Synthesising the origins of language and meaning using co-evolution, self-organisation and level formation.

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In: Hurford, J., C. Knight and M. Studdert-Kennedy (ed.) (1997)
Evolution of Human Language.
Edinburgh Univ. Press. Edinburgh.

September 5, 1997

Abstract

The paper reports on experiments in which robotic agents and software agents are set up to originate language and meaning. The experiments test the hypothesis that mechanisms for generating complexity commonly found in biosystems, in particular self-organisation, co-evolution, and level formation, also may explain the spontaneous formation, adaptation, and growth in complexity of language.

Keywords: origins of language, origins of meaning, self-organisation, distributed agents, open systems.

1 Introduction

A good way to test a model of a particular phenomenon is to build simulations or artificial systems that exhibit the same or similar phenomena as one tries to model. This methodology can also be applied to the problem of the origins of language and meaning. Concretely, experiments with robotic agents and software agents can be set up to test whether certain hypothesised mechanisms indeed lead to the formation of language and the creation of new meaning. This paper reports on recent work following this approach.

The methodology of computer simulations and experiments with robotic systems is in itself neutral with respect to a theory of the origins and evolution of language. For example, Gillis, Durieux and Daelemans Gillis (Gilles, et.al. (1995)) report on research to test through computational experiments the feasability of the Chomskian principles and parameter hypothesis and Batali (1994) has been investigating how a universal grammar, encoded as recurrent neural networks with prior weights, might result from an evolutionary process. In our own work the following two hypotheses are investigated.

1. *Language is an emergent phenomenon.* Language is emergent in two ways. First of all, it is a mass phenomenon actualised by the different agents interacting with each other. No single individual has a complete view of the language nor does anyone control the language. In this sense, language is like a cloud of birds which attains and keeps its coherence based on individual behaviors enacted by each bird. Second, language is emergent in the sense that it spontaneously forms itself once the appropriate physiological, psychological and social conditions are satisfied, and it becomes more complex due to its own dynamics and pressure to express an ever expanding set of conceptualisations and speech acts.

2. *Language and meaning co-evolve.* Language is not a mere complex system of labels for concepts and conceptual structures which already exist prior to language, but rather, the complexification of language contributes to the ability to form richer conceptualisations which then in turn cause language itself to become more complex.

Given these two hypotheses, the main technical challenge is to identify the basic principles and a possible precise scenario for the origin and progressive build up of language complexity.

The origins of complexity are currently being studied in many different areas of science, ranging from chemistry Kauffman (1993) to biology (Maynard-Smith and Szathmary (1993)). The general study of complex systems, which started in earnest in the sixties with the study of dissipative systems (Prigogine and Stengers (1984)), synergetics (Haken (1983)), and chaos (Peitgen, et.al. (1982)), is trying to identify general mechanisms that give rise to complexity. These mechanisms include evolution, co-evolution, self-organisation and level formation. It therefore makes sense to explore these mechanisms for the origins of language as well.

Before starting, an important disclaimer must be made. This work does *not* make any empirical claim that the proposed mechanisms are an explanation how language actually originated in humans. Such investigations must be (and are) carried out by neurobiologists, anthropologists (Aiello(1997)), and linguists studying historical evolutions (McMahon (1994)), child language (Halliday (1978)), or creolisation (Bickerton(1990)). Here, I only propose and examine a theoretical possibility. If this possibility can be shown to lead to the formation of language and meaning in autonomous distributed artificial agents, then it is at least coherent and plausible. Thus, if meaning creation mechanisms enable agents to autonomously construct and ground meaning in perception, action, and interaction, then it is no longer self-evident that meaning has to be universal and innate, as claimed e.g. by Fodor (1975). And if the proposed language formation mechanisms enable artificial agents to create their own language, then it is no longer self-evident that 'linguistic knowledge' must for the most part be universal and innate as claimed by Chomsky (1980) or that the origin and evolution of language can only be explained by genetic mutation and selection (Pinker and Bloom (1980)).

This paper does not focus on the origin of cooperation or the origin of communication in itself, although these are obviously prerequisites for language. These topics are being investigated by other researchers, using a similar biological point of view. For example, Dawkins (1976) has argued that two organisms will cooperate if they share enough of the same genes because what counts is the further propagation of these genes not the survival of the individual organism. Axelrod (1980), Lindgren (1995), and others have shown that cooperation will arise even if every agent is entirely selfish. MacLennan (1991) and Werner and Dyer (1991) have experimentally shown that communication arises as a side effect of cooperation if it is beneficial for cooperation. The emergent communication systems discussed in these papers do not constitute a language in the normal definition of the word, however. The number of agents is small and fixed. The repertoire of symbols is small and fixed. None of the other properties of a natural language such as multiple levels, synonymy, ambiguity, syntax, etc. are observed. The main target of the research discussed in this paper is to study the origins of communication systems that do have all these properties.

