BOOTSTRAPPING COMMUNICATION IN LANGUAGE GAMES. STRATEGY, TOPOLOGY AND ALL THAT

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Semiotic dynamics is a fast growing field according to which language can be seen as an evolving and self-organizing system. In this paper we present a simple multi-agent framework able to account for the emergence of shared conventions in a population. Agents perform pairwise games and final consensus is reached without any outside control nor any global knowledge of the system. In particular we discuss how embedding the population in a non trivial interaction topology affects the behavior of the system and forces to carefully consider agents selection strategies. These results cast an interesting framework to address and study more complex issues in semiotic dynamics.

1. The Naming Game

In recent times, the view of language as a complex dynamical system that evolves and self-organizes has gained ground in the scientific community (Steels, 2000). In this new perspective, complex systems science turns out to be a natural allied in the quest for the general mechanisms underlying the emergence of a shared set of conventions in a population of individuals.

The issue is of the outmost topicality since, for the first time, the web allows for the spreading and the study of global bottom up created semiotic systems. Recently, for instance, new web tools (such as del.icio.us or www.flickr.com) enable users to self organize systems of tags and in that way build up and maintain social networks and share information. On the other hand, many technological systems are nowadays composed of single communicating entities. The capability of developing ontologies or proto languages without any intervention from the outside would be of great importance for instance in those cases in which teams of artificial embodied agents should explore highly unknown environments, such as distant planets or deep seas.

A possible approach to the understanding of language self-organization is that of modeling artificial population of agents and studying their evolution. The choice is then between endowing agents with simple properties, so that one can hope to fully understand what happens in simulations, or with more complicated and realistic structures that yet risk to confuse experiments outputs. We choose to follow the first possibility since we are more interested in the global behavior of the population. In this perspective we do not seek answers to specific issues in the evolution of language, but rather we aim at analyzing deeply basic models that can constitute valuable starting points for more sophisticated investigations. Nevertheless, as we shall see, also extremely transparent agents and interaction rules can give rise to very complex and rich global behaviors and the study of simple models can help to shed light on general properties - a well known lesson in statistical physics.

We discuss here a recently introduced Naming Name model (Baronchelli, Felici, Caglioti, Loreto, & Steels, 2005), inspired to the one proposed by Steels (1995), in which agents play pairwise interactions in order to negotiate conventions, i.e. associations between forms and meanings. The population reaches a final convergence state without any external or global control. This is a central point, since, of course, no such control has been present in the development of natural language, and, as mentioned above, its absence is becoming a desirable feature also for many technological systems. Also, it is worth noting that this model accounts for the emergence of a shared set of conventions (a vocabulary, in our case) from the point of view of cultural transmission (Hutchins & Hazlehurst, 1995; Steels, 1995), without resorting to any evolutionary issue (Hurford, 1989; Nowak, Plotkin, & Krakauer, 1999).

The game is played by a population of N agents. Each agent is characterized by its *inventory*, i.e. a list of form-meaning associations that evolve dynamically during the process. For the sake of simplicity we do not take into account the possibility of homonymy, so that all meanings are independent and we can work with only one of them, without loss of generality. Agents aim to converge to a unique shared form (or word) to associate with the meaning (or object). Agents have empty inventories at time $t = 0$ and at each time step ($t = 1, 2, ..$) two players are picked at random to play an interaction: one of them plays as *speaker* and the other as *hearer*. Their interaction obeys the following rules:

- The speaker randomly extracts a word from its inventory, or, if its inventory is empty, invents a new word.
- If the hearer has the word selected by the speaker in its inventory, the interaction is a success and both players maintain in their inventories only the winning word, deleting all the others.

