Self-organization of a Lexicon in a Structured Society of Agents

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Abstract. The naming game is a formal mechanism that describes the development of a lexicon in a society of culturally interacting agents. We will here use a cellular automaton version of this game to study the influence of an extra-linguistic structure over the evolution of the lexicon, but also the influence of language over this a priori structure. This extra-linguistic structure will be coded by first giving a location in a 2-D world to agents, and then by allowing them to move in relation to the outcome of the naming games. The results we will present show strong self-organization phenomena, such as the appearance of language and geographical clusters, in addition to the basic properties of the game (high communication success).

1 Introduction

Language as a complex dynamical system has been increasingly studied in the last decade. Formal models have been built to investigate the question of the emergence of language through self-organisation in a society of culturally interacting agents. This work is practically done both in simulations and by using robotic agents ([3]). One of the questions raised is : how can a lexicon shared by many agents emerge ? How can initially random form-meaning associations self-organize through cultural evolution ? The naming game is a formal mechanism that has thus been introduced to tackle this question ([7]), and will be described in section 2. Many results have already been worked out, in particular by coupling it with other language games ([5]). Yet, most of them concentrated on the language itself and did not consider the possibility of having a priori extra-linguistic structure in the agent society. The first step was done in [4] where the idea of spatialization was introduced : the agent society is given a fixed topological structure (that can be based on a geographical or social distance for instance) that determines with who agents may speak, as we will see in section 2. We will present new results in section 3, based on a purely cellular automaton model of the naming game (this choice was made in order to focus on the inherent properties of this mechanism, and for the higher amount of control it gives). We will show that this topological structure has an important impact over the lexicon development, and that emergent phenomena such as the appearance of what we will call language clusters. Then, in section 4, we will generalize this model by having a variable topological structure : agents will move according to the outcome of the naming game they are involved in. By giving the language the ability to modify the structure, we will show that this coupling leads to very strong self-organized phenomena such as emergence of geographical clusters of agents that share the same forms for the same meanings.

2 The Naming Game : Formal Model

Let us first define what is a lexicon L : it is a set of associations form meaning $L = \{(f_i, m_i, s_i)\}$ where a form f_i is a symbol, a meaning m_i denotes a category/object, and s_i is the score of the association, constrained by $s_i \in [0, 1]$. Two operations can be performed over a score : increase by r or decrease by r. Because of the constraint $s_i \in [0, 1]$, when the result of an operation is greater than 1, it is mapped to 1, and when it is smaller than 0, it is mapped to 0. The increase operator is denoted by $In(s_i, r)$, and the decrease $De(s_i, r)$. Moreover, both forms and meanings can appear several times in different associations.
An agent a_i is here a t-uple $a_i = ((x_i, y_i), L_i, w_a, w_c, IS, SC)$ where (x_i, y_i) is its location in a 2-dimentional world, L_i is its current lexicon which is initially empty, w_a the probability of accepting a new association (f_i, m_i, s_i) when needed as explained below, w_c the probability of creating a new association (f_i, m_i, s_i) when needed, IS the initial score of accepted and created associations, and SC the quantity by which a score can be changed (increased or decreased) when needed.
A society of agents is defined as the 3-uple $Soc = (\{a_i\}, loc, \{m_i\})$ where $\{a_i\}$ is the set of agents, loc the locality used as explained hereafter, and $\{m_i\}$ is the set of meanings/objects that agents will have to name by associating them one or several forms.
A round of the naming game consists in picking up randomly one agent, called the speaker s, who himself chooses randomly one of its loc neighbors (the hearer h), according to the euclidean distance. Then the speaker chooses randomly a topic $m \in \{m_i\}$. Let $E = \{assoc_k = (f_k, m_k, s_k) | (m_k = m) \wedge (assoc_k \in L_s)\}$:

