Open Problems in the Emergence and Evolution of Linguistic Communication: A Road-Map for Research

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Abstract

This paper surveys issues around several grand challenge problems for the understanding of the emergence
and evolution linguistic communication, and discusses possible approaches. The identi_ed problems
the emergence of (1) advanced use of deixis, gesture, and reference; (2) predication; (3) negation;
(4) syntactic categories; and (5) compositionality.

1 Introduction

In the last decade or so, there has been an explosion of interest in the modelling and understanding of language origins. The employment of simulation and robotic agent-based, connectionist neural network, and evolutionary techniques has provided new methods for formulating hypotheses, validating mechanisms, and selecting between alternative theories on the emergence of linguistic and languagelike phenomena in controlled experimental settings that meet the scienti_c criteria of reproducibility. Recent work on the emergence and evolution of human language and more simple communication systems has been increasingly interdisciplinary, involving collaborations between linguists, philosophers, biologists, cognitive scientists, roboticists, mathematical and computational modellers . see e.g. research papers (MacLennan, 1992; Steels, 1995; Hashimoto and Ikegami, 1995; Arita and Koyama, 1998; Billard and Dautenhahn, 1999; Kirby, 1999; Nehaniv, 2000; Cangelosi, 2001; Steels, 2003) and interdisciplinary collections (Wray, 2002; Cangelosi and Parisi, 2002; Christiansen and Kirby, 2003).

This paper surveys some currently open problems in the emergence and evolution of linguistic communication that present grand challenges to those working in constructive aspects of the emergence of communication. In this paper, we address the programme of demonstrating mechanisms that achieve various language-like properties in computational agent and robotic models. This is not intended to be an exhaustive survey. Many important research articles and researchers could not be mentoned here. The discussion is instead indicative of current research activity (and inactivity) as regards a set of fundamental problems in the area.

We will discuss the following completely or largely open areas:

(1) deixis, gesture, and reference;
(2) predication;
(3) negation;
(4) emergence of syntactic categories
(5) compositionality
The emergence and modelling of these phenomena are discussed in the context of embodied, social interaction and evolution (cultural or otherwise). Ideally, mechanisms based on sensorimotor and experiential grounding in bottom-up, agent-centered models involving populations of agents will help yield deep understanding of the emergence of the above phenomena.
One area is conspicuously missing from the above list:
(0) grounding and shared vocabularies
and will also be discussed brie_y below. This area has not been included in the list of current grand challenges since there has been substantial progress in it. However grounding and shared vocabularies will need to be integrated with the answers to the grand challenge problem areas (1-5) to yield

grounded and shared language-like communication systems with much more complex types of vocabulary with grounded meaning than what has been so far achieved.

2 What is Meaning and What is Language For?

We regard linguistic and language-like communication as the capacity of an agent to in_uence the world around by the systematic use of signals mediated by their reception by other agents in its environment. Thus, language is regarded as a means for the agent to `manipulate' the world around for its own bene_t, similar to other traits of biological organisms (cf. the discussion of the transition to language from a biological viewpoint in (Maynard Smith and Szathm´ary, 1995)). As Wittgenstein (1968) taught us, the *meaning* of any signalling behaviour, such as in language, arises in how it is used by the agent to manipulate its environment (including other agents) in its interactions with other agents. This can be related to the utility to an agent (in a statistical sense) of information in a signalling channel (see Nehaniv (1999); Nehaniv et al. (1999, 2002)). According the insights of Peirce (1839-1914) [republished in (Peirce, 1995)], the relationship between signs and signi_cations is mediated by an interpretant, and the mapping between signs and what they signify is a *process* that depends on the particular agents involved and on their situated contexts. The ideas just presented follow the discussion of Nehaniv (1999, 2000). The Wittgensteinian-Peircian viewpoint outlined by Parisi et al. (2002) is similar.
In particular, these realizations lead a tremendous

amount freedom in the emergence of language-like phenomena that has often been ignored and oversimpli _ed by naively, often unconsciously, applying constraints on simulation models. This freedom and the related lack of constraints is illustrated by several corollaries. Understanding the emergence of meaning and language requires the generative synthesis of the phenomena in question beginning with the following facts:

1. Meaning is always agent-speci_c.
2. There is no privileged set of pre-existing space of possible meaning, containing ideal concepts.
3. There is no unique and no pre-existing syntactic structure on possible meanings.
4. If meanings, spaces of meaning, or syntax in meaning space do arise, they will be agentspeci _c as well.
5. The mappings between signs and meaning are mediated by interpreted signals between agents, and these mappings are also agent-speci_c and depend on the context of the interaction.

