ACCOUNTING FOR POLYSEMY AND ROLE ASYMMETRY IN THE EVOLUTION OF COMPOSITIONAL SIGNALS

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Abstract. Several formal models of signalling conventions have been proposed to explain how and under what circumstances compositional signalling might evolve. I suggest that these models fail to give a plausible account of the evolution of compositionality because (1) they apparently take *linguistic* compositionality as their target phenomenon, and (2) they are insensitive to role asymmetries inherent to the signalling game. I further suggest that, rather than asking how signals might come to be compositional, we must clarify what it would mean for signals to *be* compositional to begin with.

Keywords — Signalling Games, Compositionality, Evolution of Language

1. Introduction

Simple communication systems, which are ubiquitous in nature, are disparate from fully-fledged natural languages, which are often said to be unique to humans. This raises the question: *What are the salient differences between communication and language?* Several answers suggest themselves. Most researchers hold that the openness (i.e., productivity, generative capacity, hierarchical structure) of natural languages is a *key* distinguishing feature. For example, arbitrary, meaningless phonemes can be combined in a potentially infinite number of ways to create meaningful morphemes; similarly, sounds combine to form words, and words combine to form phrasal expressions and sentences. Thus, with a finite lexicon and a finite set of grammatical rules, natural languages 'contain' a potentially infinite number of unique, semantically meaningful, and syntactically well-formed expressions.

To account for this, researchers often point to a principle of compositionality, which is typically formulated as follows (Kamp and Partee, 1995; Szabó, 2012):

> **Definition 1.1:** *Principle of (Linguistic) Compositionality.*
> The meaning of a compound [complex] expression is a function of the meaning of its parts [constituents] and the ways in which they are combined [composed].

This formulation is 'theory-neutral' in the sense that it requires and entails no specific commitments about, e.g., what 'meanings' or 'ways of combining' might actually be. This principle arises in virtually any field of study concerned with

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language and meaning and serves to explain a number of observable facts about human language—including its productive and interpretative flexibility, and its systematicity and learnability, among others.

This provides a plausible *explanatory target* for a theory of language origins. Thus, any attempt to give an evolutionary explanation of human-level linguistic capacities will minimally need to account for the following: (1) how compositionality might arise from non-compositional communication; (2) if compositionality itself is an evolutionary adaptation, why compositional structure should be selected for in the first place; (3) why compositionality should be rare in nature, though communication is universal.

Several models have been suggested in recent years which grapple with these questions using the signalling-game framework. Signalling games show how extremely simple communication conventions might arise naturally through processes of repeated interactions. In an evolutionary context, starting with initially random signals and actions, individuals in a population learn or evolve effective communication under a number of different dynamics. Evolutionary signalling games constitute a now-standard model for explaining and studying the emergence of communication in a wide range of social organisms—from humans down to bacteria.

In this paper, I suggest that the evolutionary explanations for compositional *signalling* offered thus far fail to give a plausible account of how compositionality might arise. The reason for this failure is twofold. On the one hand, these models often (if implicitly) take compositionality *qua* linguistic compositionality (Definition 1.1) as their target for an evolutionary explanation. This gives rise to significant complications insofar as linguistic compositionality is rife with conceptual difficulties. By presupposing that the theoretical target of our evolutionary explanation is equivalent to this robust notion of compositionality, these models inherit all the philosophical baggage associated with such a notion—this will be discussed in further detail below. On the other hand, these models fail to take into account the role asymmetry of the sender and receiver in the signalling game and thus fail to capture how compositionality might be beneficial for communication. To surmount these problems, I suggest that it is more fruitful to build a notion of compositional *signalling* 'bottom-up', as it were. This requires, first, demarcating atomic and complex signals and, second, providing a clear specification of what it would mean for complex signals so defined to be compositional—as opposed to, e.g., merely combinatorial—in the first place.

