THE ROLE OF THE NAMING GAME IN SOCIAL STRUCTURE

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This paper presents a simulation study to explore the role of the naming game in social structure, which is nearly neglected by contemporary studies from statistical physics that mainly discuss the dynamics of language games in predefined mean-field or complex networks. Our foci include the dynamics of the naming game under a simple distance restriction, and the origin and evolution of primitive social clusters as well as their languages under this restriction. This study extends the current work on the role of social structure in language games, and provides better understanding on the self-organizing process of lexical conventionalization during cultural transmission.

1. Introduction

The origin and evolution of language or general communication systems is a fascinating topic in the interdisciplinary scientific community. A number of approaches from biology, statistical physics, and computer science have been proposed to comprehend some specific aspects in this topic (Oller & Griebel, 2000), among which the self-organizing emergence of a shared lexicon during cultural transmission has been extensively studied based on various forms of *language game* (Steels, 2001) models in the past few years.

The naming game is one form of language games that simulates the emergence of a collective agreement on a shared mapping between words and meanings in a population of agents with pairwise local interactions (Steels, 2001). A minimal version of it (Baronchelli and Loreto, 2006) studies the main features of semiotic dynamics. In this version, N homogeneous agents are describing a single object by inventing words during pairwise interactions. Each agent has an inventory (memory) that is initially empty and can store an unlimited number of words. In a pairwise interaction, two agents are randomly chosen, one as “speaker” and the other as “hearer”. The speaker utters a word to the hearer. If its inventory is empty, the speaker randomly invents a word; otherwise, it randomly utters one of the available words in its inventory. If the hearer has the same uttered word in its inventory, the game is successful, and both agents delete all their words but the uttered one. If the hearer does not have the uttered word, the game is a failure, and the hearer adds (learns) the uttered word to its inventory. In a mean-field system, the dynamics of the naming game can be traced by $N_w(t)$, the total number of words in the population; $N_d(t)$, the number of different words; and $S(t)$, the average successful rate of interactions among all pairs of agents. Statistical physicists (e.g., Baronchelli & Loreto, 2006; Dall'Asta et al., 2006) have further explored the dynamics of the naming game in structures such as 1D/2D lattices, small-world and scale-free networks.

Although these studies extensively discussed the role of social structures in convergence of shared lexicon, most of them neglected the reverse role of the naming game in social structure; in these studies, a successful or failed naming game only affects individual's linguistic knowledge, but has nothing to do with the predefined social structures. In a cultural environment, successful or failed interactions among individuals can not only adjust their knowledge, attitudes or opinions, but also affect their social connections or political status in the community. Factors that operate on a local scale, such as interaction procedures and geographical or social distance restriction, can adjust the possibilities of interactions among agents, thus affecting individual or group similarities on a global scale (Axelrod, 1997; Nettle, 1999). These simple factors may take place much earlier than the emergence of complex social structures, and cast their influences on formation of primitive social clusters and their communal languages. For instance, during language origin, a successful naming game towards a common object in their environment may form a social binding among the participants of this game, and share a common lexicon among them. These factors may take similar effect in modern societies during language change. For instance, a successful or failed naming game towards a salient concept may form a new binding or destroy an old one among the participants, and adjust their communal languages. Moreover, in order to establish a complex social network in a huge population in which not every two individuals could ever directly interact with, a certain degree of mutual understanding is necessary, and simple language games may play a role in achieving such mutual understanding through local interactions. Therefore, besides its dynamics in some predefined complex networks, the dynamics of the naming game under simpler constraints and its role in social structure are worth exploring as well.

In this paper, we present a preliminary study in this respect. Instead of detailed constraints determined by complex networks, we simulate a simple distance constraint, and discuss its influence on formation of social clusters and their communal languages. The simulation traces the coevolution of language and social structure based on the naming game, and the formation of mutual understanding in a population via local interactions among its members, both of which will help us better understand the self-organizing process of lexical conventionalization based on the naming game.

The rest of the paper is organized as follows: Section 2 introduces the simple distance restriction; Section 3 discusses the simulation results of two experiments; and finally, Section 4 provides the conclusions and future work.

2. The Naming Game with a Distance Constraint

The interaction scenario of our naming game is identical to its minimal version described in Section 1. To introduce distance restrictions, we situate all agents in a 2D square torus (X^2, X is the side length of the torus), and each agent can randomly move around to its 8 unoccupied, nearby locations, as shown in Fig. 1. This torus represents either a physical world, or an abstract world, such as the distributions of opinions or social status.

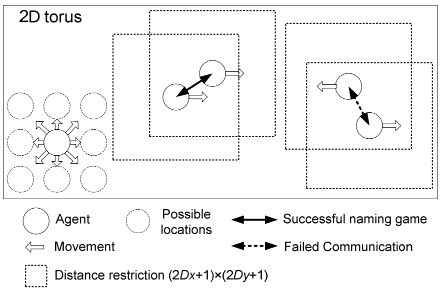


Figure 1. A 2D torus with moving agents.