- if $E = \emptyset$, then this means that the speaker has no form for m, and then he creates randomly a new form f (random symbol) and add (f, m, IS) to L_s. The round ends and the result is said to be FAILURE.
- if $E \neq \emptyset$, then s chooses randomly

  $$assoc = (f, m, s) \in \{(f_k, m, s_k) | ((f_k, m, s_k) \in E) \wedge (\forall j \neq k, ((f_j, m, s_j) \in E \Rightarrow s_j \leq s_k))\}$$

  which is an association (f_k, m, s_k) with a maximal score, and will be called the last preferred form for m for agent a_i, or just preferred form for m. Then, s points to m with an extra-linguistic tool (the hearer always understand what is the topic here), and utters f. Let us now consider the predicate $P = (\exists s_k | (f, m, s_k) \in L_h) \wedge (s_k > 0)$:

- if P is false, then this means that the hearer does not understand and the round ends with the result FAILURE. The lexicon of the speaker is updated as follows : $L_s := L_s - \{(f, m, s)\} + \{(f, m, D(s, SC))\}$. The lexicon of the hearer is updated as follows with the probability w_a : $L_h := L_h + \{(f, m, IC)\}$.
- if P is true, then this means that the hearer does understand, and the round ends with result SUCCESS. The lexicon of the speaker is updated as follows : let us note
$$A = \{(f_k, m, s_k) \in L_s | f_k \neq f\}$$
and
$$B = \{(f, m_k, s_k) \in L_s | m_k \neq m\},$$
then
$$L_s := L_s - \{(f, m, s)\} + \{(f, m, In(s, SC))\} - A + \{(f_k, m, s_k) | (\exists s | (f_k, m, s) \in A) \wedge (s_k = De(s, SC)))\} - B + \{(f, m_k, s_k) | (\exists s | (f, m_k, s) \in A) \wedge (s_k = De(s, SC)))\}$$

Finally, what we call the naming game is to compute successively rounds over the population of agents. As we will see, this latter is not necessarily fixed, for instance when a flux of agents is introduced as introduced below.

3 Experiments with agents that have a fixed position

Before presenting any results, let us state what measures we are going to use. The first one is the evolution of SUCCESS/FAILURE with the number of rounds : the curves that we will show plot points whose x is the number of the round, and y the percentage of success in the last 30 rounds. The second one is what we will call evolution of form-spread for a given meaning m, along with the number of rounds. A form-spread for m in round r is defined as

$$FS_{m,r} = \{(f_i, p_i) | (\exists a \in Soc | f_i = \text{last preferred word of a for } m) \wedge (p_i = \text{percentage of agents that have } f_i \text{ as their preferred form for } m)\}.$$

The form-spread graphs for m will thus be composed of $max_r|FS_{m,r}|$ curves, each one corresponding to one $f_i \in FS_{m,r}$ and representing the evolution of the associated p_i in function of the number of rounds. This measure allows to follow the evolution of a given preferred form for a given meaning along with the number of rounds and within the population of agents. Other measures will be used and presented when needed.

The experiments in this section deal with agents whose location does not change with time. All agents have the same parameters w_a, w_c, IS and SC. When parameters are not precised, it means that they have default value : 100 agents randomly located in 2-D space, 4 meanings, $loc = 8$, $w_a = 0.1$, $w_c = 0.1$, $IS = 0.1$ and $SC = 0.1$.
The first results yielded by those experiments are that like in the non spatialized naming game (NSNG) ([4]), success reaches more than 85 percent after 1500

games, and this at the same speed. But unlike NSNG, where one form rapidly dominates for a given meaning, several stable forms appear here and go to an equilibrium where each one keeps its percentage of users : Figure 1 shows form-spread for one of the meanings. This is true for nearly all parameters, except when $IS = 1$ as we will soon explain.