2. Signalling Games

The signalling game was introduced by Lewis (1969) to explain how conventional meaning can arise via coordination between individuals. The signalling game has two players, called the *Sender* and the *Receiver*. In the simplest case, there are two states of the world (s_1 and s_2), two signals or messages (m_1 and m_2), and two actions (a_1 and a_2). Nature picks a state at random. The sender observes the state directly and chooses a signal to send to the receiver. The receiver, who does not know the state, observes the signal and must choose an appropriate action. Each action is a correct response to a single state. If the action matches the state, then both players receive a payoff of 1; otherwise, they receive nothing. This is referred to as a 2×2 signalling game.

A pure strategy for the sender [receiver] is a function that maps each of the states [signals] to a signal [action]; the players have evolved or learned an efficient 'language' when they perform better than chance on coordinating signals to state-act pairs. Two combinations of sender and receiver strategies are perfectly communicative in the 2×2 signalling game. Lewis (1969) refers to these maximally-efficient combinations of strategies as the *signalling systems* of the signalling game. In either case, at a signalling system for the 2×2 signalling game, the sender and receiver have a communicative success rate of 1, and each signal carries exactly 1 bit of information. An evolutionary model consists of the underlying signalling game and a *dynamic*, which is a set of rules for determining how the players' strategies change over time.[1]

What signals are is generally left unspecified. In terms of modelling protolanguage, this is a theoretical virtue. A signal may be lexical, gestural, or a syntactically complex string that is interpreted as an atomic whole (as in bird song or whale song). In the signalling game, a signal is a holophrastic unit which cannot be decomposed, and which may stand for a complex proposition-like indicative (such as "there is a leopard nearby") or imperative (such as "climb up a tree!"). However, it stands to reason that it should be possible to show how structured, complex signals might evolve. Several models have been suggested to account for complex signals with compositional structure—e.g., signal-object associations (Nowak and Krakauer, 1999), syntactic signalling (Barrett, 2007), creative compositionality and lateral inhibition (Franke, 2016), and functional negation (Steinert-Threlkeld, 2016).[2]

3. Two Problems for Evolutionary Models of Compositionality

The first problem in these evolutionary explanations arises from an equivocal use of 'compositionality'. In each case, what it means for a signal to be compositional is presupposed and often undefined. It appears that the pre-theoretic assumption consists in 'compositionality' just being equivalent to the notion of *linguistic* compositionality, as given in Definition 1.1. This is problematic for at least two reasons.

On the one hand, Szabó (2012) points out that this formulation gives rise to several pressing questions. For example, does 'is a function of' mean 'is determined by'? Or, does it mean there is a function to the meaning of a complex expression from the meanings of its constituents and of the way they are combined? Further, are we concerned with the meanings that the constituents have individually, or the meaning that they have when taken together? Szabó (2012) suggests that the various ambiguities inherent in this formulation combine to give at least 8 distinct readings of what compositionality is! Any evolutionary explanation that assumes *linguistic* compositionality as an explanatory target of compositional *communication* thus inherits all of the complexity and ambiguity of this concept.

As of yet, we lack a coherent and concrete way of saying why a complex signal ought to be considered compositional, as opposed to atomic or merely combinatorial.[3] This problem directly mirrors contention within the biological and linguistic

[1] See Skyrms (2010) for a general introduction to signalling games and their extensions.
[2] More recent proposals have been offered by Steinert-Threlkeld (2019) and Barrett et al. (2019).
[3] Examples of combinatorial but non-compositional signals are discussed below.

literature on whether certain species' communication systems are indeed compositional. For example, Arnold and Zuberbühler (2008) suggest that Campbell's monkeys have syntactically complex communication systems. This and related papers are often cited as evidence of compositionality in nature; however, Hurford (2012) univocally holds that no communication system outside of human language is compositional. Might it not be the case that the latter implicitly defines 'compositionality' as linguistic compositionality, whereas the former has in mind a more simplified notion of compositionality?