The remaining sections of the paper focus on different general principles which are hypothesised to explain the origins and evolution of language: adaptive games (section 3), co-evolution (section 4), self-organisation (section 5) and level formation (section 6). Each section briefly discusses concrete experimental results.

2 Adaptive language games.

Since Darwin, evolution by natural selection has played a key role in attempts to explain the origin and diversity of species. Evolution takes place when there is a source for generating variety and a selective force that retains those variations that are most adapted. Selectionism is not restricted to genetic evolution however. The only requirements are a mechanism of information preservation (i.e. a representation), a source of variation, and a feedback loop between the occurrence of a specific variation and selective 'success'. In the case of genetic evolution, the information is preserved in the genes. Variation is caused by errors in transmission (mutation and crossover). The feedback loop is established through the reproductive success of the organism carrying a particular set of genes. This success will depend as much on the environment in which the organism finds itself as on the genes it has.

I propose that selectionism is a major force in the origin of language as well. However I do *not* mean selectionism in the genetic sense, but in a cultural sense. Information is preserved in the language memory of individuals. It is transmitted as part of a linguistic interaction because the hearer imitates or adopts the conventions of the speaker to be maximally successful in future interactions. Variation comes from many sources: there is spontaneous variation because of performance errors, overgeneralisation because a single individual has no complete overview of the language, the construction of new rules by individuals to fill gaps, changes to existing rules to be more conform to the group, etc. The feedback loop is based on minimising cognitive effort and maximising communicative success. For example, the selectionist criteria for a new phoneme or phoneme combination include: Ease of producability and reproducability for the speaker, which includes that the articulators must be able to reach the desired goal states possibly with minimum energy requirements, and ease in understandability for the hearer, which includes that there is enough information in the signal to reliably detect the sound and distinguish it from others in the repertoire Lindblom(1986).

The whole system bootstraps itself when variation is not only created by adapting of existing rules but by the creation of new rules from scratch. For example, a new gestural phonetic score could be created by assembling a random sequence of articulatory goals, a new word could be created by a random combination of phoneme segments, a new syntactic construction is created when a particular word order becomes conventionalised, etc.

Evolution is often studied in terms of games, Maynard-Smith (1975). A game is an interaction between two agents or between an agent and an environment. A game has a certain outcome which determines the course of evolution. For language games, the outcome can directly be used by the agents to adapt the structures governing their linguistic behavior. For example, if a certain association between a word and a meaning is not effective, then the agent should potentially review whether this association is to be part of his lexicon. If a certain phoneme cannot be recognised reliably by the hearer, the producing agent should reconsider whether it is to be part of his phonetics. Language games thus become adaptive, and the evolution of language becomes a kind of cultural evolution. This may explain why language evolution occasionally takes place very rapidly.

2.1 Meaning creation through discrimination games

In our Brussels laboratory we have built a variety of robots (figure 1) that execute dynamical behaviors in a robotic ecosystem. These robots, which are the ultimate hardware platform for our language experiments, have a wealth of data channels (figure 2) resulting from internal or external sensors, internal motivational states, actuator states, etc. Perceptually grounded meaning creation operates over these data channels.

One way in which meaning creation can take place is through *discrimina-*

Figure 1: Physical robots used in the experiments. The robot has on-board computational resources, a battery, left and right motors, and about 30 sensors, including vision. The robot "lives" in a robotic ecosystem together with other robots. There is a charging station as well as competition for the available energy.

Figure 2: The graph shows the dynamical sensory states of a robot. RM and RL are right and left modulated light (detecting objects competing for energy) and R and L are right and left visible light (detecting the charging station). The data is for a 25 sec. time interval. The robot is engaged in phototaxis first to modulated light and then to visible light. Data channels such as these are the starting point of discrimination games that attempt to distinguish one situation from another.

tion games: The agent attempts to distinguish two objects or situations using a repertoire of categorisers which transform the continuous values produced by feature detectors into discrete categories. For example, a value from a continuously varying intensity scale for left visible light is divided into regions, which could be lexicalised as strong, medium, and weak. When a particular value falls within one of these regions a discrete category is output by the categoriser. When the game fails, i.e. an object cannot be distinguished from a set of other objects, the agent creates new categorisers by refining existing ones or by creating a new one for an unexplored sensory channel. As shown in another paper (Steels(1996)) this leads indeed to the buildup of a repertoire of features adequate for distinguishing objects. Moreover the repertoire is adaptive. When new objects are to be considered or new data channels become available, the repertoire of categories expands if necessary.

