The Combinatorial Naming Game

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Keywords: learning in multi-agent systems, lexicon formation, naming game, source coding, language change

Abstract

In this article we introduce combinatorial form into the well-known Naming Game paradigm in which autonomous agents have to establish a globally shared communication system through strictly local interactions. While virtually all investigations of the Naming Game so far have been carried out using atomic names, we highlight some interesting aspects that arise only when naming is done using combinatorial forms. We present an analysis which relates Naming Games to information theory and discuss first results from multi-agent simulations in light of this analysis.

1. Introduction

The Naming Game paradigm (Steels, 1995; Baronchelli et al., 2006; Wellens, 2012) has been used extensively to investigate the emergence of shared communication systems. The goal of a Naming Game is for a set of agents to agree on a name for one or more objects without any central control. The agents engage in local interactions where one of the agents acts as a speaker who tries to draw the attention of another agent (the listener) to a specific object in the communicative context by uttering a name. The game fails if the listener fails to identify the object or does not agree with the name, but both agents can use their experience of the game outcome to improve their internal lexicon so as to communicate more successfully in the next game.

So far, Naming Games have only been investigated with atomic names that do not exhibit any internal structure. Human language on the other hand exhibits the interesting property of "duality of patterning" (Hockett, 1960): the smallest meaningful units in a given language (*morphemes*, such as the names for objects in the Naming Game) are again combinations of a basic inventory of meaningless units (typically called *phonemes*). This property is peculiar because compositional communication systems as expressive as human language do not in principle require this *combinatorial* nature of morphemes. There do however exist reasons for combinatoriality: the free combination of a basic inventory of meaningless sounds allows the creation of an unlimited inventory of basic words which is not constrained by the limits of perceptual distinctiveness (Zuidema & de Boer, 2009).

While a wealth of multi-agent simulations in the wake of the Naming Game have yielded interesting results regarding both lexicon as well as ontology formation (Steels, 2011), there are still many open questions regarding the role that *structured form spaces* play in the emergence of communication systems, where a form space is said to be structured if some forms are more easily confused with one another than others (de Boer & Verhoef, 2012). While the Naming Game has already been investigated using structured form spaces (Steels & Kaplan, 1998; Lipowski & Lipowska, 2009), these investigations have only dealt with atomic names but not with *combinatorial* form, where the confusability stems from the fact that the names are themselves made up of smaller units which are re-used across different names.

The most interesting aspect of such a sub-semiotic treatment of names is that part of the agents' communication strategies do not directly impact on the level of meaningful names, but only on the basic sound inventory. Of particular interest is the well known "principle of least effort" (Zipf, 1949) which states that speakers minimise the effort involved in utter-

Appearing in *Proceedings of BeneLearn and PMLS 2012*.

ing their linguistic expressions. This principle is not limited to the selection of names in the case of synonyms, it also implies that articulatory laziness leads to a constant erosion (shortening) of phonetic forms. When language is viewed as being static, such variation might appear dangerous in terms of threatening a "successful" communication system. But a recent trend in linguistics is to characterise language as a complex adaptive system (Steels, 2000) that adapts to the cognitive and communicative requirements of the language users. Much like in biological evolution, it is variation which lies at the core of languages' capability to change and adapt to different scenarios.

In this article we extend the Naming Game paradigm by investigating its dynamics in a combinatorial form space. The model will be formally introduced in Section 2, followed by an information-theoretic analysis and the results of numerical simulations in Section 3. Section 4 points out directions for future work.

2. The Combinatorial Naming Game

A basic Naming Game requires a set of objects and a population of agents who communicate about these objects in local interactions. For every interaction a context (i.e. a subset of all the objects that can be communicated about) is selected and two agents are chosen from the population. One agent is assigned the role of speaker, the other of listener. Both agents are confronted with the same context of objects. The interaction then proceeds according to the following interaction script:

1. The speaker mentally picks one object from the context (called the topic) and utters a name for it.
2. The listener interprets the name and points to the object he believes the speaker intended.
3. The speaker either agrees or disagrees with the listener.
4. Both agents have the opportunity to adapt their inventory of names.

The extensions of the Combinatorial Naming Game to the original Naming Game are twofold: firstly, the atomic names are replaced with names which are sequences of meaningless characters drawn from a fixed alphabet. Secondly, in order for this change to have more impact on the conventionalisation dynamics, this combinatorial language model is enhanced by a model of phonetic erosion (see Section 2.2).