See (Nehaniv, 1999, 2000) for further discussion of these points.

Note that none of the above discussion refers to truth values or truth conditions, which are highly derived properties of human linguistic behaviour (Nehaniv, 2000), and that therefore should not be the starting point for an attempt to understand meaning, communication, and language. The highly re_ned formal tools mathematics and logic . including truth values, predicate logic, context-free grammars, denotational semantics, etc. . have allowed scientists achieve precision and thus escape from ambiguities and dependence on context and speci_c agents. But speci_c agents and context are inherent to the emergence of language, while these tools are based on abstractions and re_nements from human language. Any explanation of the emergence of language that uses them as primitives to derive the phenomena that they are based on thus puts the proverbial cart before the horse (Nehaniv, 2000; Milikan, 2004).

This is not to say that these tools and formalisms should never be used. In computational modelling this is clearly would not be possible, simply due to the use of computers. No simulation or robotic study in the emergence and evolution of linguistic communication has been able to proceed successfully without simplifying some (or sometimes all) of the above complexity away. If agents are endowed with some of these language-like capacities, it is important to keep track of which ones. If new phenomena then emerge, one has an argument that the builtin capacities provide scaffolding for the new phenomena. For instance, the work of Kirby (1999) shows that, in populations of agents *with the capacity to use and derive context-free grammars*, processes

of self-organization resulting from attempts to learn grammar based on induction from the evidence of grammar-generated utterances of other agents lead over generations to increasingly compositional grammars. His work does not how it is that context-free grammars nor the capacity for compositionality could _rst emerge (since these are given at the start).
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3 Symbol Grounding & Shared Vocabularies

Different aspects of *symbol grounding* (Harnad, 1990) and the self-organization and maintenance of *shared vocabularies* are increasingly well-studied and coming to be understood, especially for vocabularies to identify or name objects (selecting one target of reference from an environment) or label situations (MacLennan, 1992; Steels, 1995, 1998; Billard and Dautenhahn, 1999; Baillie and Nehaniv, 2001; Parisi et al., 2002). Less work has been done on the grounding of shared vocabularies with more complexity, e.g. in which various parts of speech exist (labelling for example actions or actions on objects, or with compositional syntax), although the work of Cangelosi and collaborators has moved in this direction (e.g. Parisi et al. (2002)).

4 From Deixis, Gesture, and Manipulation to Reference

The items, deixis and gesture, in challenge area (1) are clearly related and emergence of reference. Reference is often suggested to be grounded in deixis and gesture but just how this occurs needs elucidation. Pointing, deictic gaze, joint attention, and gesture play important roles in the development of intersubjectivity and language in humans (cf. Kita (2003)).

Pointing, since it can be directed at many things and since it directs others' attention at them, could have provided for a kind .ur-pronominalization. in the emergence of linguistic communication. That is, pointing provides for a variable or variables that can be bound to object and persons in the environment, giving at least of degree shared reference via shared attention.

Rizzolatti and Arbib (1998) present a hypothesis on the emergence of language based on mirrorneurons in primates and humans. These neurons in the premotor cortex _re both when carrying out and when seeing an action performed. It is argued that this provides a substrate on which shared meaning can arise, as similar affordant gestures (e.g. manipulations such as grasping a fruit) are immediately understood by a conspeci_c interaction partner. Gestural language is then hypothesized to have developed and eventually to have given way to vocal language. Hurford (2004) acknowledges a possible role for mirror

neurons in understanding the possible emergence of language, but surveys many gaps that remain in such an explanation, such as explaining the wellknown arbitrariness of the sign in regard to its reference. Milikan (2004) has a more general notion of reference that relates to utility of information in internal states or signalling channels. A more general notion of gesture regards gesture as the signalling of such useful information. This is similar to the viewpoints on the meaning of signals in (Nehaniv, 1999, 2000; Wittgenstein, 1968).

