Dynamical aspects of the Origin and Evolution of Language*

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Legend has it that in the beginning was 'the Word'. There is at least one bit of truth in this, in the sense that it must have been a feeling of marvelous joy for our ancient ancestors suddenly to be able to give names to the world. "This is me!" "This is you!" and "Here is the sun!" It was the elevating experience of consciousness coming to itself, wrapped in language and apparently given to us by God.

Of course the Word was not the beginning. In the beginning, the Earth was covered in ashes and flames and there were no words for all these things. The creation of our world began with seemingly endless meteoric showers answered by columns of fire and sulfur. The language of this red-hot inferno 4.6 billion years ago consisted of spluttering floods of magma and apocalyptic peals of thunder. But the Earth gradually cooled down and life emerged slowly. It took 700 million years before the first blue-green algae appeared in the oceans and more than two billion years before the first eucaryotes showed up. Again, more than one billion years should pass before the emergence of multicellular organisms, and yet another 500 million years before the first bipedal hominids started to walk upright in Africa. This was around 4-5 million years ago. These hominids, our ancient ancestors, evolved gradually, although not at a steady rate, into *Homo sapiens sapiens*.

All this knowledge about our evolutionary history is quite well-established by the fossil record and conceptually well understood by Darwinian theory of evolution, which is based on the principles of variation and natural selection. The origin and evolution of language in the *Homo* lineage, however, is still a matter of debate. One reason is that the human language faculty has no apparent fossil record for direct inspection. Another reason is the above-mentioned myth about the word being with God.

This myth was, paradoxically, lent support when the Linguistic Society of Paris at its foundation in 1866 banned the presentation of any papers concerning the origin of language. Not because the linguists where god-fearing in any sense. The 'scientific' reason given was the belief that any inquiry into the origin of language must inevitably be so speculative as to be worthless. Instead linguists should work on comparative philology, for instance in relation to the discovery of the close relationship between Sanskrit, Greek and Latin. Mixing other subjects like biology or anthropology into the pure discipline of linguistics, a serious field of inquiry, was not considered prudent.

Somehow this ban managed to be upheld until the late twentieth century. In the 1990s, a wealth of books suddenly appeared on the shelves. 130 years of linguistics without Darwin was enough. Biologists and anthropologists joined with cognitive scientists, computational linguists, psychologists and primatologists to do research in the eminently cross-disciplinary field of language origin and evolution. New techniques and insights from areas such as neuroscience, non-linear dynamics, molecular biology, archaeology, evolutionary psychology and evolutionary game theory flooded the conferences with a wealth of new insights and theories.

It falls outside the scope of this paper to describe all these new approaches to the origin and evolution of language, and the reader is referred to highly readable introductions such as the seminal book by Derek Bickerton (1900) on the origin and evolution of proto-languages, Pinker's and Bloom's review (Pinker 1990) on the state of research and not least Pinker's bestselling *The Language Instinct* (1994). Robin Dunbar's (1996) discussion of the importance of social interactions among our human ancestors and Terence Deacon's (1997) analysis of the evolution of symbolic thinking both include interesting views on the field. Good overviews of the main theories on language evolution can also be obtained by reading the anthologies by Hurford et.al. (1988) and especially Christiansen and Kirby (2004). The present text, though, will mainly describe some dynamical aspects of language origin and evolution and offer some plausible explanations for certain details necessary for such a grand design. It would be rash to claim that the origin and evolution of language has been *explained* by these details. The aim is rather to point to some interesting aspects in this field of research and to broaden the mind of the reader by presenting some new perspectives.

Mendelian mechanisms

Using evolutionary and mathematical theories for social phenomena is a tricky business. Many popular evolutionary explanations for human traits and characteristics, such as humor, promiscuity or love of music, still do not surpass Rudyard Kipling's *Just So Stories*, neither in their literary imagination nor their scientific argumentation. It is therefore very important, whenever possible, to combine the argument of cause and purpose of a given trait with a demonstrable mechanism of how this trait might have been acquired and developed.

The study of language origins is certainly obliged to follow this rule. Language is probably one of the most complex traits of human nature, the result of a complicated network of biological and cultural factors. Also, language is a relatively recent invention, which might indicate that many of its features are transient. Language is characterised by a plethora of dynamical interactions and inter-dependencies, and is notoriously difficult to subdivide into well-defined parts, suitable for scientific analysis. Language needs to be learned, understood and nourished during a whole lifetime in a social community, and it is therefore quite distinct from other human skills that are rather more hard-wired into the body. In bio-lingo, one would say that language is not an individual trait but an extended phenotype of a whole population.