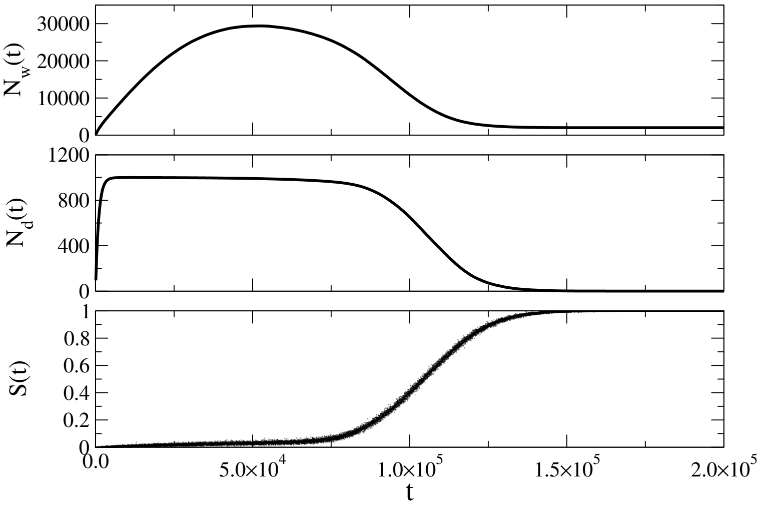

Figure 1. Time evolution of the most relevant global properties of the Naming Game. From up to down: the total number of words, $N_w(t)$, the number of different words known by the agents, $N_d(t)$, and the probability of a successful interaction at a give time, $S(t)$. Convergence is reached with a quite abrupt disorder/order transition that starts approximately just after the peak of the $N_w(t)$ curve has disappeared. Data are relative to a population of $N = 2000$ agents and averaged over 300 simulation runs.

- If the hearer does not have the word selected by the speaker in its inventory, the interaction is a failure and the hearer updates its inventory adding the new word.

The most relevant quantities to describe the evolution of the population are: the total number of words stored by the system at each time step, $N_w(t)$, the number of different words known by the agents, $N_d(t)$, and the probability of a successful interaction at a given time, $S(t)$. In Figure 1 we report the time evolution of a population of $N = 2000$ agents. It is immediately clear that the population reaches a final coherent state in which there is only one word ($N_d = 1$) and all interactions are successful (Baronchelli et al., 2005). As we mentioned above this is a remarkable fact, considering the simplicity of the rules that govern our process, and makes it worthy a more detailed analysis of the model.

The process starts with a trivial phase in which agents invent new words. It follows a longer period of time where the $N/2$ (on average) different words are exchanged after unsuccessful interactions. The probability of a success taking place at this time is indeed very small since each agent knows only few different words. As a consequence, the total number of words grows while the number of different words remains constant. However, agents keep correlating their inventories so that at a certain point the probability of a successful interaction ceases to be negligible. As fruitful interactions become more frequent the total number of words at first reduces its growth and then start decreasing. Moreover, after a while some words start disappearing from the system. The new virtuous correlations among inventories make the process evolve with an abrupt increase in the number of successes and a further reduction in the numbers of both total and different words. Finally, the dynamics ends when all agents have the same unique word and the system is in the attractive convergence state. It is worth noting that the developed communication system is not only effective (each agent understands all the others), but also efficient (no memory is wasted in the final state).

2. Interplay with topology

In the Naming Game model described above at each time step two agents are *randomly* chosen, thus implying that we deal with a completely unstructured population (i.e. we are in the mean-field case). However, the hypothesis that each agent can in principle talk to anybody else is strongly unrealistic when we deal with large numbers. The remedy is to embed agents in a quenched spatial structure, typically a regular lattice. More realistic alternatives to regular structures are given by complex networks. A network is, roughly speaking, an ensemble of nodes connected by links (or edges). Examples of such structures are common, Internet and the World Wide Web being the most obvious. Moreover, recently, it has been found out that many more systems can be described as networks (Albert & Barabási, 2002; Pastor-Satorras & Vespignani, 2004). As examples we can mention social networks in which people are the nodes and their social relations are the links (Wasserman & Faust, 1994), scientific collaboration networks, where two scientist are connected by a link if they have co-authored at least an article (Newman, 2004), metabolic networks in which nodes are the substrates and edges are chemical reactions in which the substrates participates (Jeong, Tombor, Albert, Oltvai, & Barabási, 2000) and food webs in which the nodes are species and the links represent predator-prey relationships (Garlaschelli, Caldarelli, & Pietronero, 2003). Among the most peculiar features shared by most natural or artificial networks there are the "small world" property (Watts & Strogatz, 1998) and the scale free degree distribution (Barabási & Albert, 1999). The first is the name attributed to the evidence that the minimal hop distance between each pair of nodes scales logarithmically with the network's size instead of algebraically as in usual regular lattices. The second is the fact that, said degree k of a node the number of links which connect it to other nodes, the degree distribution $P(k)$ follows a power law $P(k) \sim k^{-\gamma}$, thus allowing for the presence of very few nodes with very high connectivity that in general play a central role in the structural and dynamical properties of the system.

