Spontaneous emergence of large shared signalling systems with and without referential transmission

Richard A Blythe[*1,2] and Casimir Fisch[1,3]

[*]Corresponding Author: r.a.blythe@ed.ac.uk
[1]School of Physics and Astronomy, University of Edinburgh, Edinburgh, UK
[2]Centre for Language Evolution, University of Edinburgh, Edinburgh, UK
[3]Department of Earth Sciences, ETH Zürich, Zürich, Switzerland

The transition from a state in which signals are used randomly, and are therefore uninformative, to one in which multiple agents use the same signal to convey a specific meaning has long been studied in the field of language evolution (e.g. Hurford, 1989) and related fields (e.g. Lewis, 1969). Although initially most communicative interactions will fail, models (Spike, Stadler, Kirby, & Smith, 2017; Lipowska & Lipowski, 2022; Zubek, Korbak, & Rączaszek-Leonardi, 2022) and experiments (Galantucci & Garrod, 2011) each demonstrate that chance agreement between a pair of agents on a signal's meaning can seed the growth of an *optimal* signalling system in which the probability of a successful communication is maximised. In a recent survey, Spike et al. (2017) propose three basic ingredients that are required to make this work. These are: (i) transmission of referential information; (ii) a bias against ambiguity; and (iii) loss of memory of specific interactions over time. Roughly speaking, these are needed so that (i) the hearer has a chance of guessing the correct meaning; (ii) the system is guided towards optimality; and (iii) a suboptimal state does not become frozen in.

Here, we build on this work by addressing one technical and two conceptual limitations of the many models that Spike et al. (2017) unify into a common framework. The technical limitation is that conclusions and generalisations drawn in the language evolution literature are often based on simulations that are limited in terms of the system size (numbers of agents, meanings and signals) that can be accessed. A natural question is whether arbitrarily large signalling systems (e.g., those with many meanings) can spontaneously arise. At the conceptual level, many studies focus on the ideal case where the number of available signals equals the number of meanings to convey. The question of what happens when there are many more possible meanings than signals available to express them is less well explored. Most fundamentally, it is almost always assumed that agents have some means to communicate whether the intended referent was successfully communicated, whether explicitly (e.g. by pointing, Steels & Belpaeme, 2005) or implicitly through the response to an environmental state that delivers a payoff to signaller and receiver (e.g. Lewis, 1969). One may worry what benefit is conferred by signalling when agents already have available some other reliable means to transmit their referential intention (Oliphant & Batali, 1997).

We address all three limitations by constructing a unified *mathematical* model that includes as special cases many of the different simulation models that have been studied. The general case manifests as a combination of reinforcement learning with memory loss and lateral inhibition (simulated explicitly by Oh & Kim, 2021). It can further be related to the replicator equations of evolutionary game theory (Nowak & Sigmund, 2004), wherein referential transmission enters into the fitness. Particularly, we can apply linear stability analysis (Glendinning, 2012) about an initially uninformative state to identify when multiple agents simultaneously amplify the same signal-meaning associations. This analysis reveals that although increasing the number of agents or number of signals reduces the rate at which associations systematise, this does not pose a barrier to the emergence of an informative signalling system. On the other hand, increasing the size of the meaning space whilst holding the number of signals fixed can render the uninformative initial state inescapable when agents punish a failed interaction by decreasing the relevant meaning-signal association. In short, rewarding success, but ignoring failure, is a robust mechanism for building a shared communication system of arbitrary size.

Most significantly, we find the same outcome is possible even when agents cannot assess (let alone communicate) the success or failure of an interaction, but instead resort to cues (which need not be linguistic) to guess a plausible meaning. This is distinct from the scenario in signalling games (Lewis, 1969; Skyrms, 2010), where the signaller seeks to convey a hidden environmental state to a recipient, whose subsequent behaviour then confirms if their inferrence was correct or not. In our approach, the recipient appeals to *cross-situational learning* (Siskind, 1996), where repeated uses of a word in similar contexts allows a child to reconstruct an adult's pre-existing mapping between words and meanings, even when every instance of use is infinitely ambiguous and there is zero feedback (Blythe, Smith, & Smith, 2016). In the present work, we show that a common lexicon can be built through the same learning mechanism, even when starting from a state in which signals are uninformative. In other words, shared contexts of use are sufficient to provide the referential information required for an optimal signalling system to emerge, despite the presence of ambiguity and no pre-existing means for agents to judge or communicate the success or failure of their interaction.

Taken together, our findings suggest that small-scale computational and laboratory models of the emergence of linguistic systems and structures are representative of what happens in larger and more complex systems. Moreover, they demonstrate the existence of a process by which a species with no pre-existing ability to transmit referential information may acquire the ability to do so.

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