It appears that much of the debate is, in essence, a matter of talking past one another due to a lack of clear and coherent definition of the constitution of compositional *signals*. It is undeniable that examples of complex signals exist in nature. However, it is an open question whether these complex signals are compositional or not; a presupposition of what it means for a signal to be compositional seems to be inherited from a pre-existing conceptual understanding of linguistic compositionality. As a result, prior theoretical biases seep into the discussion of what counts as a compositional signal in the first place. It appears that, at best, 'compositionality', as it is discussed in the literature on evolutionary compositionality, succumbs to a covert polysemy; so, the question of whether a communication system in nature is indeed compositional is grossly underdetermined.

Providing an explicit specification of what it means for a complex signal to be compositional should be the preeminent target for future work in the evolution of compositional communication. Conceptual clarity in this definition will have downstream benefits in building models that explain the evolutionary emergence of this sort of target phenomenon.

On the other hand, implicitly taking linguistic compositionality as the target of one's evolutionary explanation appears to run afoul of the *gradualist* perspective necessary for an adequate evolutionary account.[4] The gradualist view posits a *protolanguage* between these evolutionary stages in linguistic development. In almost every case, the explanatory target of protolanguage is proto-*syntax*.[5] In order to explain the emergence of linguistic compositionality, we would need first to explain how some proto-compositional precursor might arise. This sentiment is certainly present in the preceding accounts of compositional signals; however, the actual *proto-compositional* target is never made explicit. For example, Franke (2016) explicitly discusses compositionality versus proto-compositionality and the need for a gradualist perspective; however, when he outlines his desiderata, he refers to the agents' ability to react to novel stimuli in a 'compositional-like' way, but does not make explicit in what this consists.

The problem is that compositionality appears to be a binary feature: a communication system either is compositional, or it is not. Similarly, a syntax either is hierarchical or not. If the focus is syntax, then the gradualist implicitly posits a significant leap from non-compositional, pre-syntactic protolanguage to full-blown compositionality.

In the rest of this paper, I examine the possibility of salvaging a gradualist perspective with respect to compositionality. In the spirit of clarity, I suggest that it is apt to abstract away the complexities of linguistic compositionality, and examine a simple model of compositional *signals*. Under these circumstances, what

[4]See LaCroix (2019a,b).
[5]See Progovac (2019).

does 'compositionality' look like? Is it possible to fill in some grey area between non-compositional communication and compositional language? Answering these questions is a requirement for clearly stipulating the conditions under which a complex *signal*, or a simple system of communication, might be taken to be compositional to begin with. In addition to helping to specify what it *means* for a system of communication to be compositional, this mode of analysis allows us to examine the evolutionary contexts under which we might expect something like compositionality to arise, thus helping to bridge the explanatory gap between the evolution of simple systems of communication and human-level linguistic abilities.

When we understand the problem in this way, it becomes clear that any talk of whether or not animal communication systems are compositional is misdirected: such talk already presupposes that we understand what it means for a complex signal to be compositional. By taking a 'bottom-up' approach to compositionality, we may come to some clearer understanding of this sort of phenomenon in order to move forward with explaining how such dispositions might evolve in the first place, and how they might further evolve to a richer degree of complexity.

4. Desiderata for Compositional Signals

Let us set aside any pre-theoretic notion of what compositionality is in order to build a conception of proto-compositionality from the bottom up. In this way, we can avoid the theoretical complexity that is associated with a full-blown notion of linguistic compositionality, while simultaneously making explicit what proto-compositionality is supposed to be. I will suggest two main desiderata. These are consistent with an intuition about the properties of linguistic compositionality; however, I do not pre-suppose these properties, but show *why* they might be desirable from an evolutionary point of view.