The issues discussed in this section evidently relate closely to the grounding of symbols and the emergence of shared systems of communication. Despite progress in these areas, constructive studies linking deixis and gesture to these problem areas remain to be carried out constructively in robotic and simulation models (but see Baillie and Nehaniv (2001); Baillie et al. (2004) for some _rst work in this direction).

5 Predication

For detailed analysis of predication and its complex structure in human language from the viewpoint of linguistics, see (Napoli, 1989). In human language, a rudimentary function of noun phrases is to pick out objects of reference from the environment (possibly even absent ones). Adjectives constrain the selection by imposing conditions on which object might be referred to.

One formal view of reference (implicit e.g. in (Steels, this volume) and classical box-world natural language processing systems) is that instances of lexical items such as a noun (.ball.) or adjective (.red.) are understood as predicating properties of object variables. Selection of referents is determined by solving constraints on such predicates over a space of objects in the environment. For example, ball(X) and red(Y), restricts the reference to a red ball if X must equal Y , as it must in the phrase .the red ball.. Similarly verbs provide another class of predicates which might take multiple semantic role arguments expressed in a given syntactic subcategorization frame that resolves variable references (Steels, this volume).

As mentioned above, predicate logic and _rstorder logic are abstractions from the predicate structure of natural language. With the approach just described, predication itself is a primitive and therefore does not emerge. However, *a transition from reference to predication* is suggested by an association that tends to identify referential variables in one-place referential predicates (like red(X)), or by grammatical rules that force the identi_cation of variables in the referential predicates.

Scenario for the Emergence of Predication.

Early on proto-words or gestural signs could have their referents *associated* in a general way, nonspeci _c way merely by co-occurring close together in time. We elaborate a suggestion on the earliest source of predication: it may be a highly derived form of *topic-comment* structure, which is itself founded on association (Nehaniv, 2000). For instance, deictic gesture serves to select a target of joint attention (*topic*), and then another gesture or utterance near to it in time serves to communicate content that was associated to the topic as *comment*. Eventually ritualization of such communicative practice produces gramaticalization of a topic-comment construction. Predication then arises via grammaticalizaton of the special case in which not only an association between topic and comment occurs, but the comment gives to the topic a labelling category: .This - food., a property label .This . bad., or a semantic actionrole .This . eat.. Thus there is a progression in the emergence of predication from association and topic-comment via ritualization to grammaticalizaton of predication.

Ritualization is well-known in animal communication systems (Smith, 1977, 1996; Bradbury and Vehrencamp, 1998) and one instance of it is grammaticalization, a well-recognized process in human language change (e.g. (Bybee et al., 1994)). A clear path for research into this open area would be to proceed to validate this proposed scenario by building computational or robotic realization and showing whether and how the transitions

association ! topic-comment ! predication

could occur (ideally including *grounded referencing*). This should shed light on the details of the emergence of predication and the mechanisms required for this to occur.

If this could be done, more complex predication and modi_cation could then be addressed. In more complex human language, both predicates and modifers occur. Predicates tend to mark more highly salient assertions, while modi_ers tend to act in the background to tune reference via constraints (Nehaniv, 1987).

Let us again remark about the at best low relevance of truth values here. In early language as in animal communication system, the emphasis was of course manipulation of and in_uence in the environment via signalling to others (cf. Maynard Smith and Szathm´ary (1995); Milikan (2004); Nehaniv et al. (2002)), rather than on propositional assertions. Truth values of predicates on objects was only a later invention and abstraction of humans.

6 Negation: A Small Research Programme

It seems little has been done in emergence of negation

in constructive evolution of language models.
A discussion of negation of speach acts and within speech acts occurs in (Searle, 1980/1969). A comprehensive book on negation is (Horn, 2001).

Early Scenarios for Negation.

