Evolution of synonyms and homonyms in signaling game with reinforcement learning

Dorota Lipowska (Adam Mickiewicz University, Poznań, Poland)

keywords: synonymy, homonymy, signaling game, reinforcement learning

Evolution and structure of language is often analysed using computational modelling (Cangelosi, Parisi 2002, Nolfi, Mirolli 2010, D'Ulizia *et al*. 2020). The idea that language might have spontaneously appeared in a population of communicating individuals, possibly with some adaptive features (Pinker, Bloom 1990), prompted numerous analyses of multi-agent models, which mimic such communication trying to infer the properties of the emerging language and its possible further evolution (Steels 2012, Gong *et al*. 2014, Kirby *et al*. 2014).

In particular, language emergence and evolution can be studied using a signaling game (Lewis 2002), where agents can utilise, e.g., reinforcement learning to select a signal to send or interpret a received signal (Lenaerts *et al*. 2005, Barrett 2006, Skyrms 2010, Franke 2016, Lipowska, Lipowski 2018).

Signals can be regarded as words and the form-meaning mapping that emerges during the signaling game as language. It can be a one-to-one correspondence (a signaling system) but homonyms or synonyms can also emerge and then change in time (their frequency may vary, some forms may disappear). Although linguistic data are difficult to interpret, there are some indications that in natural languages synonyms are quite rare in contrast to homonyms, which appear to be more common (Hurford 2003, Clark 1990). Some linguists even insist that true synonyms do not exist or at best are very rare compared to homonyms (Lyons 1981, Goldberg 1995). There are some arguments that the difference in the frequency of synonyms and homonyms may be due to evolutionary pressures favouring speakers rather than hearers (Hurford 2003), or to language acquisition in childhood (Markman 1989).

Let us notice that synonyms actually compete in quite a different way from homonyms, which can be demonstrated already within the framework of the signaling game. While synonymous words compete for being selected by a speaker, for a homonymous word, it is the hearer's role to assign an appropriate interpretation. It is thus possible that such a difference can affect an overall dynamics of synonyms and homonyms and eventually result in different degrees of their prevalence.

We approached the problem of evolution and stability of synonyms and homonyms using computer simulations of a multi-agent signaling game (Lipowska, Lipowski 2022). We show that an agreement with the above mentioned linguistic observations is achieved when the reinforcement learning that we implemented operates in the so-called super-linear regime with probabilities of selections increasing faster than linearly with the accumulated weights. The linear regime would, instead, lead to languages with very stable synonyms and relatively fast decaying homonyms.

An interesting question is why nonlinear rather than the simplest linear feedback drives linguistic processes. Related studies in marketing or economic contexts showed that the total value of certain competing consumer products grows faster than linearly with the number of users, which is referred as Metcalfe's Law (Shapiro, Varian 1998). In a signaling game and in linguistic context, it would mean that a benefit of using a certain word (and thus a probability of its future selection) increases faster than linearly with the number of successful communications. Furthermore, such studies can be carried out under mathematical setup of the so-called urn models (Arthur 1994), which is basically similar to our approach. Overall, our work indicates that the analysis of the prevalence and evolution of synonyms and homonyms in natural languages may give us some valuable clues as to the nature of the mechanisms that drive linguistic processes.

References

Arthur, W. B. (1994). *Increasing returns and path dependence in the economy*. University of Michigan Press.

Barrett, J. A. (2006). *Numerical simulations of the Lewis signaling game: Learning strategies, pooling equilibria, and the evolution of grammar*. UC Irvine: Institute for Mathematical Behavioral Sciences.

Cangelosi, A., Parisi, D. (Eds.). (2002). *Simulating the evolution of language*. London: Springer-Verlag.

Clark, E. V. (1990). On the pragmatics of contrast. *Journal of Child Language*, 17(02), 417–431.

D'Ulizia, A., Ferri, F., Grifoni, P. (2020). A survey on modeling language evolution in the new millennium. *New Generation Computing*, 38(1), 97–124.

Franke, M. (2016). The evolution of compositionality in signaling games. *Journal of Logic, Language and Information*, 25(3), 355–377.

Goldberg, A. E. (1995). *Constructions: A construction grammar approach to argument structure*. Chicago: University of Chicago Press.

Gong, T., Shuai, L., Zhang, M. (2014). Modelling language evolution: Examples and predictions. *Physics of Life Reviews*, 11(2), 280–302.

Hurford, J. R. (2003). Why synonymy is rare: Fitness is in the speaker. In: W. Banzhaf, T. Christaller, P. Dittrich, J. T. Kim, J. Ziegler (Eds.), *Advances in Artificial Life. Proceedings of the Seventh European Conference on Artificial Life ECAL 2003* (Vol. 2801, pp. 442–451). Berlin, Heidelberg: Springer-Verlag.

Kirby, S., Griffiths, T., Smith, K. (2014). Iterated learning and the evolution of language. *Current Opinion in Neurobiology*, 28, 108–114.

Lenaerts, T., Jansen, B., Tuyls, K., De Vylder, B. (2005). The evolutionary language game: An orthogonal approach. *Journal of Theoretical Biology*, 235(4), 566–582.

Lewis, D. K. (2002). *Convention: A philosophical study*. Oxford, UK: Blackwell.

Lipowska, D., Lipowski, A. (2018). Emergence of linguistic conventions in multi-agent reinforcement learning. *PLoS ONE*, 13(11), e0208095.

Lipowska, D., Lipowski, A. (2022). Stability and Evolution of Synonyms and Homonyms in Signaling Game. *Entropy* 24(2), 194.

Lyons, J. (1981). *Language, meaning and context*. London: Fontana.

Markman, E. M. (1989). *Categorization and naming in children: Problems of induction*. MIT Press.

Nolfi, S., Mirolli, M. (Eds.). (2010). *Evolution of Communication and Language in Embodied Agents*. Berlin, Heidelberg: Springer-Verlag.

Pinker, S., Bloom, P. (1990). Natural language and natural selection. *Behavioral and Brain Sciences*, 13(4), 707–727.

Shapiro, C., Varian, H. R. (1998). *Information Rules: A Strategic Guide to the Network Economy*. Harvard Business Press.

Skyrms, B. (2010). *Signals: Evolution, Learning, and Information*. Oxford, UK: Oxford University Press.

Steels, L. (Ed.). (2012). *Experiments in Cultural Language Evolution* (Vol. 3). Amsterdam: John Benjamins.