Historical linguistics might view language evolution as primarily culturally determined, and hence not amenable to Darwinian theory. But on the time scale of hundreds of thousands or even millions of years, effects of variation and natural selection can not be ignored. It is these large time-scale effects which are the subject here. In addition, culturally induced language changes are often seen as irrelevant to Darwinian theories because they are thought to be selectively neutral and thus do not fit into the prevailing adaptionist views. This misconception of modern Darwinism will be addressed later in the text, where it will be shown that the deterministic slant of neo-Darwinian theory should be replaced by a general recognition that chance plays a major part in evolution. Random linguistic drift as a result of selective neutrality might be just as important for the evolution of communicative systems as standard positive selection.

Although we should have a good theoretical basis for explaining language evolution in the framework of modern Darwinian theories, we are still looking for 'Mendelian mechanisms', that is, the dynamic principles behind the process of combination and recombination of the basic units of language. And we may need a lot of Mendels. Linguistic capacities of individual speakers, such as the lowering of the larynx (Lieberman 1971) and the increased size of the brain within the last five million years, are important aspects in the evolution of language. But it seems more important today to try to understand the general dynamic principles that support the inner workings of language structure in a community of speakers and listeners.

The question addressed here is whether researchers within the last ten years have been able to formulate sensible mathematical descriptions of such a self-organised general-purpose communication system, based on the principles of variation, neutrality and adaptive selection. How and why is language structured the way it is? How can evolution create such apparently highly ordered mappings between signs and representations, words and meaning, syntax and semantics, containing all kinds of hierarchical structures, principles and parameters, while language at the same time remains flexible and open for continuous change?

The key to understand the complex features of human language lies in explaining how they could have evolved from less complex features. Separating out the basic necessary components and principles and recombine them by identifying emergent features must be the way ahead. Actually, as we will see below, this is the path the language faculty itself seems to have used in order to become a versatile communication device for *Homo sapiens*.

Outline

Many models of language origins and evolution have been proposed (Hurford 1988; Cangelosi 2002) and it is beyond the scope of this text to present all of them here. I have therefore chosen to confine this reading primarily to the work done by Martin Nowak and co-workers (Nowak 1999a; Nowak 1999c; Nowak 2000; Nowak 2001; Komarova 2003) because it is one of the most simple and clear-cut applications of techniques developed within mathematical biology and complex systems theory, probably representing the best shot 'hard science' has to give in this field at the moment. To get language 'off the ground', Nowak used evolutionary game theory and standard population dynamics to show how protolanguages can evolve in a nonlinguistic society. The beauty of their approach lies in its simplicity. In essence it is a model for the emergent self-organisation of words, syntax and grammar as a result of misunderstandings and limited intelligence. Somehow this sounds very human.

The mechanism by which a population can obtain a common communication system in this model-world requires only a minimal number of assumptions: first, there must exist an ability to express conceptual information in some kind of transmission channel (vocal, gestural or other) within a population of individuals who act as senders and a receivers. And secondly: both the senders and receivers should gain a fitness-payoff (become better at hunting, sharing or whatever is increasing the likelihood of survival of their offspring) if the information is successfully transmitted.

There is, of course, no way by which a mathematical toy model of an imagined math-world can capture the complexity of a real-world communication system. But I hope to make a good case for the approach by demonstrating a simple mechanism by which some of the most important features of human language – the arbitrariness of signs, the duality of patterning and the plasticity of language use – have self-organised and evolved. In the following, it will be discussed how a group of individuals (humans or other animals) can evolve a communication system where arbitrary signals become associated with specific referents. Secondly, it will be shown how mistakes in communication lead to an error limit, which in turn can be overcome by sequencing basic signal units (such as phonemes or syllables) into words. This will be followed by a formulation of some necessary conditions under which natural selection will make syntactic communication an advantage. Subsequently, a cursory framework for the evolution of grammar acquisition is presented, again as an argument that grammar originated as a simplified rule system, which evolved by natural selection to reduce mistakes in communication. Finally, it will be discussed what other dynamical mechanisms from the toolbox of the modern synthesis and complex systems theory should be considered when we make models of language evolution. Genetic assimilation, adaptive fitness landscapes and neutral networks of mutant distributions are presented and offered as promising objects for further inquiry.