The first of these is lexical composition. This is the notion that is usually targeted in evolutionary accounts of compositionality. However, we will also see that a notion of systematicity is desirable for a proto-compositionality to be truly effective—this is the notion of compositionality that is usually targeted by researchers in machine learning who focus on *emergent communication*. This analysis makes clear a further problem in evolutionary accounts of compositionality: they often ignore role asymmetries inherent in the signalling game, focusing solely on syntactic combination, which provides benefit only to the sender. Thus, in the very least, any account of proto-compositionality is going to require figuring this role asymmetry.

4.1. Lexical Composition / Combination.

There is an obvious adaptive advantage for combinatorial capacities in a communication system: fewer elements are required to be stored in memory in order to produce the same possible number of messages, thus allowing for more efficient communication.[6] In order to avoid conflating this notion of syntactic composition with the type of syntactic composition required in *linguistic* compositionality (Definition 1.1), I will refer to this as *lexical combination*. How can we demarcate combinatorial signals from atomic signals?

Scott-Phillips and Blythe (2013) try to clearly differentiate 'combinatorial' or 'composite' communication systems from 'non-combinatorial' or 'non-composite' (i.e., atomic) communication systems. A signalling system, on their account, is

[6]See the discussion in Nowak and Krakauer (1999); Nowak et al. (2000).

composite if it contains at least one pair of composite signals—where the combination of two signals, $m_k = (m_i \circ m_j)$, is produced in at least one non-composite state, $s_k \neq (s_i \circ s_j)$. The signalling system of putty-nose monkeys is composite in this sense. The presence of eagles elicits a 'pyow' signal, which in turn elicits the action *climb down a tree*; the presence of leopards elicits a 'hack' signal, which in turn elicits the action *climb up a tree*. However, the absence of food elicits the combinatorial 'pyow-hack' signal, which in turn elicits the action *move to a new location* (Arnold and Zuberbühler, 2008).

This captures a similar notion of *syntactic* combination as in the syntactic signalling game (Barrett, 2007). However, Scott-Phillips and Blythe (2013) stipulate that (atomic) signal-order does not matter in their model, so the meaning of $(m_1 \circ m_2)$ is equivalent to the meaning of $(m_2 \circ m_1)$. Thus, their model fails to capture sensitivity to syntactic structure which is apparent in complex signals in, e.g., bird song and whale song. Barrett (2007) is sensitive to signal order, but complex signals get *interpreted* atomically.[7] Thus, the meaning of a fully composite signal pair need not have anything to do with the meaning of its parts when we consider lexical combination in isolation. In order to account for meanings, we require a separate notion of systematicity.

4.2. **Systematicity / Generalisation.** In spite of the fact that signal combination is an obvious target for an evolutionary explanation of compositional signals, this cannot, itself, give rise to any form of proto-compositionality. The reason for this, as has been highlighted by Brochhagen (2015); Franke (2016); Steinert-Threlkeld (2016) with respect to Barrett's syntactic signalling game, is that it does not capture a notion of *generalisation* that appears to be required for compositionality. For a receiver to *interpret* a complex signal compositionally, she must be able to *decompose* the meaning of the signal based upon the meaning of the parts. By example, if the receiver knows the meaning of 'pick up…' and the meaning of 'the book', but not the meaning of 'put down…', then she might understand the command 'pick up the book', though she does not understand the (complete) meaning of 'put down the book'. Even so, she may still understand that the latter expression has *something* to do with the book.

Syntactic signalling, which accounts for lexical combination alone, only offers a benefit to the sender, insofar as the sender can communicate more with a smaller lexicon (and a small set of rules for combining lexical items). However, the receiver must still learn to interpret each complex signal atomically, so there is no efficiency gained on her end.