Based on the interaction script of the Naming Game, the dynamics of the simplest version of a Combinatorial Naming Game are dependent on the following parameters:

- $n \geq 2$: the number of agents
- $o \geq 1$: the total number of objects
- $c \leq o$: the number of objects which are presented at the same time in individual contexts
- $p \geq 2$: the size of the phoneme inventory, i.e. the number of distinct phonemes that can be combined to form names
- $l \geq 1$: the initial length of newly invented names
- S: the agents' strategy for storing names and selecting which names to produce (see Section 2.1)
- U: the utterance production model which determines how a word might erode (see Section 2.2)
- $0 \leq e \leq 1$: the probability of phonetic erosion occurring while uttering a name

Before we go into the details of the different strategies, it is insightful to discuss the kinds of conventionalisation problems the agents face in this game. At the core of all Naming Game scenarios lies *synonymy* or *word form competition*, which means that there are multiple competing names for the same object in a population instead of one shared convention. We also find this basic property in the Combinatorial Naming Game, but here not alone due to distributed invention of multiple names by different agents, but also due to phonetic erosion which introduces competitors in the form of shorter variants of the same name.

A second, even more interesting effect of the combinatorial form space is that it also introduces *homonymy*, i.e. it is possible that the same form is used to refer to multiple different objects. This problem does not occur in the traditional Naming Game, and it is indeed a property normally associated with language games involving *referential uncertainty* of the intended meaning, such as in the Guessing Game (De Beule et al., 2006). Next to establishing one shared name for every object, the agents' strategies thus have to solve the additional problem of making sure that no two objects share the same name.

2.1. Name Selection Strategies

The strategies according to which the agents select the names they use are the most interesting aspect of language games, because they determine if and how well the communicative tasks at hand are solved. Due to the homonymy introduced by using structured names, it is not possible to employ the simple name lookup like in traditional Naming Games. A name for an object might also be used to refer to some other object present in the current communicative context, which would result in referential ambiguity of the name.

To counteract this, the strategies used in the Combinatorial Naming Game make use of a feature called re-entrance (Steels, 2003). Re-entrance is analogous to the symmetry principle found in human language: speakers only use utterances for a communicative purpose if they think that these utterances would have the same effect when used by someone else on themselves. Before uttering any name, an agent thus first attempts to interpret the name in the given context to see if it does indeed unambiguously pick out the desired topic.

Based on this general condition, the agent which is selected as the speaker proceeds by selecting an unambiguous name from its lexicon according to one of the following strategies:

winner-take-all strategy: of all the names the agent knows for the intended topic, it deterministically selects the one with the highest frequency, i.e. the one that the agent has most often seen being used for the topic by other speakers in previous interactions. The same bias is used in interpretation, so if there are multiple possible interpretations of the name in the context, they deterministically pick the object which they have most often heard being referred to with that name.

economical strategy: the agent selects the shortest name known to them which unambiguously refers to the topic in the given context. This strategy explicitly follows the "principle of least effort" on the side of the speaker. Interpretation is in this case stricter: the listener only points to an object if it is the only possible interpretation of the name in the context.

minimal strategy: this strategy is based on the eponymous *minimal strategy* known from the original Naming Game (Baronchelli et al., 2006). As speakers, the agents sample a random name from all the names they know for the chosen topic. This set of synonyms is constantly expanded by new forms that are encountered, but when a listener hears the same name for an object for the second time it discards all other synonyms, thereby settling on a single name for the object.

If the agent does not yet know a name for the object or none of the names would unambiguously refer to the intended topic in the given context, the agent invents a new name, which is a random, not necessarily unique sequence of l characters from the phonetic inventory.

2.2. Name Production

To get variation on top of the invented names, we introduce a very simple speech production model which might shorten the utterance intended by the agent. If the agent wants to produce a certain name of length $i > 1$ which is the sequence of characters $[c_1 \ldots c_i]$, then with a certain probability e the utterance will *erode* at the end, i.e. the name will instead be produced as $[c_1 ... c_{i-1}]$.

The utterance erosion model introduces stochastic variation into the population, and the goal of our model is exactly to investigate how different strategies can handle the homonymy it introduces as well as exploit this variation to arrive at more economical communication systems.