The first arbitrary sign

Let us take a look at human speech. As a first step towards spoken language we may assume that early hominids used a single sound for a single object, for an action, or for a whole situation. Our cousins, the vervet monkeys, are doing exactly this on some occasions: They cry "leopard", which is a loud barking call, when a leopard or some other predator cat is approaching. Quickly they head for the trees. When an eagle is approaching they cry "hawk", which is a cough-like sound, and every vervet will look up in the air and run to the bushes to hide (Tomasello 2004). Thus, as a first step there may well have been arbitrary pairings of sounds (calls and cries) with meanings.

This is of course a crucial step: it is the move from an individual compulsive sound to a bidirectional Saussurean sign, a discrete symbolic vocalisation, which a population of speakers and listeners tacitly agree upon is referring to a particular concept. In 1989, James Hurford used evolutionary game theory to show that this is a direct consequence of the dynamic interplay between communicating agents in a population: he showed that the Saussurean strategy, where individuals create their own internal representation of the mapping, produces individuals who communicate more successfully than individuals endowed with other communication strategies such as simple imitation or calculation methods without the use of internal representations (Hurford 1989).

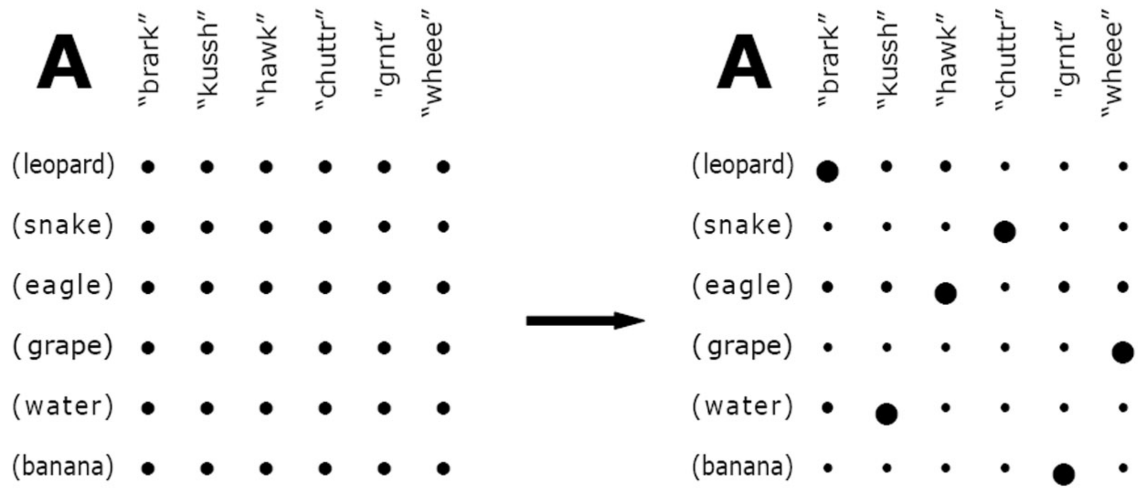

Figure 1: Self-organisation of the Saussurean sign. This is represented mathematically by the association matrix A which links signals (columns) to meanings (rows) for a whole population. Initially, all individuals in the population have random associations between signals and meanings, making A uniform. After a period of communicative interactions where successful communication gives a fitness payoff in terms of more offspring, specific sounds begin to be associated with specific objects. This is indicated by the size of the black circle elements in A. The signals ("brark", "kussh", etc.) and corresponding meanings ((leopard), (snake), etc.) in this figure are only examples of possible associations. Interestingly, the simulations showed that errors during signal-meaning mapping increase the likelihood of reaching an optimum solution.

Also Nowak and Krakauer (1999b), using simple dynamical equations from game theory and molecular evolution, managed to demonstrate that a population with random signal-meaning pairings would in time converge towards a stable association matrix, given that both speaker and receiver would benefit from correct information transfer. Figure 1 shows is this setup how a protolanguage can emerge in a prelinguistic society. Initially, the speakers and listeners have random associations between sounds (signals) and their meanings. Many different sounds are attributed to the same object (meaning) and vice versa, making communication difficult. But as a consequence of iterated communication efforts, a coherent mapping emerges, so that one sound is voluntarily associated with one object only.

Although the vervet monkeys provide an informative analogy, it is not likely that vervet monkey calls are a direct precursor of human language (vervet monkeys do not, actually, "learn" these mappings, although they do sometimes cheat each other with these sounds, indicating intentional use). The analogy is only provided to suggest that this model could present a mechanism by which coherent symbols emerge and self-organise in a population of socially interacting and communicating animals. According to Bickerton (1900), animal signals use primary representations that refer to only food or predators. Human proto-language, in contrast, uses secondary representations that refer to parts of meanings, which are then combined to make holistic utterances. We will turn to these now.