(The material in this subsection is modi_ed from text by Donna Jo Napoli (Napoli, pers. comm.).) Early predicates used by early humans likely indicated actions such as .come., .hide., .be quiet., .run., or referenced objects, such as .food., .water.. Negation can operate on nouns as well as on verbs, or other parts of speech, and is, of course, a predicate in itself.[1] Letting others know there is nothing in the cave, for example, was probably a pretty important early message. So one would expect .nothing. or .no living thing. to be an early negation.

Non-verbal, facial and manual gestures may have played an important role in early negation. When hunting, when trying to be quiet for any reason, people have always used their faces and hands. We all recognize the hush gesture. We know to raise our eyebrows to ask yes/no. This sort of thing is extremely common around the world. In Australia, many tribes used to have sign languages just for hunting. (They had sign languages for other things, too . like to use with widows . and for the deaf).

The _rst negation was likely either facial or gestural . perhaps a head shake or lowered brows (as in American Sign Language (Neidle et al., 2001)), or protruded lips. Also, early negation was likely simultaneous with whatever was being negated, whether spoken words or other gestures. So shake your head and say .buffalo. - or shake you head and say .swim/enter water. or shake your head and gesture .walk (whatever that gesture might be for those peoples) . and you're getting across the messages .there are no buffaloes. . .don't go in the water. . .don't walk.. (Scenario and examples due to Napoli (pers. comm.). The author is responsible for any misrepresenations of her views.)

[1] Or a modi_er, where modi_cation is plays a role, e.g. a specifying a constraint on reference within consituent syntactic structure, and is generaly less marked than predication.

Computational Scenarios for Emergence of Negation.

We now give several ideas for constructivist approaches to negation:

1. It seems straight forward to use inhibition in arti_cial neural networks to suppress the behaviour in the presence of a negation signal N. Suppression of all action could yield compliance (by inaction) with commands such as .don't touch that.. This could be realized to many existing models.
2. A research scenario into the use of more speci_c negation could employ connectionist neural network models of agents using linguistic signalling

such as those of Cangelosi (2001), which can have a noun-verb distinction (see below) that they exhibit in language games. We propose that these be extended by the introduction of tasks into the language games that sometimes involve negation: When the new signal N co-occurs with a previously learned linguistic signal S the language game task requires choosing a *different* object/property (.(proto)noun./.(proto)adjective.) or action (.(proto)verb.), respectively, than would be for the signal S. Tasks without the signalN must also be carried out by the agents and require the original interpretation of S. That is, the agents could carry commands such as .pull cup., .not-pull [e.g. push] cup., .pull not-cup. (i.e. pull an object other than the cup), , or even .not-pull not-cup. (e.g. pushing a ball would be a correct response). The meaning of the negation signalN would be grounded in the language game tasks these agents have to perform. Demonstrating that evolving populations of neural network agents could learn this task would establish a connectionist basis for speci_c negation of constituents of simple linguistic utterances. Alternatively, one could do the same kind of study using agents such as in the work of Steels (2003).

3. We note that in many human sign languages such as American Sign Language (ASL), the scope of negation can be given over syntactic subunits by non-manual gestures. In ASL non-manual marking (furrowing of the eyebrows and side-to-side headshake) may spread over the (c-command) domain of constituent syntactic node, and moreover such spread is obligatory in the absence of manual marker (Neidle et al., 2001). (This property agrees well with the likely simultaneity in the early negation described in Napoli's scenario above.) Thus in constructivist studies of the emergence of language, it would be very interesting to investigate scope of negation. For example, in neural network agent models, the use of a negative signal would have presumably to involve the persistence in the network of internal state over the scope of the negated constituent. Synthetic neural imaging techniques like those of Cangelosi and Parisi (2004) could be useful here.