2.3. Naming as Source Coding

Apart from the conventionalisation dynamics, the combinatorial form space adds a new characteristic to the naming game, namely that of *source coding.* Source coding is a mapping from symbols from a finite source alphabet Σ_1 (in our case the atomic objects) to a sequence of symbols from a finite target alphabet Σ_2. The Combinatorial Naming Game introduced here can be interpreted as the negotiation of a source code among distributed agents, with alphabet sizes $|\Sigma_1| = o$ and $|\Sigma_2| = p$.

Most importantly, Shannon's source coding theorem (Shannon, 1948) provides us with bounds on the average name length that an optimal communication system can use while maintaining the capability to reconstruct the exact original message (lossless source coding). Assuming that all o objects occur with equal probability $\frac{1}{o}$, this means that the entropy of each name is $\log_2(o)$ bit. Since in all Naming Game experiments to date the successive symbols (or contexts) are randomly drawn in an independent fashion, the overall entropy H of the communicative contexts as an information source is also $\log_2(o)$ bit.

The shortest possible representation to encode the messages (the objects) in a given alphabet is their entropy divided by the logarithm of the number of symbols in the target alphabet, i.e. $\frac{\log_2(o)}{\log_2(p)}$. We will use these values as a baseline against which the results of our simulations in the following section can be related.

3. Experiments

We implemented the Combinatorial Naming Game laid out in the previous section as a multi-agent system to study its dynamics through numerical simulation.

Due to space limitations, the discussion in this paper is necessarily limited to a subset of the huge parameter space. Particularly, because we are actually more interested in the languages' characteristics rather than the spreading of conventions across the population of agents, we set the size of the population to its minimal possible value of $n = 2$ agents, as has previously been done in other investigations of structured form spaces (Lipowski & Lipowska, 2009).

To facilitate the information-theoretic analysis of the resulting languages, we set the size of the phoneme inventory to $p = 2$. With three different name selection strategies, erosion probabilities and initial name lengths, the remaining parameter space is still large. To further simplify later analysis, we stick to powers of two for the number of objects ($o = \{4, 8, 16, 32, 64\}$) while always using an identical context size of $c = o$.

A crucial choice for the model is the initial length l of new words that the agents can invent. Given the fact that names can only get shorter through erosion, it is also an boundary for the maximum possible word length the agents can use. If we interpret the set of objects as a source alphabet with o characters, the Shannon information of every single object will be $\log_2(o)$.

A minimally optimal language for unambiguously naming o objects uses all different names of length $\log_2(o)$ characters, which therefore provides an absolute lower bound for the length of initial words which might feasibly work together to form a fully successful language (i.e. a losslessly reconstructable source code). Because we are interested in seeing how agents might converge towards such an optimal language themselves, we combine every combination of the other parameters with initial word length settings of $l = \{\log_2(o), \log_2(o) + 1, \log_2(o) + 2, \log_2(o) + 3\}$.

3.1. Evaluation Measures

In order to evaluate and understand the game dynamics the following population-level measures are used:

communicative success captures how successful agents are at solving the communicative task of identifying the topic intended by the speaker. While individual interactions result in either success or failure, averaging over many trials with the same parameter settings can be used to analyse the overall development of communicative success as a percentage of successful interactions.

alignment success is based on communicative success, but with the extra condition that the name used by the speaker is *the same name* that the listener would have used to name the object if she or he would have been chosen as the speaker. This measure is thus more indicative of whether the agents actually converge on a *shared* set of conventions, rather than simply remembering every form they encountered in their input.

average name length is the number of phonetic characters used by the agents to name objects in the communicative contexts. While this integer measure will again vary a lot between individual interactions, averaging over many trials can be used to determine overall trends.

3.2. Results

We ran 200 simulation trials in 180 different conditions, for 4000 communicative interactions each. All plots in this section display the average behaviour of the simulation across these 200 trials.

Of prime interest is of course how the different strategies fare in terms of establishing a shared communication system. A comparison of the three strategies using a representative parameter setting can be seen in Figure 1. The *winner-takes-all* strategy (left) is the only one to reach full alignment success, disrupted only by occasional cases of ambiguity caused by random erosions. The frequency-biased production and interpretation leads to a strict 1:1 mapping bias between objects and forms which completely ignores variation of the form, and the agents converge on the set of (full-length) names which were invented first. While this strategy is thus most successful at establishing a working communication system, it exhibits no dynamics whatsoever in terms of form.