The distance restriction, inspired from our previous study (Gong et al. 2005) and applied on agent selection during pairwise interactions, is defined as follows:

The distance restriction: interactions only take place between agents whose coordinates are within a limited block distance (D_x and D_y), as shown in Eq. (1), where x_i, y_i are agent i's coordinates in X^2, the second part of each condition calculates the situation where agents are located in boundaries but their block distance may still be within D_x and D_y since they are in a torus:

$$|x_i - x_j| \le D_x \text{ or } |x_i - x_j - 0.5X| \le D_x \text{ ; } |y_i - y_j| \le D_y \text{ or } |y_i - y_j - 0.5X| \le D_y \quad (1)$$

This concept of distance can either represent geographical distance such as the city-county distance, or social distance such as the dissident opinions. Under this distance restriction, each agent in the torus can interact with at most $(2D_x+1)\times(2D_y+1)-1$(itself) nearby agents. When D_x and D_y equal 1, each agent only interacts with those lying in its 8 nearby locations. This restriction provides a *binding* (bias) for the participants of the naming game: a successful naming game can bind the speaker with the listener, and they tend to *move together* to maintain their block distance within D_x and D_y (in other words, either of them can move in such a way that after movement, their block distance is still within D_x and D_y); however, a failed naming game may break down this binding (in other words, either of them can randomly move in any direction).

This restriction is much simpler than those defined by complex networks. Based on it, some big social clusters containing agents who share a common lexical but may not necessarily interact directly with each other may emerge and be maintained. These clusters and their shared words could be the prototypes of complex social structures and their communal languages.

We design two experiments to evaluate the influence of this simple restriction on formation of social clusters and conventionalization of shared lexicon. In Exp. 1, 100 agents are situated in a 10^2 torus (each location in the torus is occupied by an agent), and D_x and D_y range from 1 to 10. In Exp. 2, 100 agents are put into tori whose side length X ranges from 10 to 55, but D_x and D_y are fixed. In each time step, a random sequence of agents is set, and following which, each agent is chosen to interact with one of the others lying within its distance restriction (if any), and then, it moves, based on the interaction result (successful or failed), to one of its unoccupied neighboring positions (if any). The total number of time step is 100, and the maximum number of possible interactions is 100×100=10000. In each condition, the results of 20 simulations are collected for statistical analysis.

After a time step, S (the average successful rate of interactions among all pairs of agents) and N_d (the number of different words) are evaluated. If all agents gradually share a common lexicon, S will gradually increase to 1.0 and N_d reduce to 1. In this situation, N_T (the number of time steps required to reach the highest S) indicates the degree of efficiency of the distance restriction on lexical conventionalization in the population. On the contrary, if all agents cannot share a common lexicon, but form different clusters, S and N_d will not reach 1. In this situation, N_d indicates the number of isolated clusters, and N_T the effect of the distance restriction on lexical conventionalization within clusters. The following sections discuss the simulation results of the two experiments.

2.1. *Exp. 1: fixed torus size but various distance restriction*

In this experiment, all 100 agents lie in a 10^2 torus; D_x and D_y change from 1 to 10. In all simulations, after 100 time steps, a common lexicon is shared in the population; both S and N_d become 1 at the end of simulations. Fig. 2 illustrates the average and standard deviation values of N_T under different D_x and D_y.

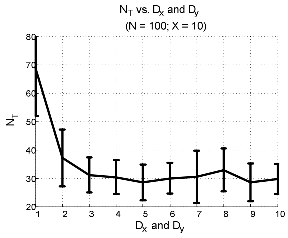


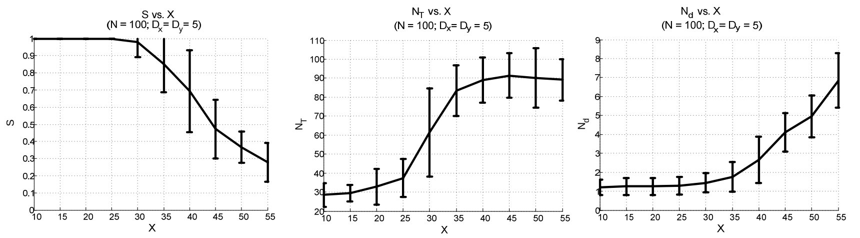
Figure 2. The statistical results of N_T in Exp.1, each point is calculated based on 20 simulations after 100 time steps and maximum 10000 possible naming games.

As shown in Fig. 2, with the increase in D_x and D_y, the process of lexical conventionalization follows two regimes: as D_x and D_y increase from 1 to 4, agents can interact with more nearby agents and adjust their words, then, the lexical convergence is accelerated and N_T drops; when D_x and D_y are greater than 5, each agent can already interact with all the others in the population, then, the lexical convergence is not further accelerated and N_T becomes stable. In addition, in a 10^2 torus, when D_x and D_y are small and each agent cannot directly interact with all others, lexical conventionalization is still accomplished after not many interactions via intermediate agents, and a cluster having agents who cannot directly interact with each other but share a lexicon is established.

2.2. *Exp. 2: various torus size but fixed distance restriction*

In this experiment, 100 agents are randomly situated in tori whose side lengths increase from 10 to 55 with a step of 5. D_x and D_y are fixed to 5. Fig. 3 illustrates the average and standard deviations of S, N_T, and N_d in Exp. 2.

