

# Iterated Learning versus Language Games. Two models for cultural language evolution.

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## **Abstract**

The paper compares two models that are currently intensely studied for explaining and modeling the origins and evolution of language: the iterated learning model and the language game approach. It introduces a number of challenges that all evolutionary language models must satisfy and examines how further progress might be achieved.

## **1 Introduction**

Almost since the beginning of research in Artificial Life and the simulation of adaptive behavior, there have been efforts to apply biological principles and the methodology of building artificial systems to understand the origins and evolution of language, not only by abstract software simulations but also by experiments with situated embodied robotic agents operating in real world environments ([11], [3]). The key idea is to view language as a complex adaptive system which emerges in a bottom-up fashion from local one-on-one interactions between situated embodied agents, and evolves and complexifies based on biologically inspired principles like selection or self-organisation. Rather than looking only at natural languages as they exist today, this research in 'artificial language evolution' tries to evolve artificial languages with natural language like properties - and thus explores the space of possibilities the same way artificial life explores the space of possible life forms [6]. Moreover the languages are not considered to be static: Attempts are made to have them evolve in ways that are similar to human language evolution.

Research on artificial language evolution is relevant in several ways to the general questions of the evolution of social behavior and the role of self-organisation. Communication is obviously a very important feature of higher animals, particularly humans, and it is intimately tied with social behavior. Indeed it has been argued that it is through the increasing power of communication that complex social structures have been able to evolve and conversely that language itself is primarily driven by social needs [4]. Moreover research into the origins and evolution of language gives a concrete domain for studying the origins of social norms in a group and how such norms can be preserved through cultural transmission.

The meaning-form mappings used in natural languages are extraordinarily intricate. The lexicon more or less directly maps meaning onto form (such as the concept 'red' into the word "red") but the grammar clearly introduces a multilayered mapping. For example, almost every language features a grammar of case to express the role of objects in events. English uses word order and prepositions (as in "John gave Mary the ball" versus "Mary gave John the ball"). German uses morphological endings attached to nouns and articles. Rather than mapping a certain event-object relation directly to a marker (which would imply a large repertoire of markers), the event-object relation is first categorised in terms of semantic roles such as agent, patient, beneficiary, etc. which is then mapped onto syntactic cases such as nominative, accusative, etc. and those are then mapped onto surface forms. Other grammatical systems like for the expression of tense and aspect have equally complex multi-layered and language-dependent mappings. Moreover the meaning-form mappings are not uniform throughout the population and are in constant evolution [16]. Sometimes this evolution is very rapid, taking place during the lifespan of individuals.

So, a theory of the origins of language must address (at least) the following questions:

- [1] Origins of structure: How do meaning-form mappings originate and how can they become more complex.
- [2] Origins of coherence: How do agents in the population arrive at a shared set of mappings. This is a major issue because one cannot assume that agents can mind read nor that they have a global view. There is also no centralised control on how everybody should speak.
- [3] Origins of meaning: How can language-specific conceptualisations (like semantic roles) originate in co-evolution with grammar and become shared by the members of the language community?

[4] Realism: What does it take to evolve 'natural language like' grammars? For example, how can we explain the emergence of parts of speech, cases, tense, mood, and aspect, determiners, subclauses, relative pronouns, topic-comment structures, etc.?

This paper compares how two models which have been widely discussed in the literature, the Iterated Learning Model (ILM) and the Language Game Approach (LGA), address these issues. Both models emphasise a cultural evolution of language, in the sense that agents acquire language conventions (lexicon and grammar) by a learning process instead of being supplied with these conventions by direct copying from 'parents' as in some of the earliest Alife models of language evolution [7].

## 2 The Iterated Learning Model

Around 1995, a group of researchers, mostly working from Edinburgh, started to develop a model for cultural evolution which has been called the Iterated Learning Model (ILM) [5], [1] [17]. This work focuses particularly on the transition from a holistic language (where a complex meaning is expressed by a single form) to a compositional language (where composite meaning is expressed with composite form). Very briefly, the model consists of four components: (1) A finite meaning space which is shared a priori by all agents. In some experiments this space consists of random numbers, in other experiments predicate calculus expressions are used. (2) A form space which typically consists of random combinations of characters, (3) A population of language learning agents, and (4) A population of language producing agents. Each agent has an associative memory of meaning-form mappings. These mappings either associate a complete meaning with a complete form, or map partial meanings into a combination of terminal and non-terminal symbols, thus realising a compositional syntax. There is no strict separation of lexicon and grammar. The language producing agents have the capability to produce sentences relating meaning to form using the grammar. The language learning agents have the capability to learn the grammar produced by the language producing agents through statistical learning. It does not matter so much which learning algorithm is used; results have been reported ranging from neural networks to symbolic grammar induction based on minimal description length [1].