7 Syntactic Categories

In arti_cial neural network connectionist models, Parisi et al. (2002) have shown the grounded emergence of rudimentary nouns and verbs: Nouns, as linguistic signals that co-vary with sensory stimuli, and verbs, as linguistic signals that co-vary with actions (largely independent of sensory stimuli). They have suggested that this could be extended to (proto)adjectives, that select a referent within a noun category using some intrinsic property, and to nonadjectival modi_ers, such as location indicators (e.g.

left, right, above), that re_ect more temporary properties of objects which are not instrinsic to the object but depend on the relationship of object to speakers and the environment. This remains to be done, as does increasing the complexity of syntactic categories the approach can generate (e.g. to verbs with a patient and recipient role, as .give the apple to Mary..

Steels (this volume) also considers the emergence of shared semantic and syntactic frames based on grammaticalization driven by computational needs of disambiguation.

This issue of emergence of syntactic categories, which are restricted in the types of semantic environments where they can occur (as in the work of Parisi et al. (2002)), and in their signal contexts, and in the types of arguments they can take (if any), leads to the next grand challenge, the achievement of full-blown compositional syntax in a grounded communication system.

8 Compositionality

The emergence of lexical items that take arguments (such as transitive verbs that take an noun-phrase as object) is called compositionality. This has syntactic and semantic aspects, and accounts for much of the combinatorial richness of human language. There have also been a growing number of studies on the emergence of various aspects of syntax (e.g. (Kirby, 1999; Cangelosi, 2001; Steels, this volume)). While there has also been some pioneering work on syntactic categories (e.g. Cangelosi and Parisi (2004); Parisi et al. (2002)), and grounded compositionality (Steels, 1998), many aspects of compositionality in linguistic

communication remain completely open for constructive modellers to begin to explain.

Segmentation and pauses in modern human speech, e.g. arising from the need to breath or the temporal nature of cognitive processes, combined with local context have been shown informationtheoretically to improve the disambiguation of speech, suggesting that sequential process of smaller sequential units may help provide the basis for syntax in language evolution and language processing Lyon et al. (2003).

Cangelosi (2001) showed the emergence of verbs for actions that take target objects references in neural network agents that can manipulate simple objects in the environment in an evolutionary simulation, but non-compositional communicative signals could also evolve.

Assuming a _xed and syntactically structured meaning space, and a capacity to use and learn context-free grammars, Kirby (1999, 2001), as mentioned above, has shown that grammars with high degrees of compositionality arise and are easier to transmit

over the course of generations of learning in such agents starting from agents using non-compositional `holistic' grammars (i.e. with a different utterance for each meaning). Extending this work to agent-centred spaces of meaning grounded in interaction and language games remains to be achieved.

Steels (this volume) argues that the purpose of compositional grammar is to reduce the number of variables in a decoded meaning structure in order to hope with compuational complexity in interpretation. He constructs agents in simulation studies that apply this principle and are able to converge on shared grammars by reinforcing and modifying syntatic and semantic role-structural frames (to propogate referental constraints) based on communicative success and failure. The same structures are used for parsing and for production.

Recursive composition structure is possible if the expansion of argument can non-trivially include the same argument type (as with clauses embedded in other clauses). When this occurs, in principal the language becomes unbounded in size.

9 Conclusions

Our list of grand challenge areas identi_ed _ve challenges beyond symbol grounding and the emergence of shared systems of communicating meaning: (1) the role of deixis, gesture, and manipulation in the grounding and emergence of reference, (2) predication, (3) negation, (4) syntactic categories, and (5) full syntax - compositionality and recursive structure. Challenges (2), on predication, and (3), on negation, have been the most neglected by the evolution of language community. We hope this paper stimulates discussion on these issues and promote research especially into those areas.

The problem of predication (2) is argued to be related to associative processes and to topic-comment structures, as precursors. Predicates as the exist today in human languages are seen as a highly derived special case of related processes.

Computational scenarios for studying the emergence of predication and of negation have been proposed and discussed in order to encourage the investigation into their hemergence.

Other immediate work to be done to meet these grand challenges includes: (4) emergence of syntactic categories needs to be shown without assuming an underlying categorization on some pre-existing space of meanings in grounded language games. (5) compositionality (and recursion) needs to be shown to emerge in a setting of grounded meaning without the assumption of an underlying grammatical ability, such as the capacity to learn and use context-free grammars.

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