Recent work in machine learning highlights an interesting problem with respect to learning compositional linguistic structures. Neural networks are the 'workhorse' of natural language comprehension and generation—Bahdanau et al. (2018) highlight that neural networks play a significant role in machine translation and text generation in addition to exhibiting state-of-the-art performance on several benchmarks, including *Recognising Textual Entailment*, *Visual Question Answering*, and *Reading Comprehension*. However, training an AI to emerge compositional communication in an artificial context runs into parallel problems as giving an evolutionary account of emergent compositionality in a natural context. Whereas evolutionary explanations tend to focus on the syntactic side of the problem—and thus hit upon

[7]See the discussion in Franke (2016); Steinert-Threlkeld (2016).

the roadblocks described in Steinert-Threlkeld (2019)—computer scientists working in machine learning tend to focus on the generalisation aspect of compositionality.

Thus, compositionality in communication will require some notion of combination, but this must account for both the production *and* interpretation of complex signs. In order for a system to be fully compositional, the sender needs to be able to construct a sign with some internal structure, and the receiver must be sensitive to that structure:

> A communication system that is genuinely complex and combinatorial is one in which rich combinatorial structure figures into the rules on both sides of the signs, rather than a system in which simple nominal signs are produced but complex interpretations are possible given the social context, and rather than a system with very complex production but where most of the complexity is insignificant to interpreters. (Godfrey-Smith, 2018, 120)

Thus, the ambiguity concerning what it means for complex signals to be compositional, discussed in 3, is exacerbated further by the fact that the role asymmetries of the sender and receiver are often ignored in such discussions.

While syntactic or combinatorial signalling show a step toward combinatorial richness, wherein a smaller lexicon is required because signals can be combined in a systematic way to express a greater number of states, these accounts ignore the role asymmetry between the sender and receiver in the signalling game. The ability to combine signals is only beneficial to the sender, insofar as combinatorial syntax allows the sender to communicate effectively with a smaller lexicon. In either case, though, the receiver still needs to learn the distinct combination of signals atomically. Thus, the emphasis on *lexical* composition ignores any possible benefit to the receiver.[8] Accounting for this will require a further notion of *semantic* composition, or generalisation.

4.3. **Moving Forward.** I have suggested that the evolutionary explanations offered thus far fail to give a plausible account of how compositionality might arise. On the one hand, there is an inherent complexity in the meaning of *linguistic* compositionality, which is inherited by these models to the extent that they (at least implicitly) take *this* as their target, as opposed to a simpler proto-compositionality. The latter, to the best of my knowledge, is not explicitly defined anywhere. This gives us a target for a model: to give a 'bottom-up' definition of what it means for a complex signal to be compositional in the first place, which requires explicitly defining a notion of compositional signalling (a sort of proto-compositionality) that is distinct from, and significantly more simple than, *bona fide* linguistic compositionality.

This further highlighted that these evolutionary explanations are not sensitive to the asymmetric roles of the sender and receiver in the simple signalling-game framework. This provides a restriction for our target definition. Compositionality is only fully effective to the extent that it is possible to *productively* compose simple

[8]This is a bit subtle, since the role of the sender and receiver should be interchangeable. Barrett (2007); Franke (2016); Steinert-Threlkeld (2016) all depend upon simple urn-learning, where the roles of the sender and receiver are clearly demarcated.

signals in a systematic way, on the part of the sender, and also to effectively *decompose* those complex signals in order to understand the meaning in a systematic way on the part of the receiver.

We might begin by noting a distinction between atomic and complex signals, as follows. A signal is ATOMIC if it is a holistic unit—i.e., it cannot be decomposed into simpler meaningful parts; thus, a signal is COMPLEX if it is not atomic.[9] We further note that complex signals may be compositional or not. This is the key distinction that needs to be fleshed out moving forward. On the face of it, we might suggest the following definition: *A complex signal is* COMPOSITIONAL *if it is both lexically and semantically compositional.* To be clear, let us refer to the compositionality that is given by a compositional signal as *proto-compositionality*; this is compared to the full-blooded *linguistic compositionality* of Definition 1.1. A signal is thus compositional only to the extent that it is beneficial to both the sender and the receiver.[10] The notion of what it means for a *signal* to be (proto-)compositional takes account of both *lexical* composition, in the sense of syntactic combination outlined in Section 4.1, and semantic composition, in the sense of systematic generalisation outlined in Section 4.2.