The agents in the initial population start with a random lexicon/grammar

so that they can always produce, as speakers, an utterance to express a randomly generated meaning. The simulation goes through cycles. Each cycle iterates through a series of cultural transmissions. Each step involves the following actions: The language producer constructs an utterance for a specific meaning in the meaning space and transmits to the language learner both the utterance *and* the meaning. The language learner attempts to use his existing grammar to relate this utterance to the meaning and expands or adapts the grammar if that fails. After a certain number of iterations, the population of language producers is replaced by the population of language learners and a new population of language learners is created. There is no genetic transmission of language.

Simulations with the iterated learning model consistently show an important phenomenon. Agents have a choice whether to use compositional or holistic language. When there is a very small sample set from which they can learn, no stable language emerges. When there is a very large set of examples, the language expresses all meanings that can be expressed in an ad hoc way. However when the training set is medium-sized, a learning bottleneck arises because the agents do not have enough data to learn separate forms for every meaning. In those circumstances, a compositional language is preferred. Agents develop rules that compactly represent a broad range of situations through the use of non-terminal symbols and these rules get culturally transmitted.

The ILM clearly addresses the first issue raised earlier (namely the origins of structure). It shows that starting from a random initial grammar in which complex meanings are expressed by single forms, a compositional language arises, due to efforts of the learning agents to find a syntactic description that is more compact than a mere list of meaning-form pairs. This complexity arises by the introduction of non-terminal symbols that support compositional syntax. The more compact (and thus more structured) the grammar, the more reliably it can be learned and hence transmitted across the learning bottleneck.

It is not clear however how ILM addresses the second issue (namely the origins of coherence). In simulations shown so far, the learning population is reduced to a single agent and the producing population to a single agent as well. In such circumstances the issue of coherence does not arise. But it is not obvious that, if language learners sample from a set of language producers, there is ever going to be global coherence. It is also not clear how language-specific conceptualisations and hence realistic grammars could

evolve in this framework. The primary motivation of grammar is seen as enabling transmission in the absence of exhaustive data. The structure that is imposed by language learners is not motivated by expressive needs but is stochastic, and it will survive if this structure can be learned.

### 3 Language Games

From around 1995, I have been developing an alternative set of models for cultural evolution, together with students and collaborators. For the remainder of this text, this approach is called the Language Game Approach (LGA). Work has focused first on the lexicon [10], and then on the co-evolution of language and (grounded) meaning in large evolving populations [14]. More recently the transition from a lexical language to a grammatical language has become our focus of attention [13].

The language game approach starts again from a population of distributed agents. The agents maintain a repertoire of meanings (the meaning space) which is open-ended and co-evolving with the language system. Agents maintain knowledge about the language in terms of meaning-form mappings that are used both for parsing and for producing. However, no distinction is made between learners and producers. Agents take turns being speaker and listener. When they play the role of speaker they may take the initiative to expand their own lexicon or grammar whenever they fail to express adequately what they want to say. When they play the role of hearer they may learn a new piece of lexicon/grammar if they fail to parse adequately what was said but could still guess the meaning based on shared context. Hearers learn from randomly drawn members of the population not just from a single 'adult' language producer. The composition of the population is allowed to change, but it consists of deleting single individuals or adding new ones (without any prior knowledge of the language) at a certain rate, rather than a wholesale replacement of the population in every cycle, as in the ILM.

Agents engage in interactions called language games. A language game is a routinised interaction between two situated embodied agents in a shared environment. In some experiments, the agents are autonomous physical robots freely interacting with the environment [15]. Each language game goes as follows: The speaker chooses what to say depending on the game. For example, in a guessing game where the speaker wants to identify an object in the environment, the speaker chooses the object and the distinctive proper-

ties that can be used to identify it. Next the speaker uses his own language system (lexicon and grammar) to produce an utterance. The utterance is transmitted to the hearer - but NOT the meaning that it expresses. The hearer then parses the utterance with his own language system to obtain a semantic structure that is then interpreted in the shared situated context. A language game typically involves some action in the world, like identifying an object, carrying out an action, etc. When this action fails the speaker gets pragmatic feedback which could lead to further exchanges (including gestures) to nevertheless reach communicative success.