The *economical* strategy (Figure 1 middle) behaves quite differently. It implements an explicit bias towards shorter forms, and convergence towards the shortest possible expected name length for a losslessly reconstructible source code occurs rapidly. While the resulting code is more economical, the unconditional acceptance of shorter conventions comes at the expense of a robust communication system, as is reflected in significantly lower communicative success rates.

The *minimal* strategy (Figure 1 right) exhibits less extreme behaviour than the other two. Rather than being geared towards some absolute external property (absolute frequency or economy), the name selection behaviour of this strategy is based on the agent's local interaction history. The language also converges towards the minimal possible name length, but with higher communicate success than the economical strategy. Neither of the two latter strategies achieve the same level of communicative success as the winner-take-all strategy, but this is a consequence of the resulting set of conventions: because the most economical codes are not redundant in any way, any occurrence of erosion is almost guaranteed to result in ambiguity and thus in communicative failure.

Let us now turn to the role of the initial word length l. Having a small inventory of possible initial names means that a lot of the randomly invented names for different objects will be homonymous from the start, resulting in ambiguity which cannot be resolved because many of the few other possible names will already be taken by yet other objects. This problem gets worse with increasingly small initial name lengths, as can be seen in the left-most panels of Figures 2 and 3. Because the form space is too small, a completely successful communication system is simply never able to get off the ground. Different strategies do however exhibit different sensitivity to the initial word lengths, confirming previously identified characteristics: the winner-take-all strategy (not shown), while inevitably suffering from a small initial inventory, still manages to establish a working set of conventions with limited communicative success. The economic strategy on the other hand struggles tremendously with small name lengths, as can be seen in Figure 2. The minimal strategy (Figure 3), while also exhibiting convergence on an economic code, does seem to do so in a more adept way, as it is able to recover as quickly as the winner-take-all strategy.

4. Conclusions & Future Work

In this article we have presented a model which extends the Naming Game paradigm to structured, particularly combinatorial, form spaces. The numerical simulations laid out here are of course only a first step, and we are already investigating how the strategies scale with larger population sizes, as well as establishing convergence proofs for the different strategies.

Our model has used the simplest possible phonetic space with only one distinction, a next step will be to introduce more structure by increasing the size of the phoneme inventory and allowing mutation of characters by modelling truly continuous phonetic spaces where the distinction of phonemes is based on their contrastive nature. This most simple simulation presented here is thus only a first endeavour into the Combinatorial Naming Game, a general model for the systematic investigation of structured form spaces.

Acknowledgments

This research was funded by a PhD grant of the Agency for Innovation by Science and Technology (IWT).

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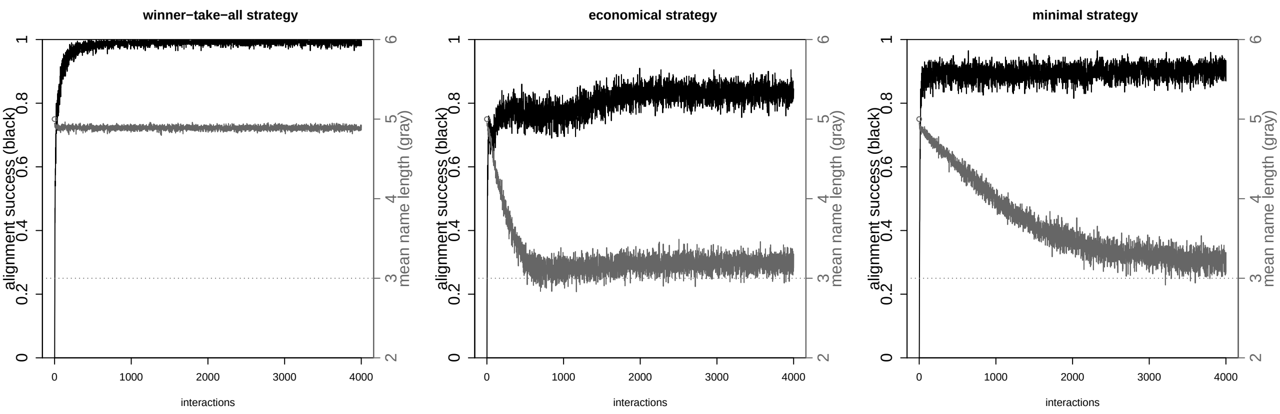

Figure 1. The impact of the the three different name selection strategies on the dynamics of the Combinatorial Naming Game with 8 objects, a context size of 8, two agents using an initial word length of $l = 5$ and an erosion probability $e = 0.05$. The graph shows the average values over 200 separate trial runs. With the economical as well as minimal strategy, the average utterance length converges towards the shortest possible expected name length for a losslessly reconstructible source code, indicated by the dotted line.