A typical example of a discrimination game (from Steels(1996)) is the following: An agent (a-5) tries to distinguish an object called the topic (o-6) from other objects making up the context (o-2 and o-5). The game is successful because the feature obtained for one object sc-5-2 with value v-0 does either not apply or results in a different value for the other objects:

```
Discrimination by a-5: o-6 <-> {o-2 o-5 }
Existing features:
   o-6 = ((sc-5-2 v-0))
   o-2 = NIL
   o-5 = ((sc-5-2 v-1))
Distinctive: ((sc-5-2 v-0))
Success
```

The following game is not successful because the topic o-7 has the same value for attribute sc-1-2 as o-2. The agent therefore creates a new feature detector sc-3-2. Whether this feature detector will do the job will only become clear in later discrimination games.

```
Discrimination by a-5: o-7 <-> {o-1 o-2 }
Existing features:
   o-7 = ((sc-1-2 v-1))
   o-1 = NIL
   o-2 = ((sc-1-2 v-1))
Distinctive: NIL
```

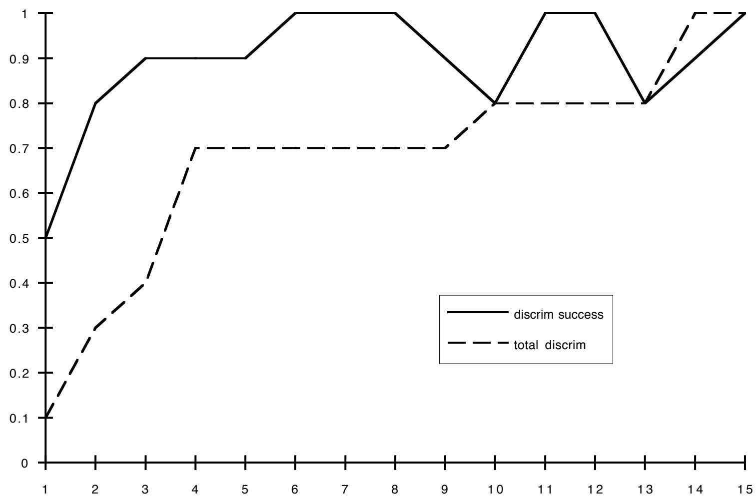

Figure 3: The graph shows the evolution of the discriminatory capacities of a single agent. The total number of objects (10) is fixed. There are 5 data channels. The average success in discrimination games as well as the total success is shown on the y-axis. The number of discriminations is mapped on the x-axis (scale 1/10). All objects can be discriminated after 150 discrimination games.

```
Failure
 No distinctive features but
  new ones possible on channels: (sc-2 sc-3 sc-8)
 New attribute created: sc-3-2
```

Figure 3. shows an experiment where an agent builds up a repertoire of feature detectors, starting from scratch. The graph shows the increasing discrimination success as experienced by the agent in discrimination games. It also shows the total success with the features so far, i.e. all objects are compared to all other objects and it is calculated which percentage can be distinguished. Average success during a certain time period is higher than total success because not all objects are encountered within each period. Many other kinds of meaning creation games can be imagined. For example, an agent can attempt to classify an object against a list of classes and extend the feature repertoire or change the definitions of classes in order to be successful. An agent can attempt to predict aspects of a situation by

formulating some features and deducing other features from them. Success in a game then equals predictive success and failure leads to the construction of more refined features or the revision of prediction rules.

2.2 Lexicons through language games

We now turn to the lexicon. As discussed in other papers (Steels(1996),Steels(1996)), adaptive language games can be set up that lead to the formation of a lexicon. In each game, there is a speaker and a hearer and a set of objects making up a context. The speaker identifies one object (the topic), for example by pointing. Both then find a feature set discriminating the topic with respect to the other objects in the context by playing discrimination games of the sort discussed in the previous subsection. The speaker attempts to code this feature set into language by using words in a lexicon that relate words to meanings. The hearer decodes the resulting expression using his lexicon and the game succeeds if the distinctive feature set decoded by the hearer matches with the expected distinctive feature set. When the game fails, the speaker or the hearer change their lexicon. For example, if the speaker does not have a word yet for the distinctive feature set that he wants to express, he may create a new word and add a new association to his lexicon; if the feature set decoded by the hearer is more general than the one expected, then the hearer can refine his associations between words and meanings, etc. There is additional complexity because one word may have multiple meanings and one meaning may be expressed by multiple (competing) words.

A typical experiment shows a rapid creation of a lexicon which is adequate to reflect the meanings that are necessary for discrimination among a certain set of objects (see figure 4). There is again adaptivity. When new meanings need to be expressed or new agents enter the group, the lexicon expands with new lexicalisations or contracts when ambiguity gets resolved.