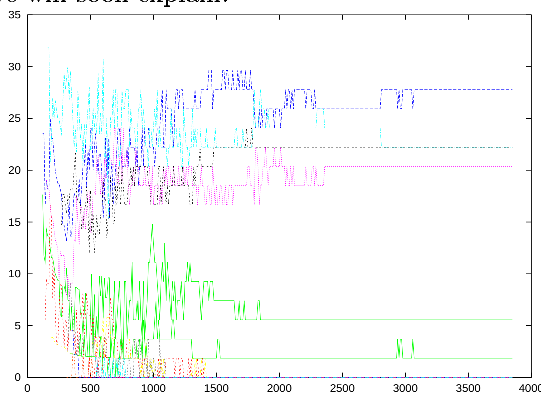

Figure 1 : evolution of form-spread for meaning 1 with 100 agents

Moreover, language clusters for a given meaning m appear : users of a given preferred form for m are geographically neighbors as shown on Figure 2.

Figure 2 : clusters of agents sharing the same form for meaning m

Clusters are so well defined that it allowed quantitative study of them. The first one was about the the variation of the number of these clusters (at convergence state) along with locality. This is a relevant question because for a given locality (and set of other parameters), the number of clusters appeared extremely stable. Thus, an experiment repeated a high number of times and performed over 300 randomly located agents (with other parameters set to default value) yielded the following result, as shown on Figure 3 which represents $log(nclusters(loc))$:

$$nclusters(loc) = \frac{1}{c_1^{c_2 * loc + c_3}}$$

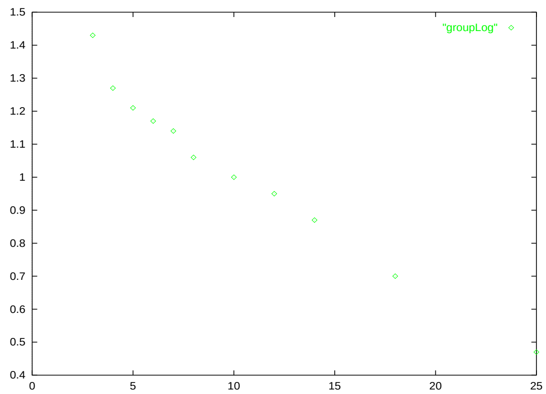

Figure 2 : $log(nclusters(loc))$

A similar experiment studied the occurence of a given size of cluster (defined as the number of agents that constitutes it) for a fixed locality and showed, as represented in Figure 3 with $loc = 4$, that, on both sides of a peak value, again a power law emerges, and gives a new example of the general phenomenon of self-organized criticality discovered by Per Bak ([8]) :

$$occurence(size) = \frac{1}{c_4^{c_5 * size + c_6}}$$

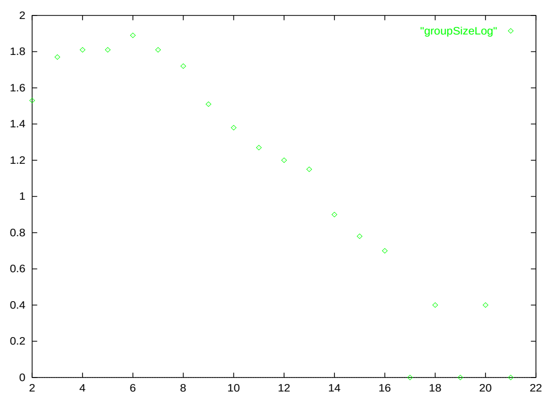

Figure 3 : $log(occurence(size))$

Another question about the equilibrium state is its stability. Experiments have shown that if any of the parameters w_a, w_c is suddenly changed, equilibrium is not affected. More surprisingly, if one removes suddenly locality (agents are suddenly given the opportunity to talk to any other one), and if the number of agents is not too large (experimentally inferior to 100), form-spread moves a bit and quickly return to a multiple-stable-form equilibrium, as shown on Figure 4. Yet, success falls to about 50 percent. This means that most agents keep their preferred form (their "difference") for a given meaning even if communication success is relatively low.