The creation of words

With growing social complexity over time, the number of sounds needed to describe the number of objects and events increase. Merely adding new sounds to the repertoire only helps to a certain point, however, because it also makes it more difficult to discriminate sounds which are auditively closer to each other. This threshold is an auditory error limit and delimits the boundary of the overall ability to transfer meaningful information by the use of signal calls only. Thus, the most important evolutionary selection pressure on prelinguistic communication systems became the minimisation of signal errors. Nowak and Krakauer showed that the error limit could be extended by decreasing the number of sounds producible by the vocal apparatus into easily distinguishable sounds (phonemes, or more likely syllables) and stringing them together into a sequence of sounds spoken quickly, that is, into protowords or morphemes. The error limit is removed by the simple combinatorial trick of sequencing a small number of (meaningless) sounds into meaningful protowords, like in the word ‘banana’. From a mathematical point of view, this is equivalent to the transitions from an analogue to a digital communication system.

All existing human languages only use a small subset of the sounds producible by the vocal apparatus and combine them to generate a large number of words. For instance: the average number of phonemes used in human languages is around fifty, which means that the number of possible words consisting of just two phonemes exceeds 2,000. The number of possible protowords consisting of just five phonemes exceeds 150 million (although not all combinations are feasible because of physical requirements of sonority and other rules of morphology). Thus, when phonemes become the basic units of words, they only require a linear increase in memory capacity but lead to an exponential increase in communicative ‘fitness’. This transition is probably “post-genetic” in the sense that it needs to be learned through experience and trial and error, just like the brain uses combinatorial neural ways to solve the problem of combining the many muscular movements of speech to a fluent whole.