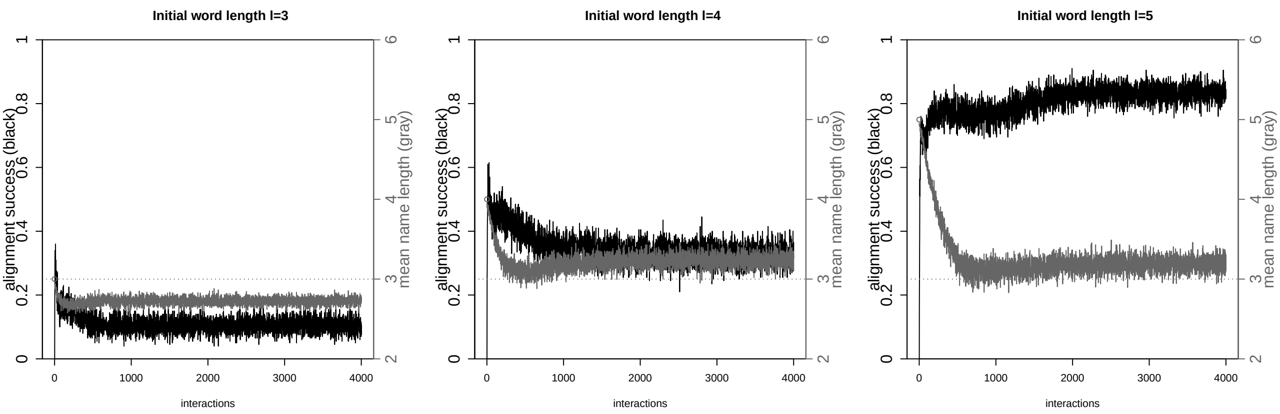

Figure 2. The impact of the the initial word length l on the dynamics of the Combinatorial Naming Game with 8 objects, a context size of 8, two agents using the *economical* strategy and an erosion probability of $e = 0.05$.

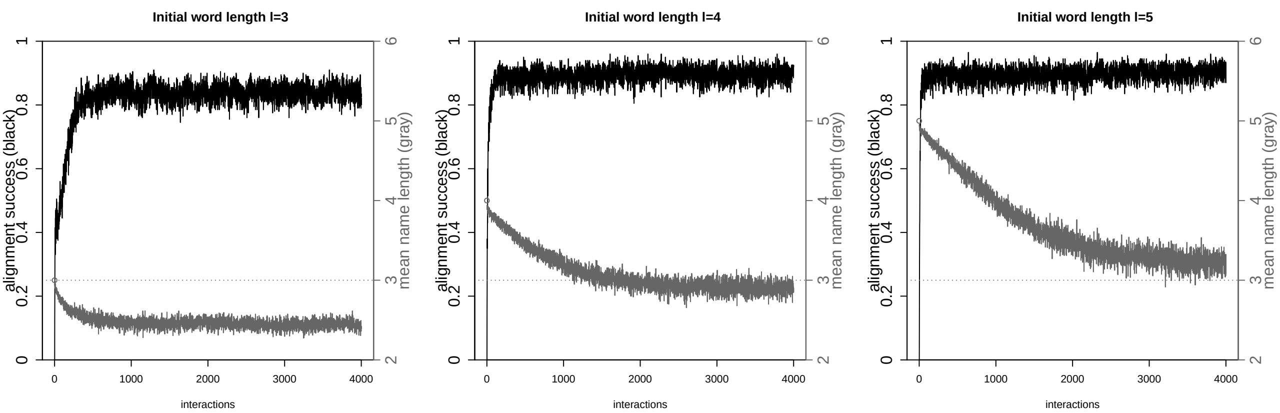

Figure 3. The impact of the the initial word length l on the dynamics of the Combinatorial Naming Game with 8 objects, a context size of 8, two agents using the *minimal* strategy and an erosion probability of $e = 0.05$.