Here are two examples from simulated adaptive naming games. The agents talk about themselves. The speaker (a-1) is describing himself to the hearer (a-3). The context includes a-2, a-3 and a-6. There are two possible distinctive feature sets that distinguish a-1 from the context. One is chosen, namely ((*size tall*) (*color white*)). It is translated to the sentence "(*k a*) (*v o*)" and subsequently decoded correctly by the hearer. The language game succeeds because the resulting feature set was expected by the hearer.

```
Dialog 2301 between a-1 and a-3 about a-1.
    Context: {a-2 a-3 a-6 }
    Distinctive:
      (((size tall) (color white))
       ((weight light) (color white)))
 a-1: ((size tall) (color white))
          -> ((k a) (v o)) ->
 a-3: (((size tall)) ((color white)))
Success
```

Here is another language game where the hearer does not know the word and extends his lexicon. Because there is uncertainty (both (*size tall*) and (*weight light*) are possible discriminating features), an ambiguity enters into the hearer's lexicon:

```
Dialog 423 between a-3 and a-1 about a-2.
    Context: {a-3 a-2 a-5}
    Distinctive:
       (((size tall)) ((weight light)))
 a-3: ((size tall)) -> ((z u)) <- a-1: nil
Failure
   new word: a-1: ((size tall)) -> (z u)
   new word: a-1: ((weight light)) -> (z u)
```

When later the word "(z u)" is used to identify the same object within the same context, the communication succeeds and so no disambiguation is possible. Disambiguation only takes place when a-1 uses "(z u)" in a situation where one of the descriptions is not appropriate.

2.3 Shared sounds through imitation games

In another series of experiments, conducted together with Bart de Boer, we have shown that a *shared sound repertoire* can evolve through imitation games. The repertoire consists of phonemes and phoneme segments which are admissable and distinctive in the language. Agents must develop both the capacity to produce the phonemes and the capacity to recognise them from acoustic signals. This is achieved by engaging in adaptive imitation games. An imitation game works as follows: A speaker picks a phoneme or phoneme

Figure 4: The figure shows the evolution of the communicative success (left y-axis) in a fluctuating population of agents (right y-axis) as it develops over time (x-axis). The population starts with the formation of a lexicon from scratch and quickly reaches total communicative success. The experiment shows that the communication remains stable even though the population renews itself. New agents enter with a probability 0.00005 and depart with the same probability. 50.000 language games are shown.

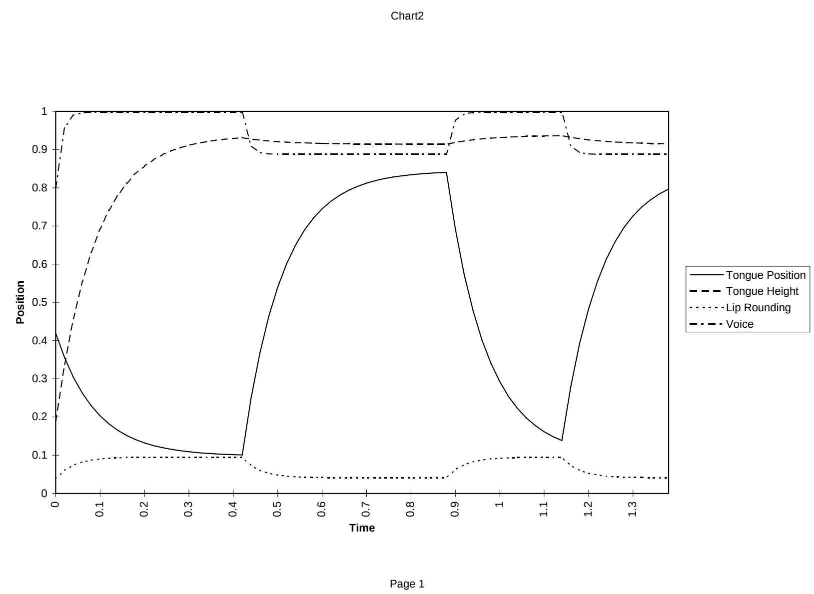

Figure 5: A gestural score based on two phonemes is generated by a speaker as part of an imitation game. The score sets articulatory targets which are to be reached dynamically at specific timings.

sequence from his repertoire, or possibly creates a new phoneme or phoneme sequence by producing a random gestural score. A gestural score is a sequence of articulatory targets. An example of such a score from our simulations is shown in figure 5. The hearer then applies low level feature detectors to the signal (figure 6) in order to recognise the phonemes. When this recognition is successful, the hearer attempts to reproduce the phonemes again. The speaker now attempts recognition and can provide feedback on whether the result is compatible with the originally produced phoneme sequence.

Our experiments show that a common phoneme and phoneme sequence (syllable) repertoire indeed develops and under the demands of the lexicon expands. These experiments confirm hypotheses formulated by Lindblom, among others, that selectionist criteria such as distinctiveness, minimisation of articulatory energy, etc. explain the characteristics of natural phonetic systems Lindblom(1986).