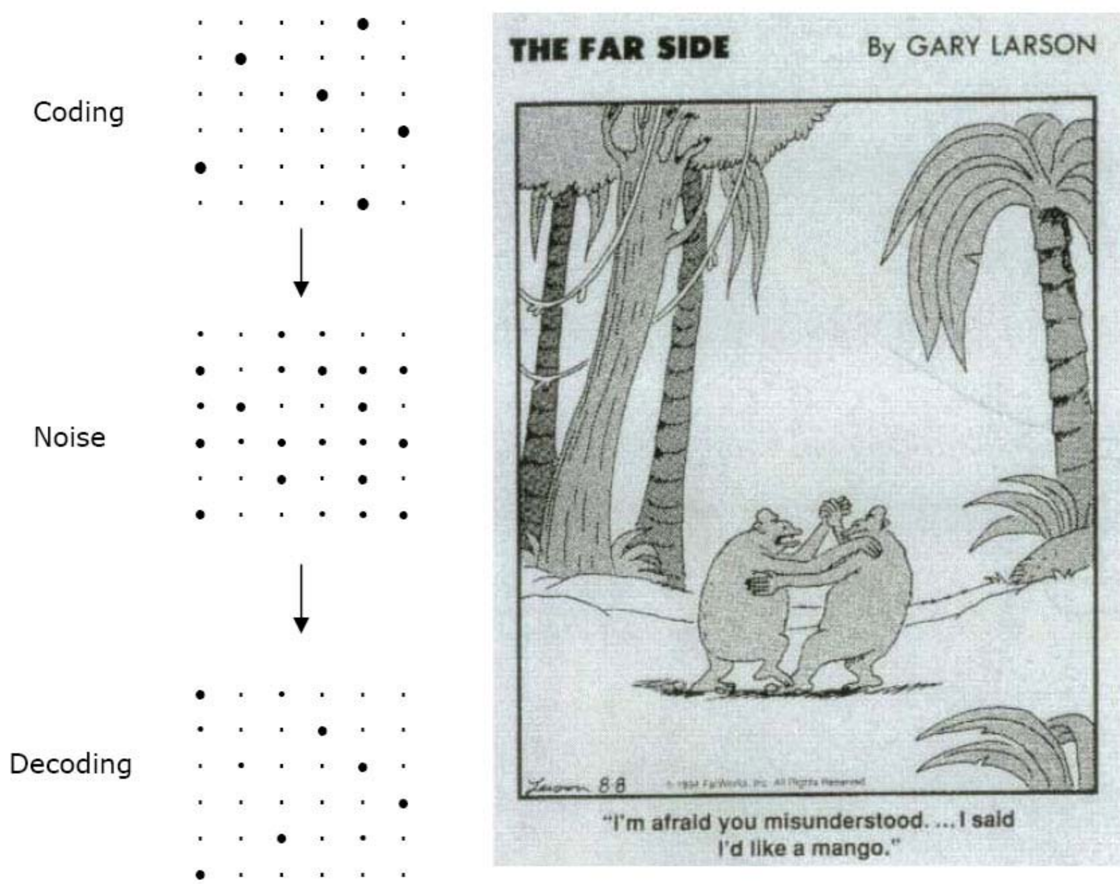

Figure 2: Now the matrices to the left represent word-meaning mappings instead of signal-meaning mappings. It could for instance be the word-meaning mappings of the concepts (tango), (mango),

(bamboo), (banana), etc. with the words ‘tango’, ‘mango’, ‘bamboo’, ‘banana’, etc. The dynamics of this system is the same as before: Noise or an insufficient articulatory apparatus can lead to ambiguous or deficient coding/decoding of information, leading to low communicative fitness. If the number of required concepts exceeds a threshold value, natural selection will favour the emergence of distinct phonemes, which can be sequentially combined into composite sounds, that is, into protowords or morphemes.

Charles Hockett argued that language structure is characterised by a duality of patterning (Hockett 1960): the first being the combination of different sounds in a specific order to make a single identifiable word or morpheme as presented above, and the second the combination of words to make sentences by the use of syntax.

Compound words and syntax

In a hominid society where you only need to agree on a few symbols (e.g. words and concepts based on strings of syllables), it might be sufficient to settle for utterances of a holophrastic nature, which is to say for holistic vocal gestures, which stand for whole sentences such as “baby-want-food-now!”. The problem is that you never really know what is meant. Also, it quickly becomes impossible to say all that in one word when more complex descriptions are needed, such as “I want the food that is hidden under the bush 300 metres to the northeast”. And it also becomes difficult to memorize and agree upon all the necessary one-time-use-only words that have to be invented continuously. Not knowing or misunderstanding of certain words increases, and as a result the error rate of information transfer to an unacceptable level which defines the next error threshold for language evolution.

In order to overcome this error threshold, hominids probably started to concatenate words and use compound words. At some point this was not enough and they started to assign ‘reusable’ words to each actor, object and action and combine them into sentences. Separating verbs from nouns for instance would decrease the number of words to be learned to only v+p, but still make it possible to form v*p utterances (see figure 3). Not all of these combinations will be useful, obviously, but the advantage is that new utterances can now be coined ‘on the fly’ instead of each one requiring group mastery of a novel utterance.

This combinatorial trick, which constitutes the second part of Hockett’s duality of patterning, and which might very well be a unique discovery of *Homo sapiens,* requires high levels of abstraction because all individuals now must be able to create separate Platonic concepts of ‘mangos’ and ‘eating’ instead of referring to a concrete situation with a single word. A person with unlimited memory, like Jorge Luis Borges’ fictional character, Ireneo Funes, would probably be irritated “that the ‘dog’ of three-fourteen in the afternoon, seen in profile, should be indicated by the same noun as the dog of three-fifteen, seen from the front” (Borges 1962).

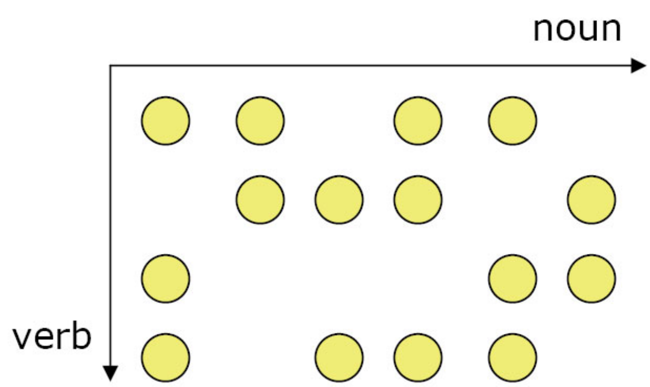

Figure 3: Adopted from (Nowak 2001). Non-syntactic communication supposedly uses words for each of the nine possible situations "leopard sleeps", "leopard hunts", "leopard eats", "eagle sleeps", "eagle hunts", "eagle eats", "snake sleeps", "snake hunts" and "snake eats", but only six words in syntactic communication. Thus, when the number of needed words exceeds a certain threshold value, syntactic communication becomes favorable. The graph shows how not all verb-noun combinations are sensible. For example, if it is twice as hard to memorize a syntactic signal than a non-syntactic signal, and if only one third of all noun-verb combinations describe meaningful events, then at least an 18x18 system is required for syntactic communication to have any chance of evolving (Nowak 2000).