In our simulations we have chosen to place agents on the nodes of Barabasi-Albert network (Barabási & Albert, 1999). This is an artificial network which displays a power law degree distribution $P(k) \sim k^{-3}$. It is built starting from

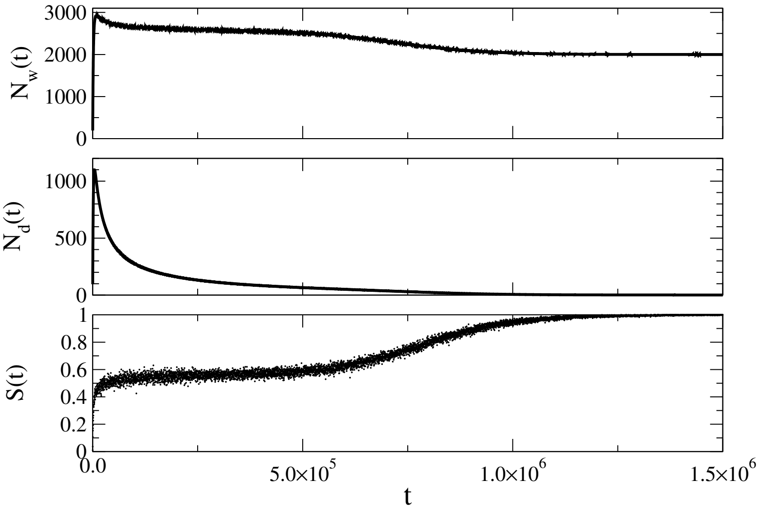

Figure 2. Time evolution of the Naming Game played by a population of $N = 2000$ agents embedded in a Barabasi-Albert network with $m = 2$. Convergence is considerably slower and the maximum number of words is smaller than in the mean field case.

a core of fully connected nodes and adding sequentially new nodes with m links each. The existing nodes to be linked with the newcomer are chosen with a probability proportional to their degree (the well-known "preferential attachment" rule), so that new links are likely to be added to well connected nodes (Note that for each node, the initial degree is m, but it can subsequently grow when newcomers attach to the node; the average degree in the network is $\langle k \rangle = 2m$). In Figure 2 we report data relative to a Naming Game played by a population of 2000 agents placed on the nodes of a Barabasi-Network graph with $m = 2$. The radical difference with Figure 1 is manifest. When the network is present, the convergence time is extremely longer (than for the mean-field case), while the maximum number of total words is smaller. Moreover the curves of both total and different words are qualitatively modified, since in the latter the plateau region disappears, while a flat region is now present in the first. This can be understood observing the success rate curve, that at first grows very rapidly, but then remains stuck in a very long plateau. The first growth is due to the consensus reached locally among small clusters of agents, while global ordering takes a much longer time and is responsible for the quasi constant success rate. However, to gain a clearer picture of what goes on, it is crucial describing how the interacting agents selection takes place (Castellano, 2005). In the simulations we have just discussed, the first extracted agent played as speaker. This is a relevant information since, due to the scale-free degree distribution, a randomly selected node is, with high probability,