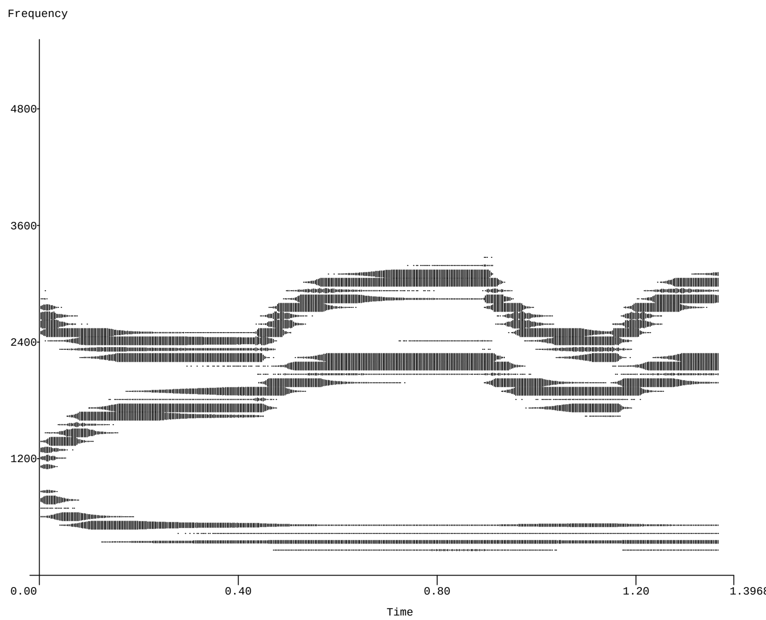

Figure 6: Frequency diagram corresponding to the gestural score produced in figure 5. The hearer applies feature detectors to this signal in order to recover the phoneme sequence.

3 Linguistic co-evolution

In genetic evolution the selectionist criteria are not fixed but derive from an environment which is constantly changing due to co-evolution. For example, one species, acting as a prey, is evolving to become better in escaping its predator. But this causes the predator to evolve again towards becoming better in catching the prey. Whereas evolution in itself causes an equilibrium to be reached, co-evolution causes a self-enforcing spiral towards greater complexity.

Also in the case of language, co-evolution appears to play a crucial role for pushing a language towards greater complexity. The ultimate pressure comes from the growing complexity of agent-agent and agent-environment interaction partly enabled by an increasingly more powerful linguistic ability. Thus language complexity feeds on itself and escalates. The lexicon puts pressure on phonetic creation to create an adequate repertoire of phonemes. If there are not enough phonemes new ones will be generated through imitation games. The language game puts pressure first on the meaning creation modules, for example, to have enough distinctions. When there are more different types of objects, more distinctions are needed. It also puts pressure on the lexicon to lexicalise the meanings that need to be communicated. Thus the more meanings are used in language games the bigger the lexicon will have to be.

We can investigate these phenomena by coupling the different adaptive games in two ways: The output of one is used as input by the other, and conversely the 'user' provides feedback to the producing module. For example, a category used in discrimination is more appropriate in a language game if it also has been lexicalised. When one agent uses a word and thus certain categories, the other agent may have to expand his category repertoire accordingly before being able to decode the word. Thus there are two selectionist pressures on categories: (1) Are they adequate for discrimination and (2) do they have or are they needed for lexicalisation? Similarly a phoneme is not only appropriate as part of the phonetic repertoire when it can be produced and understood, it must also be used by the lexicon.

Another paper (Steels(1997)) illustrates this in more detail based on experiments for the co-evolution of words and meanings by a combination of discrimination games (discussed in 2.1) and language games (discussed in 2.2). The agents engage in a series of language games and as part of each

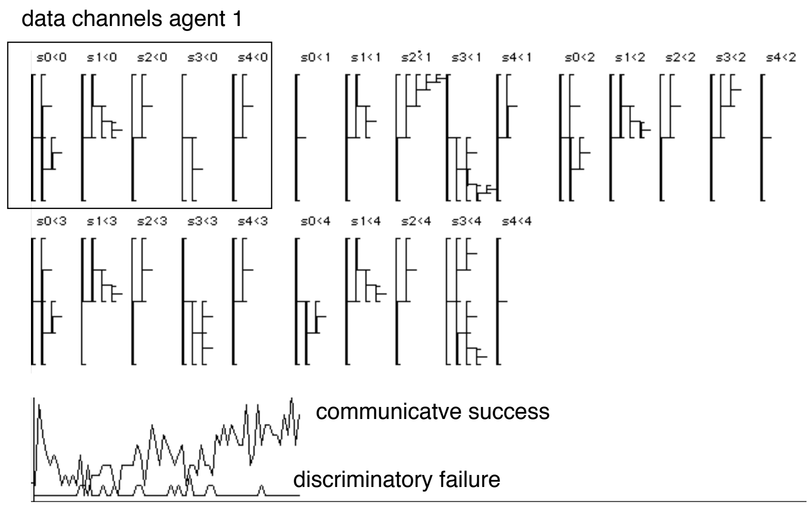

Figure 7: Experiment in the co-evolution of words and meanings. The top window shows evolving binary discrimination trees operating on 5 different data channels (s-0 through s-4) for 5 agents. The bottom window shows on the one hand the failure in discrimination (descending) and the success in communication (ascending) after 500 language games (and consequently 1000 discrimination games)

language game each agent performs one discrimination game. Figure 7 and 8 illustrate these experiments which show a co-evolution of distinctions and words to lexicalise them driven by an expanding set of objects. The top shows the binary discrimation trees for each channel and each agent. The continuous space of each channel (between 0.0 and 1.0) is first divided into two regions (resulting in one attribute with two possible values and thus two categories). Each of these may be further refined. The lines are thicker when there is a lexicalisation of a particular category. Not all meanings are lexicalised.