The invention of other major syntactic categories such as adjectives and prepositions reduces the vocabulary in similar ways. Of course there is a lot more to this story, for instance all the additional necessary grammatical paraphernalia that had to be invented in the wake of syntactic communication, such as relative clauses, complement structures, case and agreement and so on. But the general picture should be clear: With the invention of combining words into sentences, it became possible to talk about things that lacked words or referred to extremely rare but important events. Equipped with syntax, human expression was increased almost infinitely and this gave people the ability to transmit thoughts in a previously unrealised way.

But syntactic communication comes at a cost. First of all, the total number of relevant messages to be communicated must be large enough. This is not given to everybody. Many animal species probably have a syntactic understanding of the world, but natural selection did not produce a syntactic communication system for these species because the number of relevant signals was below the threshold value. This increased demand for communication must have happened for our human ancestors at some point in the plio-pleistocene, presumably caused by changes in their social structure (Dunbar 1996).

Another requirement for the emergence of syntax is that the sentences must consist of few but common words that occur in many different contexts. There would be little chance for a syntactic communication system to out-compete a non-syntactic communication system if the words were only used in rare situations. The third and probably most interesting requirement of course is that a syntactic communication system needs rules – a grammar.

The evolution of grammar

Grammar is the calculation system by which people can create an unlimited number of sentences. This striking power to formulate almost everything human imagination can think of was what Chomsky referred to Humboldt saying when he defined human language as the "the infinite use of finite means". In fact, grammar is the general architectural regulator for three parallel combinatorial systems: phonetics, syntax and semantics (Jackendoff 2002). It combines linguistic form with meaning through rules by which a sentence can be sampled, combined and phrased.

In between the process of hearing and speaking and the process of perception and action there is a tripartite architecture: phonological rules, syntactic rules and conceptual rules. The phonological rules are tightly linked to the process of hearing and speaking, while the conceptual rules are linked to perception and action. The overall process is illustrated in the following figure:

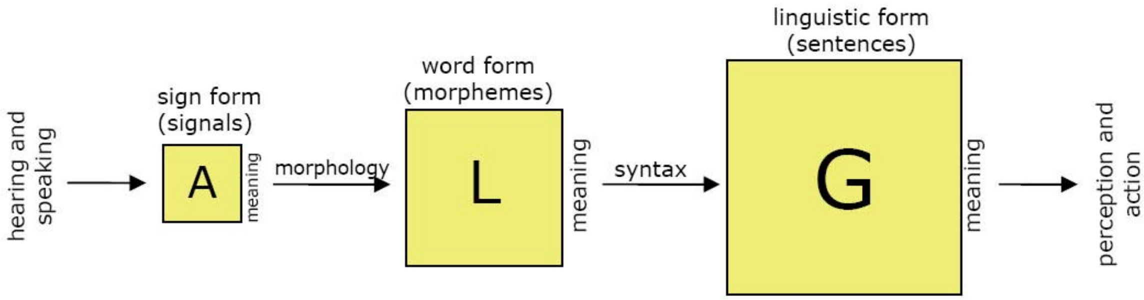

Figure 4: Recapping the story so far, we have seen that the first prerequisite for the origin of language was that a population of interacting agents should agree on common symbols (Saussurean signs) communicated via an association matrix A. If we assume that the prime medium for information transfer in such a population was sound, there would be a limit to the size of the signal-meaning system due to restrictions in the vocal apparatus and deficient accuracy of sound transmission. This may have led to the creation of words (or protowords), composed of a small number of 'digitalised' phonemes and organised by morphological rules. This combinatorial trick of sequencing meaningless sounds eventually led to an infinite reference repertoire of protowords, as represented in the Lexical matrix L. But an increasing need for new meanings and new descriptions opened up the possibility for yet an other combinatorial trick: the concatenation of protowords into listemes and their endless combination and recombination into sentences by the use of syntax and generative grammar, as represented by the grammar matrix G.

Grammar generates the mapping between linguistic form and meaning in a similar way as the lexical matrix uses morphological rules to link word form to word meaning. The most important difference is that of size: In principle the lexical matrix L consists of an infinite number of words, but is nevertheless of limited use because of a limited number of memorizable words. The grammar matrix has infinitely many entries and is not limited by the vocabulary, because grammar rules can expand or compress expressibility to an arbitrary degree.