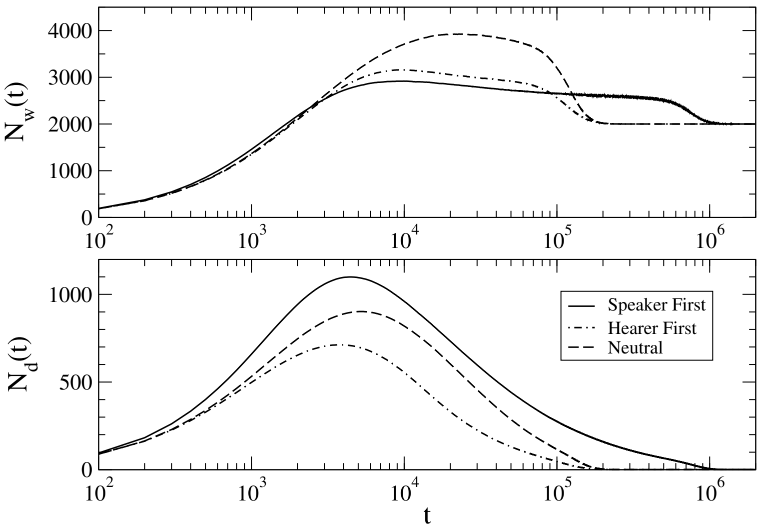

Figure 3. Interacting pairs selection strategies; in "Speaker First" the speaker is at first selected and one of its neighbors plays as hearer, while the opposite happens in the "Hearer First" approach. These strategies lead to very different outcomes since, due to the scale free nature of the network, the first selected node is usually low connected, while the second has great chances to be a hub. The neutral method, finally, consists in selecting a link and tossing a coin to attribute roles to its extremes; it gives rise to hybrid behavior. Curves are the results of 300 simulation runs performed for a population of $N = 2000$ agents embedded in a Barabasi-Albert graph with $m = 2$. Note logarithmic scale on the abscissa.

one with low degree. Such nodes form, in fact, a vast majority. The hearer, then, being selected among the neighbors of the speaker, is likely to be a high degree node, i.e. to be directly reachable from many nodes. So, low degree nodes invent a large number of different words at the beginning and pass them to the hubs, which tend to store on average a larger amount of words. Highly connected nodes are thus obviously the necessary go-between of successes, but their passive role slows down the dynamics. On the other hand, their low number allows the total number of words to stay low.

Given that the rules chosen to assemble interacting pairs are likely to be determinant, we have performed experiments following two different gathering strategies. The first consists in picking up at first the hearer and then one of its neighbors as the speaker. The last one is a "neutral" strategy in which a link is randomly selected and then a coin toss assigns the speaker/hearer roles. Results relative to numbers of words are shown in Figure 3. The curve relative to the "hearer first" strategy confirms our picture. Noticeably, here the convergence is much faster than when the speaker is selected at first. The reason is due to the active role played by hubs which, being most frequently speakers, tend to propagate successful words to low connected nodes. Their active role in the initial invention process also keeps the number of different words low. The other side of the coin is the larger number of words the population has to store during the process, due to the fact that low connected agents need to store more words than in the ”speaker first” case. Finally, neutral strategy determines an hybrid behavior between those of the ”speaker/hearer first”, the only relevant feature being a peak of the $N_w(t)$ curve higher than those recorded for the other strategies.

Before concluding two remarks are in order. First of all, it must be noted that pairs selection strategies are so crucial due to the non trivial topology on which the games are performed. Both for complete graphs and regular lattices, in fact, the three strategies mentioned above are completely equivalent and give rise to identical results. Secondly, we stress that, while in our case we have embedded the population on a static interaction pattern, it would also be desirable to consider a dynamically evolving topology. In this respect, an interesting study of co-evolution of language and social structure has been done by Gong, Ke, Minett and Wang (2004), for a more complex language game.

3. Conclusions

In this paper we have presented a very simple model able to account for the emergence of shared conventions in a population of agents. In our case individuals agree on the name to assign to an object, but the model can be straightforwardly enriched to study the genesis of more complex language structures. In this perspective, the study of the Naming Game model provides a fundamental first step towards more realistic modeling.

After studying the most important global properties of the mean-field case, we have performed simulations in which the population is put on a non-trivial quenched interaction topology. In particular, we have shown that the topology strongly affects the way in which final convergence is reached. Moreover, due to the heterogeneity of the underlying network, pair selection strategies become crucial in determining the behavior of the system. This is due to the role of highly connected nodes, the hubs, which considerably speed up the convergence when are able to distribute conventions actively and slow it down if used as passive agents connectors.

These findings offer useful hints to understand real systems. For different reasons, as a matter of fact, in social networks not all the individuals play the same role. Indeed, the structure of such networks is scale free, but the ways in which a node can become a hub can be very different. In web based communities, for instance, a node can attract connections providing passively useful or interesting material to the community, or on the contrary can increase its social influence being very active in establishing relations with other users. In this perspective, our work contributes to shed light on how such different human-based mechanisms underlying the emergence of social interaction structures can heavily affect the semiotic dynamics happening upon them. Finally, an important consequence concerning the *role* of the hubs is that, when we are interested in the semiotic processes taking place on a non trivial social structure, the mere knowledge of its topology might be insufficient to make predictions.

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