Interestingly enough, each agent develops his own repertoire of categories. Nevertheless a relative coherence emerges between the agents because they

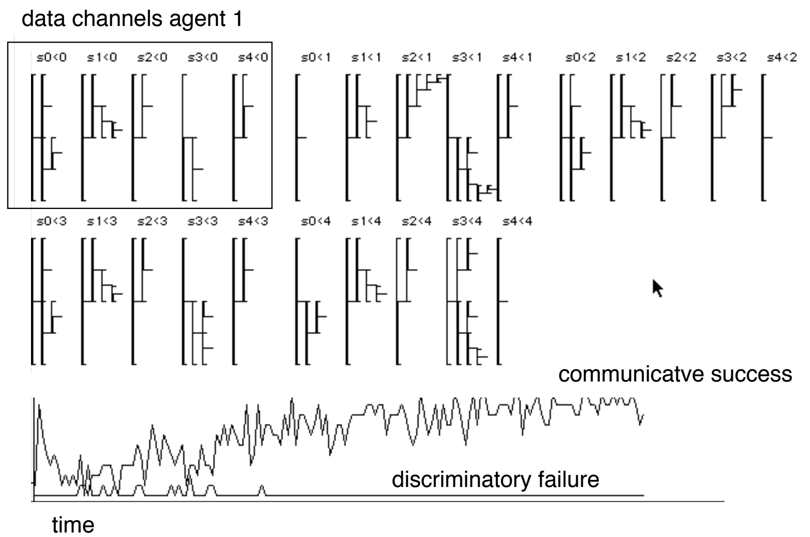

Figure 8: Continuation of the experiment given in figure 8 after 5000 language games. We see that the discrimination trees have further grown and that more categories have become lexicalised. The communicative success reaches its absolute value(1.0) and discrimination failure has fallen to 0.0.

are in the same environment and thus encounter the same objects. This can be seen by comparing the trees of the different agents for each respective channel. We see for example that agent 1 has less refinements on channel 3 than the agent below it (agent 3). What counts however is communicative success. Differences in word meaning may go unnoticed by the agents until a situation arises that forces disambiguation.

4 Self-organisation

Evolution and co-evolution are in themselves not enough. Usually there are many possible structures which are equally plausible from the viewpoint of the selectionist criteria operating for language. But out of the many possibilities only one is usually selected and adopted by the linguistic population. Language and meanings are *shared*. This is a big puzzle for anyone who seeks a non-nativist theory of language and meaning. If meaning and language is innate then it is genetically shared and coherence comes for free. But if language and meaning are not innate we must explain how coherence may arise without central control and with agents having only access to each other's states through localised interactions.

The origins of coherence in a distributed system with many interacting elements have been studied in biology and other sciences under the heading of self-organisation. A typical example is a cloud of birds or a path formed by ants. Examples of self-organisation are also found at lower levels. For example, regular temporal or spatial patterns in the Bhelouzow-Zhabotinsky reaction or the sudden appearance of coherent light in lasers are chemical and physical examples of self-organisation, Nicolis and Prigogine(1985).

The principle of self-organisation prescribes two necessary ingredients: there must be a set of possible variations and random fluctuations that temporarily may cause one fluctuation to gain prominence. Most of the time these fluctuations are damped and the system is in a (dynamic) equilibrium state. However if there is a positive feedback loop causing a certain fluctuation to become enforced, then one fluctuation eventually dominates. The feedback loop is typically a function of the environment so that the self-organisation only takes place for specific parameter regimes. When these parameters are in a lower regime they leave the system in equilibrium. When the parameters are in a higher regime, they bring the system in (deterministic) chaos. Structure arises and is maintained on the edge of chaos (Langton(1995)).

In the computational experiments, self-organisation has proven to be an effective way to arrive at coherence (see figure 9). The positive feedback loop is based on success in games that involve multiple agents. Those rules are preferred that are the most used and the most successful in use. For example, for each word-meaning pair, a record is kept how many times this pair has been used and how many times the use of the pair in a specific language game was successful. The (speaking) agent always prefers the most successful word. This causes the positive feedback effect: the more a word is used, the more successful it will be and the more it will be used even more. Initially there will be a struggle between the different word-meaning pairs until one dominates. Coherence crystallises quite rapidly once a word starts