Chomskyan intermezzo

In certain periods during child development, children acquire words and grammatical rules very easily. Children seem to need very little interaction with other people and exposure to normal language use before grammatical competence is obtained. Noam Chomsky pointed to the fact that the evidence available for the child during language learning is not enough for determining the whole set of grammatical rules (Chomsky 1965). This empirical finding has led to Chomsky's notion of the 'paradox of language acquisition' or the 'poverty of stimulus'. Therefore, he argues, the child must have an innate 'hard-wired' Language Acquisition Device (LAD) that contains a preformed language theory/structure which chooses the appropriate grammar on the basis of only a small amount of linguistic input. This preformed language theory in the LAD was by Chomsky introduced by the term Universal Grammar (UG). Universal Grammar was seen as a kind of rule system that constitutes the search space for all languages to find a usable grammar. Today the LAD and UG are viewed as more or less synonymous concepts, providing the mechanisms for language acquisition.

But because there is not much universality nor grammar in the definition of UG, it might be preferable to use the shortening LAD or the even weaker phrase 'the mechanisms for language acquisition' when talking about the parts of communicative action that are used by the human phenotype. Most importantly, this should include not only the individual biological propensity for language acquisition, the genetic makeup, etc., but also the dynamical principles that are responsible for ensuring communicative coherence and plasticity in a population. It is worth remembering that the theory of grammar has been dominated for the last forty years by the ideas of Chomsky, for whom the central question of linguistics has been why humans acquire a language so rapidly and efficiently in the first years of life. In contrast, the interpersonal dynamics of language change and its role for language evolution, has not had the same attention. Also, Chomsky has (like the linguistic society in 1866) explicitly discouraged research in language evolution, with the strange result that many linguists only reluctantly accept biological approaches to individual language acquisition with reference to an innate linguistic endowment, and even less consider a population dynamical framework of language change, which is at the core of neo-Darwinian evolutionary theory.

In any case, surely a kind of LAD exists, on that incorporates some language-specific inductive learning bias in favour of some proper subspace of possible languages (Brisco 2004). If not, the incredible ease with which children learn a specific language would not make much sense. In fact, there is a mathematical analogy which quite definitively validates the existence of a LAD in the weak sense mentioned above. It is called Gold's theorem (Gold 1967): Suppose that you are asked to determine the rule for the unfinished (and perhaps meaningless) sequence of the numbers 2, 4, 24, 6, 46, 56, 90, 1644, 12, … . You will not be able to solve this problem, in a rigorous sense, if not you could use some preformed or *ad hoc* generated ideas like 'the rule might include all even numbers' or 'the rule might not allow the numbers 3, 7, 8'.). In the case of sentences and not numbers, generating an understanding of the rule (the grammar) is an unconscious process for overcoming the same poverty of stimulus. Therefore, there must exist a LAD, even if it just is a kind of unconscious pragmatic pattern recognition device. In addition, human imagination is probably quite limited in finding clever rules: The act of information processing in the human mind has the tendency quickly to converge towards the most simple and pragmatic patterns possible, and stick to them as long as they seem feasible.

By using deterministic population dynamics to model grammar evolution, Nowak (2001) has shown that the necessary conditions for a coherent grammar to emerge, there must be a sufficient degree of learning accuracy, which in turn depends on the structure of the LAD (the UG in his terms). If, for instance, a learner has no memory at all (i.e. the LAD is a memoryless learning algorithm), the learner will start with a hypothesis of how to speak a certain language and stick to it as long as the sentences are compatible with the hypothesis. When a sentence fails to comply with the hypothesis, the learner will randomly choose another hypothesis, maybe even the already rejected one (since the learner is consistently memoryless). Grammatical coherence in this situation is possible if the number of input sentences exceeds a constant times the number of candidate grammars available from the LAD.

If, however, we have a whole population of people like Ireneo Funes, Borgesian learners with limitless memory, the situation is different. After remembering all sentences that have been spoken, they choose the candidate grammar that is most compatible with the input. In this limit grammatical coherence emerges when the number of input sentences exceeds another constant times the logarithm of the number of candidate grammars. In other words, grammar evolves much easier for Funes than for the memoryless population. For real life communicating humans, the coherence threshold should be somewhere in between these two extremes.