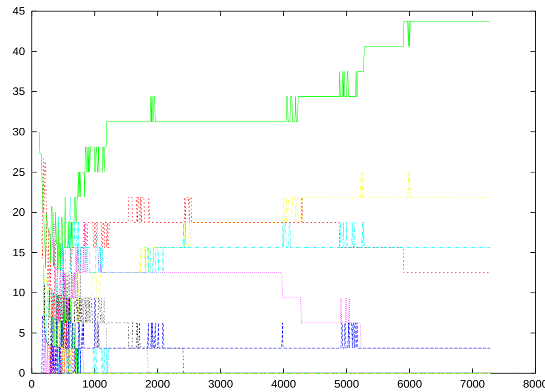

Figure 4 : locality is removed after 3000 rounds

As introduced above, there is an exception for this behavior of converging to a “frozen” state : when the initial score $IS = 1$, and even more when $SC = 1$ also (which means : every form is either preferred or forgotten, and new forms are directly introduced as potentially preferred ones). In this case, which corresponds to extreme parameters a priori “fighting” against order, this latter still emerges in terms of formation of language clusters for every meaning, but does not freeze as the frontier between two clusters keeps moving in a random walk manner. The result is that some clusters sometimes disappear (“eaten” by their neigbors), and eventually one big cluster remains : a unique common preferred form appears for each meaning.

Another possibility to break this frozen state is to introduce agent flux : every n rounds, one agent is randomly choosen and removed while a fresh one (with empty lexicon) is added in a random place. We can notice that here topology of course changes every n games, but this change is not here coupled with the naming game itself. Furthermore, flux is here introduced when the equilibrium has been reached. A low flux (every 30 games in a population of 25 agents) produces no change in communication success, but destabilizes language clusters and surprisingly one preferred form quickly dominates for a given meaning (see Figure 5) , in the same way as in non-spatialized naming game : instead of bringing diversity, agent flux brings unity to the language. Medium flux (every 15 games) shows the same phenomenon, but now success falls to about 50 percent. Finally and logically, when flux is high (every 10 games), language collapses : success falls to 30 percent and no form manages to install itself.

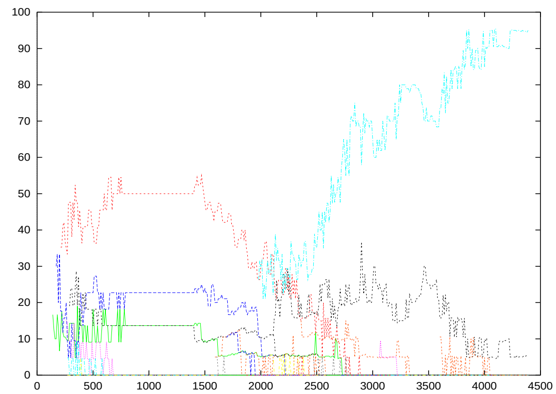

Figure 5 : form-spread for meaning 1 with 25 agents and flux ($n = 30$) introduced after 1400 rounds

4 When Agents Move

Now that we have studied basic properties of the impact of a structure in the society over the development of a lexicon, we will investigate the case in which agents have no more a fixed location but instead move according to the outcome of the rounds : topology and language are bi-directionnaly coupled. Let us first precise how this coupling is defined. At the end of each round, if the result is a SUCCESS, then the speaker moves towards the hearer in the following way :

$$(x_s, y_s) \Longrightarrow (x_s + C * (x_h - x_s), y_s + C * (y_h - y_s))$$

where (x_s, y_s) is the position of the speaker before he moves, (x_h, y_h) is the position of the hearer, and C a constant typically equal to $\frac{max_i(x(a_i)) - min_i(x(a_i))}{|Soc|}$ where $x(a_i)$ stands for the abscisse of agent a_i in the first round : this does that agent displacements are very smooth. When the result of a round is a FAILURE, the speaker performs the same displacement but with $-C$ instead of C. Last, in all experiments agents have a random position in the first round.