The process of lexical conventionalization in Exp. 2 also follows two regimes: when X is smaller than 30, all agents in the population form a huge cluster and share a common lexicon; however, after X reaches a certain level (say, 30), S begins to drop, and both N_T and N_d begin to increase. In a relatively small torus (X is smaller than 30), although agents may not find many others within their distance restrictions, through moving around, they can encounter some agents and get their words converged to a shared lexicon. However, in a big torus (X is bigger than 30), this 1-step movement is insufficient for agents to meet many others and the big torus size greatly restricts the local interactions among agents, then, isolated, smaller clusters gradually emerge, and each of which shares a common lexicon. The drop of S and increase of N_d both indicate the emergence of small clusters. Within a cluster, S among the cluster members is high, but between clusters, S among members of different clusters is low, since they may share different words. In addition, once such clusters are formed, it is difficult for agents within clusters to interact with outsiders, since they tend to maintain their distance among each other and not to freely move. In a sense, the bindings within clusters are relatively strong, and these clusters and their shared words are relatively stable, which are indicated by the stable values of $S(t)$ and $N_d(t)$ for a long time in specific simulations.



(a) (b) (c)

Figure 3. The statistical results of S (a), N_T (b), and N_d (c) in Exp. 2, each point is calculated based on 20 simulations after 100 time steps and maximum 10000 possible naming games.

A "*local convergence, global polarization*" phenomenon (Axelrod, 1997) is shown in Exp. 2 under a big torus: agents within clusters clearly understand each other via a shared lexicon, but those between clusters do not, since they may share different words. This phenomenon partially reflects the coexistence of many languages in the world, and it is mainly caused by the distance restriction and mutual understanding during local interactions. Besides, if we assume that agents are developing a basic vocabulary using the naming game, these simulations may actually trace the concurrent emergence of different vocabularies, and later on, different languages in the early stage of language development in the world.

Second, combing Exp. 1 and Exp. 2, the boundary values of the distance restriction and torus size suggests a quantitative relation between the local view and the world size. Roughly speaking, the current results seem to show that given a certain number of time steps (100), once the local view $(2D_x+1)\times(2D_y+1)$ is smaller than 1/10 of the torus size, the whole population will neither efficiently form a cluster nor share a common lexicon. Further statistical analysis in simulations with bigger populations can confirm this prediction.

Finally, people may intuitively think that under random or biased movements, sooner or later, all agents will encounter all others, and since the naming game can easily make the participants' vocabularies converge in one interaction, all agents will eventually form a big cluster. However, two arguments are against such prediction. First, in the case of random movements, this process may take extremely long time. In our model, once agents form close clusters, those in the central may not easily move since all their neighboring locations are occupied by others. Therefore, even given an extremely long time, the formation of a big cluster may not occur. Second, the convergence role of the naming game may also cause divergence of a cluster, since the convergence is made via deleting all the other words in the participants' vocabularies. For instance, if Agent 1 with Word A interacts twice with Agent 2 in a cluster where all agents only use Word B, Agent 2 may diverge from this cluster and form a new one with Agent 1 using Word A, and then, the agents in Agent 2's original cluster has to interact at least twice with Agent 2 to drag it back to their cluster. This process introduces fluctuations that may delay lexical conventionalization. Therefore, even if agents, through random or biased movements, have chances to encounter all others, or all of them are within certain distance restriction, their vocabularies might not quickly converge. This partially explains why in the mean-field system all agents still need many rounds of naming games to conventionalize their vocabularies. Such fluctuations also show in our results and help to maintain the polarization state; the clusters are *dynamically stable*; their boundary agents may occasionally change, but their shared lexicon, sizes, and majority candidates remain roughly unchanged in a long run.

3. Conclusions

The simulations in this paper demonstrate the role of the naming game in social structure: the naming game under the simple distance restriction can adjust the social binding among agents and form primitive clusters based on mutual understanding. This line of research is largely neglected in contemporary studies that mostly focus on the impact of social structures on language games (e.g., Delgado, 2002; Dall'Asta et al., 2006).

We present two experiments to illustrate the dynamics of the naming game under distance restrictions and word sizes. First, a big cluster sharing a common lexicon can be formed among individuals whose *local views* (distance restriction) might not allow them to see all members in the population. In addition, there is a close relation between the local view and the world size: under a fixed world, the increase in the local view accelerates the conventionalization of individual knowledge; under a fixed local view, the increase in the world size triggers the emergence of different clusters and *linguistic divergence*, i.e., common knowledge (shared lexicon) is developed within clusters, but heterogeneity (different shared words) occurs between clusters. Furthermore, the enlarging local view may be reminiscent of the growing mass media and the "global village" phenomenon in recent centuries, while the fixed local view with increasing world sizes may represent the reality that people do have such a constraint of a relatively limited view. Considering these, our model may address a scenario with these two competing conditions, and other activities like opinion formation (Rosvall & Sneppen, 2007) may follow a similar scenario.

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