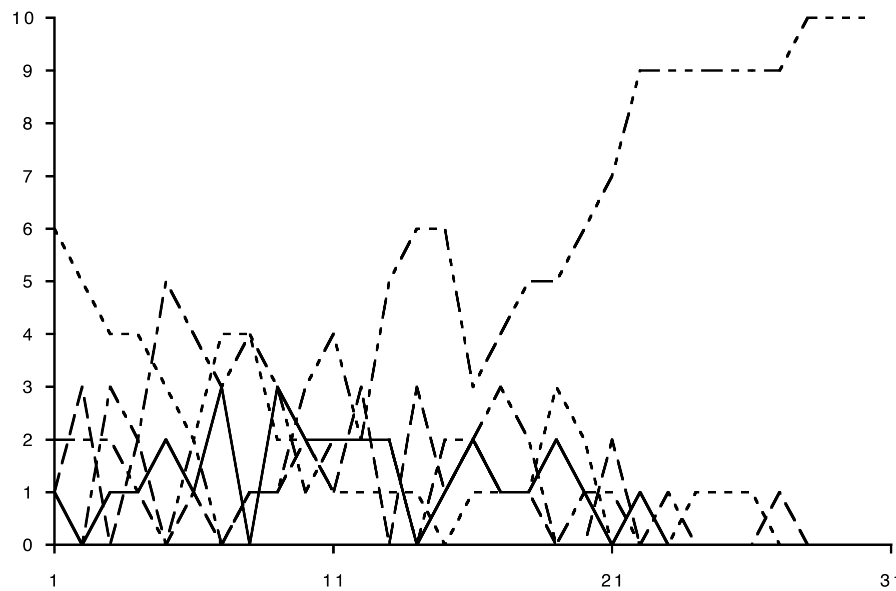

Figure 9: This figure plots the results of a computational experiment in lexicon formation with 10 agents, 5 competing words, and 1 meaning. It plots the communicative success of each word (y-axis) over time (x-axis). We see a search period in which different words compete to express the same meaning until one gains complete dominance.

to dominate, similar to a phase transition.

5 Level formation

Many linguists argue that a representation system is only a language when it also features a complex syntax. In the experiments discussed so far, there was no syntax yet, although there is a steadily increasing lexicon, sound and meaning repertoire. All the ingredients are therefore in place of a protolanguage (Bickerton(1995)). Although syntax is obviously important, these other aspects of language are just as crucial and no theory of the origins of language is complete without explaining how they might evolve. Nevertheless the origins of syntax is an essential part of the problem and it must be addressed. I hypothesise that level formation is the key towards solving it.

Level formation is not exclusively restricted to syntax but is most prominent to explain it.

Level formation is very common in biosystems. It occurs when a number of independent units develop a symbiotic relationship due to co-occurrence, eventually making the units no longer independent. Level formation has for example been used to explain the formation of cells (deDuve(1996)) and the origin of chromosomes which group individual genes (Maynard-Smith and Szathmary(1992)). In the case of the cell, there were initially free floating organisms and structures which came to depend on each other, for example because one organism produces products for another one or destroys lethal products. Gradually the relationship between these organisms and structures becomes so strong that they give up some of their independence to become a fixed part of the whole.

As shown in another paper Steels(1997b), the emergence of grammar may start as soon as there are multiple word sentences (which arise naturally from the meaning creation and naming games discussed in the previous sections). The different words are grouped in a *schema* which is initially completely word/situation specific. When one of the words re-occurs again, it triggers the same schema so that expectations are set up about the other elements and their constraints. From this humble basis, the formation of grammatical complexity takes off through a variety of operations:

- Schemas may be fused to give larger schemas. For example, when w1 and w2 were grouped in f1 and w2 and w3 in f2, a new schema can be created by fusing f1 and f2.
- Semantic and syntactic classes form on what can fill a slot in an existing schema, i.e. the constraints on a frame may generalise. The generalisation could be based on semantic criteria (features of the objects or situations concerned) but could also be based on tagging words as belonging to certain syntactic classes.
- Hierarchical structures emerge because the elements in a schema become themselves schemas. These hierarchical structures co-evolve with the emergence of the hierarchical structures implicit in more complex language games.
- Constraints in the form of additional syntactic devices are added to

distinguish one schema from another one, to enable more rapid recognition, etc. The addition takes place by a variety of operators. One of them is overinterpretation. Observed properties of a schema application, such as word order, are taken to be obligatory as opposed to a mere side effect.

Here is an example of an implementation of these mechanisms at work. A language game takes place in which the speaker uses two words. A schema is created with slots for the parts of the semantic structure and slots for the parts of the syntactic structure. These slots are filled by members of newly created classes. Both semantic and syntactic constraints are recorded

```
Game 297. Speaker: head-40 Hearer: head-41
    Topic: im-37 Context: im-36 im-39 im-42 im-38
++> head-40 #<FUNCTION-FRAME #x605A91E>
Distinctive: ((feature-1 v-221)(feature-7 v-227)(feature-5 v-230))
             ((feature-11 v-234))
Meaning: ((feature-7 v-227)(feature-5 v-230)(feature-1 v-221))
Lemmas: (#<SCHEMA #x5EB9E96> #<SCHEMA #x5E8FFB6>)
++> head-40 #<FORM-FRAME #x605B8FE>
Failure: MISSING-SYNTAX-SPEAKER
=> Extend grammar:
Schema: #<SCHEMA #x5ED026E>
  Function: ((slot-26 cl-26)(slot-28 cl-28))
       ((conjunction (>> slot-26) (>> slot-28)))
    cl-26 = {(feature-1 v-221)}
    cl-28 = {(feature-5 v-230),
             (feature-7 v-227)}
  Form: ((slot-25 cl-25)(slot-27 cl-27))
       ((ordering (>> slot-25) (>> slot-27)))
       cl-25 = {(E D)}  cl-27 = {(D E)}
```