In ILM, new structure comes primarily from language learners. In LGA, new structure is primarily a side effect of language producing. It is driven by three objectives: increase the expressive power of the language, optimise the chance of communicative success, and economise on means. The agents achieve this by recruiting general cognitive abilities such as analogy. More concretely, the language producer introduces new words if necessary and these will be picked up by the hearer based on his (partly guessed) interpretation of the utterance. In the simulations reported in [13] the language producer re-parses the utterance he is about to produce with his own current lexicon/grammar to detect ambiguities, chances of misinterpretation, or inefficient processing and then introduces additional forms to alleviate these problems. For example, the ambiguity about which object plays what role in an event can be avoided by explicitly marking these roles, thus laying the foundation for a grammar of case. The drive towards an economy of means is the main motor to introduce an extra layer in the grammar. Rather than introducing new markings, the language producer seeks an analogy and reuses existing markers thus introducing grammatical categories as a side effect. The listener then uses the same sort of analogies to induce the expanded use of a form. Of course, the language structures introduced by language producers must be learnable, otherwise they would not survive in the population. But the introduction of new structure in LGA is crucially driven by the needs to optimise communication. The learner hypothesises meanings of unknown words or grammatical constructs by guessing the meaning gaps they may fill.

The Language Game Approach has paid a great detail of attention to the question how coherence may arise in a population, not only of the language conventions themselves but also the meanings that underly them. The principle of self-organisation, which has been pioneered in the study of natural complex systems [2], has turned out to be an effective solution. Self-

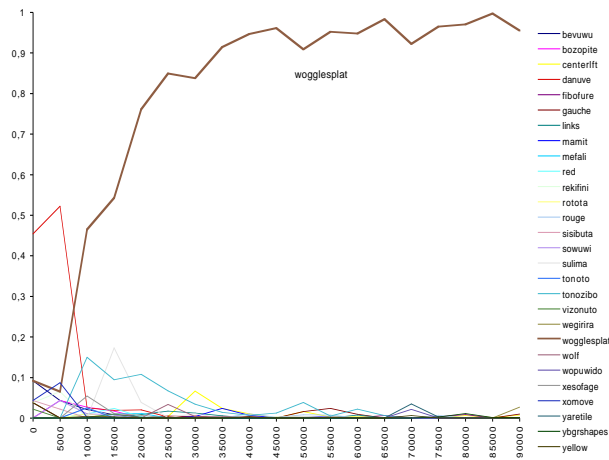


Figure 1: A meaning-form diagram which graphs for a specific meaning all the possible forms and their score. A winner-take-all situation is clearly observed. X-axis shows language games and y-axis the score of forms. There is a steadily growing population reaching 1500 agents towards the end.

organisation (in the sense of global coherence from only local interactions between the agents) arises when there is a positive feedback loop, so that certain fluctuations get reinforced and spread in the total system. It occurs in a wide variety of natural systems, from the Bhelouzow-Zhabotinsky reaction to lasers and ecosystems. In all LGA models, self-organisation is implemented by coupling use and success, see also [9]. Agents keep a score for each rule in their lexicon/grammar. In case of multiple rules (more than one rule covering the same meaning or more than one rule covering the same form) the one with the highest score is preferred. When a game succeeds, i.e. when there is communicative success, the score of the rules used is increased and that of competitors is decreased, thus causing lateral inhibition. In case of failure, the score of each rule that was used is decreased. The positive feedback between use and success indeed causes coherence in the population, as shown abundantly in computer simulations and supported by mathematical analysis. (see figure 1). Moreover a structural coupling of language evolution and meaning creation causes coherence in the meaning spaces used by the agents [14].

In conclusion, computer simulations and robot experiments with the Language Game Approach have consistently shown progress for the four main

challenges introduced earlier: (1) A set of meaning-form mappings arises, which gets more complex, particularly by the introduction of grammatical categories mediating between meaning and form. (2) These mappings become gradually shared by the members of an evolving population, even one containing thousands of agents, due to self-organisation. (3) The language-specific conceptualisations co-evolve with the syntactic means to express them. (4) More realistic grammars evolve (so far only in the domain of case grammars [13]) although much more additional research is needed to investigate other domains of grammar.