Therefore, all we require is a clear definition for each of these notions. Note that defining compositional signals in this way already takes account of the role asymmetries of the sender and receiver. Further, this definition of compositional signalling will capture the desired pre-theoretic properties that were argued for in Section 4.1 and 4.2.

To account for productivity, structural properties that are common between elements of complex signals must be recognisable (and indeed recognised) in order for it to be possible to learn how to (de)compose two such elements in such a way that this can be generalised over their classes. In particular, as we have seen, if each combination of elements needs to be learned case-by-case and mentally stored in a lexicon for interpretation, then this will not provide any advantage to the receiver.

The symposium panel, *Evolutionary Explanations of Compositional Communication*, at the Philosophy of Science Association Meeting (2018) brought to light several important considerations for provision of an explicit model of compositionality. Steinert-Threlkeld (2019) proves that the type of compositionality that is modelled by, e.g., Barrett (2007) and others necessarily entails a 'trivial' form of compositionality.[11]

The model presented in Barrett et al. (2019) avoids this by taking account of complexity in nature (the states of the world in the signalling game) and modelling hierarchical structure within the game itself. who proposes that the human language faculty evolved as the product of complex feedback mechanisms that gradually diversified and changed humans (perhaps hominins) into different kinds of animals from other living primates. This involves interrelations between social organisation, complex cognition, and environmental modification. Relevant semantic enrichments involve extended capacities for tracking mental states, as well as cognitive capacities supporting extractive foraging, including tool-use; larger and more variable habitat

[9]Note that atomic signals may be syntactically complex: whale songs and bird songs adhere to strict syntactic structure, but only carry meaning as a whole. Thus, a sequence is meaningful, but its parts are not.

[10]Note that beneficial is a relative notion to the extent that globally suboptimal strategies may persist due to entrenched practice—i.e., when they are locally optimal.

[11]See Steinert-Threlkeld (2019).

ranges; more coalition partners in larger groups; and the formation of planned actions with variable components.

Armstrong (2019) suggests a distinction between compositional communication and social coordination with compositionally determined meanings—compositional systems of communication form a mere subset of systems of social interaction that are mediated by compositionally structured internal representations. Compositionality thus plays a larger role in social and cognitive phenomena over and above the power that compositionality might bestow upon communication.[12]

5. Morals

I have suggested that, due to the inherent ambiguities and complexities of natural languages, the question of whether or not languages are compositional is grossly underspecified. As such, an alternative approach to discussing the compositionality of language from an evolutionary standpoint is to discuss simple communication systems in order to determine the conditions under which they would be taken to be compositional. In particular, if compositionality is a necessary condition for the generative nature of languages, and if languages evolved from simpler communication systems, then compositionality itself evolved. Thus, in order to clarify how this sort of compositionality might have evolved, it is necessary to determine what counts as a compositional *signal*.

In light of evolutionary considerations, we should not appropriate a notion of compositionality from natural languages, but rather analyse complex signals in a simpler communication context. Thus, we built a simple notion of compositionality from the ground up, as it were. This helps to avoid many of the conceptual difficulties arising from the discussion of compositionality in natural languages, in the same way that simple models of the world avoid the complexities of the actual world for the purpose of conceptual clarity and tractability. A precise specification of lexical and semantic composition is left open—these definitions need not be all-encompassing, but a family of clear, more or less rich notions of compositionality that is sensitive to the considerations outlined herein. Indeed, though the models I am considering fall short of this goal, there is work being done along these lines to capture richer notions of compositionality. Progress in this area has the purely epistemic benefit of filling in a bit of the picture of how language evolved; further, such conceptual progress would find immediate application in work on emergent communication in the machine learning community.

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[12]See also, Seyfarth and Cheney (2018).

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