Later on this frame is re-used, which includes the imposition of a certain word order:

```
Game 356. Speaker: head-40 Hearer: head-41
    Topic: im-37 Context: im-36 im-42 im-39 im-38
++> head-40 #<FUNCTION-FRAME #x605A91E>
```

```
++> head-40 #<FORM-FRAME #x605B8FE>
Distinctive: ((feature-1 v-221)(feature-7 v-227))
   ((feature-3 v-234))
Meaning: ((feature-7 v-227)(feature-1 v-221))
Lemmas: (#<SCHEMA #x5EB9E96> #<SCHEMA #x5E8FFB6>)
Syntax: (#<SCHEMA #x5ED1686>
          (slot-27 #<SCHEMA #x5E8FFB6>)
          (slot-25 #<SCHEMA #x5EB9E96>))
Expression: ((E D) (D E))
```

The following is a step in the process of accomodating a new situation by expanding an earlier created schema:

```
Game 347. Speaker: head-40 Hearer: head-41
    Topic: im-39 Context: im-36 im-38 im-42
++> head-40 #<FUNCTION-FRAME #x61DF806>
++> head-40 #<FORM-FRAME #x61E080E>
Failure: MISSING-SYNTAX-SPEAKER
=> Expansion synt class cl-27 with (A F) for #<SCHEMA #x5ED2AB6>
=> Expansion sem class cl-28 with #<SPEC #x5E8FB0E>
      for #<SCHEMA #x5ED2AB6>
```

Current research is focusing on a large-scale application of these schema forming processes coupled with the meaning creation and lexicon formation processes themselves coupled to visually grounded sensory stimuli.

6 Conclusions

This paper proposed a number of mechanisms that together might explain the origins of language: adaptive games, co-evolution, self-organisation and level formation. Each of these mechanisms is known to play a critical role in the origins of complexity in biosystems Maynard Smith and Szathmary (1993), which justifies that they are also applied to the origins and evolution of language. A key point of the present paper is that these mechanisms are not applied to biological structures (for example genes or neural networks), but rather to language itself. For example, no 'catastrophic' genetic mutation is proposed, as in Bickerton (1995), to explain the origins of syntax, rather syntax is hypothesised to originate spontaneously through level formation based on the pressure to express more meanings with limited resources of time, memory and processing power.

An analogy can be seen between language and species and between an individual's language rules (at different linguistic level) and genes. Evolutionary processes operate on the individual rules causing the language to bootstrap and evolve. Selectionist criteria are not in terms of reproductive success (as in the case of genetic evolution) but rather success, ease and efficiency in linguistic communication. Coherence emerges through self-organisation.

Of course, the individual brain must have the appropriate capabilities to engage in the operations necessary to represent and enact the linguistic rules. This includes fine motor control of the articulatory system, frequency analysis of the speech signal, associative memory, discretisation of continuous sensory data channels, set operations over feature structures, monitoring and establishment of feedback loops between use and success, planning and recognition of sequences, etc. But none of these functions is unique for language. The fine motor control needed for the articulatory system is similar to the one needed for controlling a hand. The frequency analysis of the speech signal is identical to that needed for recognising other kinds of sounds. Set operations, associative memory, planning and recognition of action sequences all are needed for daily survival and can be found in lower animals, albeit with much less sophistication.

Testing the adequacy of mechanisms for the origins of language by building software simulations and robotic agents, has proven to be a very effective methodology although it requires a large amount of work. So far, concrete positive results have been obtained for meaning, lexicons and phonology. Much more research needs to be done, particularly in the area of syntax and in the evolution of language games and speech acts. But many exciting new insights are clearly within reach.

7 Acknowledgement

The research and writing of this paper has been financed by the Belgian Federal government FKFO project on emergent functionality (FKFO contract nr. G.0014.95) and the IUAP 'Construct' Project (nr. 20) of the Belgian government, with additional support from the external researcher program of the Sony Computer Science Laboratory in Tokyo. The contributions of Angus McIntyre of Sony CSL to the simulation of language games, are gratefully acknowledge, as well as the contributions of several members of the VUB AI Laboratory, particularly Paul Vogt on grounding the language games in mobile robots, and Bart de Boer on the phonetics experiments.

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