## 4 Discussion

Although both approaches discussed here for the cultural evolution and transmission of language share many characteristics, there are some clear differences. These differences are not just a matter of style or focus, they point to profoundly different assumptions about how the origins of grammar can or should be explained. The main difference concerns the nature of grammar itself. In the ILM, grammar is a system for the compact coding of meaning into form. Its primary purpose is to overcome the transmission bottleneck through a compositional as opposed to holistic mapping. In LGA, grammar is above all a way to optimise communication: to express more meaning with less form and increase the chance that the communication succeeds. These different views on grammar reflect the ongoing debate which occurs in the linguistic community between formalists and functionalists [8]. If a functionalist position is taken, as in LGA, communication is the essential background against which language evolves. In the ILM, which adopts a formalist view on grammar, communicative success and scope does not play a role. In the LGA, communicative success determines whether certain structures will propagate and be maintained by the population. Increasing communicative success is the prime motivator of new structure.

A second important difference lies in the use of self-organisation. In LGA self-organisation is viewed as a corner stone, because it is the way coherence arises in the population. The implementation of self-organisation requires pragmatic feedback on success in the communication and a more complex internal representation of the lexicon/grammar using scores. ILM does not address the issue of coherence (at least not in its current form) and it may require a major revision to do so. Specifically, it may well be that the

purely observational approach to language learning (i.e. without pragmatic feedback) is insufficient to reach coherence, particularly if language learners are NOT given the unique meaning being expressed by the language producer and if the population is large enough that some agents may have developed other competing rules.

A final important difference concerns the question of the origins of meaning. From the viewpoint of LGA, meaning co-evolves with language. It is not possible to provide all meanings in advance because meaning is open-ended and to a large extent language-specific. Hence the emphasis on using embodied agents grounded by their perceptual system in the real world.

## References

- [1] Brighton, H. (2002). Compositional Syntax from Cultural Transmission. *Artificial Life*, 8(1)
- [2] Camazine, S. J-L Deneubourg, N. Franks, J Sneyd, G. Theraulaz, and E. Bonabeau (2001) *Self-Organization in Biological Systems*. Princeton University Press, Princeton.
- [3] Cangelosi, A. and D. Parisi (eds.) (2001) *Simulating the Evolution of Language*. Springer-Verlag, Berlin.
- [4] Dunbar, R. (1997) *Grooming, Gossip, and the Evolution of Language*. Harvard University Press, Cambridge Ma.
- [5] Kirby, S. and J. Hurford (2001) The Emergence of Linguistic Structure: An Overview of the Iterated Learning Model. In: [3].
- [6] Langton, C. (ed.) (1989) *Artificial Life*. Addison-Wesley, Reading Ma.
- [7] MacLennan, B. (1990) Synthetic Ethology: An Approach to the Study of Communication In: Langton, C. et.al. eds. (1992) *Artificial Life II: The Second Workshop on the Synthesis and Simulation of Living Systems*. Addison-Wesley. pp. 631-658.
- [8] Newmeyer, F. (1998) *Language Form and Language Function*. The MIT Press, Cambridge Ma.

- [9] Oliphant, M. and J. Batali. (1997) Learning and the emergence of coordinated communication. The newsletter of the Center for Research in Language, 11(1), 1997.
- [10] Steels, L. (1996) A Self-organizing Spatial Vocabulary. *Artificial Life Journal*. 2(3) 1996.
- [11] Steels, L. (1997) The synthetic modeling of language origins. *Evolution of Communication*, 1(1):1-35.
- [12] Steels, L. (2001) Language Games for Autonomous Robots. *IEEE Intelligent systems*, September/October 2001, p. 16-22.
- [13] Steels, L. (2002) The Grounded and Situated Learning of Case Grammar. *Conference on Cognitive Linguistics*. Valencia, Spain.
- [14] Steels, L., F. Kaplan, A McIntyre and J. Van Looveren (2001) Crucial factors in the origins of word-meaning. In Wray, A., editor, *The Transition to Language*, Oxford University Press. Oxford, UK, 2002.
- [15] Steels, L. and F. Kaplan (2001) AIBO's first words. The social learning of language and meaning. *Evolution of Communication* 4(1).
- [16] Traugott, E. and Heine, B. (1991) *Approaches to Grammaticalization*. Volume I and II. John Benjamins Publishing Company, Amsterdam.
- [17] Zuidema, W. (2001) Emergent syntax: the unremitting value of computational modeling for understanding the origins of complex language. In: Kelemen, J. and P. Sosk (eds.) *Proceedings of ECAL01*. Springer Verlag, Berlin, pages 641-644.