A remark we can do before presenting any result is that by coupling the outcome of a round with topology, we introduce a strong interaction between meanings (which was very weak and only due to chance when agents did not move). Indeed, if in one round a topic m_1 is choosen by an agent a_i and happens to lead to a certain displacement, in a later round a_i could choose another topic m_2 and the result of this round (particularly in terms of updating the (f_k, m_k, s_k)), is influenced by the former displacement caused by m_1. Thus, associations (f_k, m_k, s_k) interact strongly (but blindly) through the change they produce in the structure of the society.

Let us now come to what we observe. First, the evolution of success is the same as when agents did not move, contrarily to the a priori idea that it would grow faster because agents try to avoid failure and foster success : the reason is the interaction between meanings. On the other hand, we also reach a similar stable-state in form-spread for a given meaning but the difference is that the number

of stable forms is here much smaller and grows very slowly with locality and size of population, and that these stable forms are not frozen for ever : small changes appear, which will be explained below.
The most interesting result comes if we now look at the evolution of topology in relation to these stable forms for a given meaning. Indeed, geographical clusters (defined only by the location of agents) quickly emerge as shown on Figure 6.

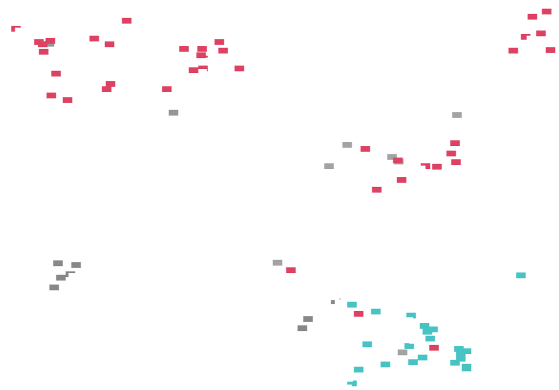

Figure 6

Moreover, most of the time, these geographical clusters are also language clusters for every meaning. This means that in the same geographical cluster, most of agents share the same preferred word for each meaning.
Exceptions occur in which for a given meaning, two (or even more rarely three) forms co-exist in a cluster. The main explanation is as follows : because agents do not stop moving even when they are in a cluster with other agents having the same preferred forms, clusters also move, and this is done in a random walk manner. The consequence is that sometimes two clusters simply bump into each other. Two behaviors may appear : either they bounce and continue independantly their walk, or they melt. The possibility of melting is given when these two clusters have a common form for one or more meanings : this constitutes an attraction force that can hold them together. Thus, the result is strictly equivalent to removing locality for these concerned agents : they are suddenly forced to talk with others that independantly built their own lexicon. As we have seen in the non-moving naming game, few agents converts themselves to the other forms, but most of them keep their "before collision" preferred forms. Other factors foster these exceptions, but we will not get into them for reason of space.
Finally, let us investigate the particular case $IS = 1$ and $SC = 1$ that we discovered in section 3. What we here observe is again self-organized phenomena that lead to geographical clusters that are also language clusters. The difference, easily explained by the results of section 3, is that exceptions soon disappear. Furthermore, when geographical clusters bump into each other, they melt very often, and the resulting cluster has a very interesting property explained by the dynamics imposed by these parameters : one form soon dominates for each meaning. The important thing is that the origin of these winning forms (one

cluster or the other) is random. Thus we observe a real fusion of languages : for instance, cluster c_1 could have form f_1 for m_1 and f_2 for m_2, cluster c_2 have form $f_1^{'}$ for m_1 and $f_2^{'}$ for m_2, and the resulting cluster $c_1 + c_2$ can happen to have form f_1 for m_1 and form $f_2^{'}$ for m_2.

5 Conclusion

We have shown that the simplest form of the naming game presented here can lead to already complex self-organized phenomena. The main point was that introducing extra-linguistic structure in a society of agents that use the mechanism of the naming game lead to the emergence of language clusters. Moreover, by coupling the outcome of the rounds to displacements of agents, we saw that language can also provide cluster organization to the structure of the society. The bidirectionnal interaction between structure and language finally leads to a precisely organized society. Further work is to see if those results still hold when the naming game is coupled with for instance the discrimination game ([6]) and by using non-idealized situations with robotic agents.

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