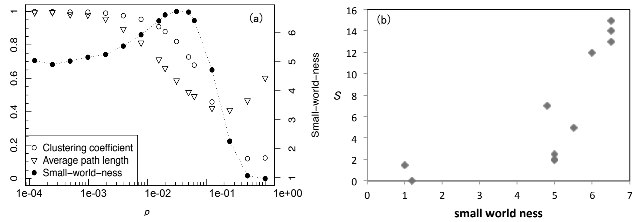

Figure 2: (a) Small-world-ness coefficient as a function of rewiring probability p in the Watts-Strogatz model. Also shown: clustering coefficient and average path-length normalized by their values for regular lattice ($p = 0$). (b) A correlation of S and small-world-ness of $K = 0$, $D = 0.2$.

We suspect that the small levels of altruism emerging in the scenario shown in Fig. 1b can be explained by the mechanism of spatial locality: on regulator networks, close cooperators survive by benefitting each other (cooperative clustering). In the small world networks, however, we think altruism emerges owing to the degree heterogeneity (Pacheco and Santos, 2005). More precisely, the agent at the center of a hub has a high number of partners for interactions, therefore, it can get higher gain than the agent with the lower number of neighbors (assortative interactions). This causes agents around hubs to imitate altruistic strategy of the hub's central node, and potentially spreading the strategy further.

Conclusion The correlation between small-world-ness and emergence of altruistic behavior observed in the DDG model, suggests that small-world networks may be essential for the emergence of altruism. Furthermore, we found that the gathering property of resource further strengthens the propensity of agents to behave in an altruistic way, which would otherwise not happen for resources that resemble material goods. We believe that DDG model sheds new light on the importance of social network structure for the emergence of cooperation as well as the powerful effect of synergistic resource effects.

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