In the following, I wish to discuss some other dynamical mechanisms necessary for language evolution, because human spoken language not only evolves on the time scale of Darwinian natural selection but also on the historical time scale of language change, and on the ontogenetic time scale of individual language acquisition. One mechanism proposed for these cultural changes is the supposed 'Lamarckian' process by which language systems evolve, which I will argue against, and the other has to do with whether canonical non-Lamarckian positive selection should be supplemented by models of neutral evolution and random linguistic drift, which I will argue for.

Cultural evolution and the modern synthesis

In modern biology it is frowned upon to argue in favour of Lamarckian evolution, that is, for a process by which a phenotype can acquire characteristics from the environment and pass them on to its genotype by inheriting them to its offspring. Nevertheless, it has been argued that the language faculty is different from an eye or from the beak of a finch. Richard Dawkins (1976) for instance has played with the thought that the basic unit of cultural transmission, which he called a 'meme', evolves by Lamarckian mechanisms. Examples of memes are spoken sentences, written sentences, live music, recorded music, theatre, cinema, etc.. Other researchers have also argued for the existence of Lamarckian mechanisms (Boyd 1985; Mufwene 2001) , and been criticised for it.

However, there is a less known but well-established Darwinian process, which mimics Lamarckian evolution to a point where they look the same from the outside. It is called 'genetic assimilation' or 'canalization' (Waddington 1942) and is also known as the Baldwin Effect (Baldwin 1896). The biologist John Maynard Smith explains it this way: "If individuals vary genetically in their capacity to learn, or to adapt developmentally, then those most able to adapt will leave more descendants, and the genes responsible will increase in frequency. In a fixed environment, when the best thing to learn remains constant, this can lead to the genetic determination of a character that, in earlier generations, had to be acquired afresh each generation" (Maynard Smith 1987).

Genetic assimilation is probably important for language evolution. Organisms responds to their environment by learning through natural biofeedback and by adjusting to physical and societal conditions. This is what is called phenotypic plasticity. A population can learn a particularly successful mode of behaviour such as psychological traits, physical responses or social behaviour, which can be inherited as part of culture to the next generation. If it increases inclusive fitness, it will proliferate in the population. Given sufficient time, evolution has a good chance to find a rigid mechanism that can replace the plastic mechanism. Or plasticity itself could be selected for. Thus, a behavior that was once learned may eventually become instinctive, that is genetically coded. What was originally ontogenetic has become phylogenetic. Genetic assimilation has been confirmed repeatedly by experiments *in vivo* (Ho 1983; Scharloo 1991) and by computer simulations (Hinton 1987; Nolfi 1994). The consequences for our understanding of Darwinian theory are profound. After all, human behavior and culture are not only traits that resulted from blind evolutionary forces, but traits that *shaped* those forces directly. The environment is as much a result of us, as we are a result of the environment. Direct alteration of the genotype, based on the experience of the phenotype, as proposed by Lamarck, is not possible, but indirect alteration is, as validated by secondary dynamical effects on populations moving in a complex fitness landscape.

Finding the right models

Every individual has a personal idiolect, that is, a personal grammar use, a personal vocabulary and personal pronunciations. People understand each other anyway. It does not matter whether you say things right or wrong (whatever right and wrong means in this context) as long as the message is transmitted to a satisfactory degree. From a modeling point of view this resembles the situation for a population of viral species, described by the theory of molecular quasi species (Swetina 1982; Eigen 1988; Eigen 1992). There exists a cloud of neutral or even slightly deleterious mutants where every single viral strain differs from the others to some degree, but which nevertheless in total defines the 'consensus sequences' of the mutant distribution - in theoretical biology sometimes called the 'wild type' of the population (see figure 5). This wild type would in models of language evolution correspond to the communal, e.g. "correct", way to use a language (not to be confused with Chomsky's E-language). But at least for viral species, it is a huge benefit to have a broad network of mutants in order to adapt quickly to change in their environment (Biebricher 1986). This is probably also the case for languages. If, however, the collective cloud of mutants (e.g. different language uses) is unable to maintain the wild type, the language would disintegrate immediately into a Babel of confusion. Information would melt away through the accumulation of errors.

The modeling approaches described above are well established within the modern synthesis and are quite suitable for modeling language evolution. But there is one possible caveat: they are population dynamical approaches using the classical apparatus of deterministic mass action kinetics. This may be problematic because mass action kinetics relies on the assumption that there is just a small number of compositionally dissimilar entities, each of them present in a very large amount (like in chemical mixtures).

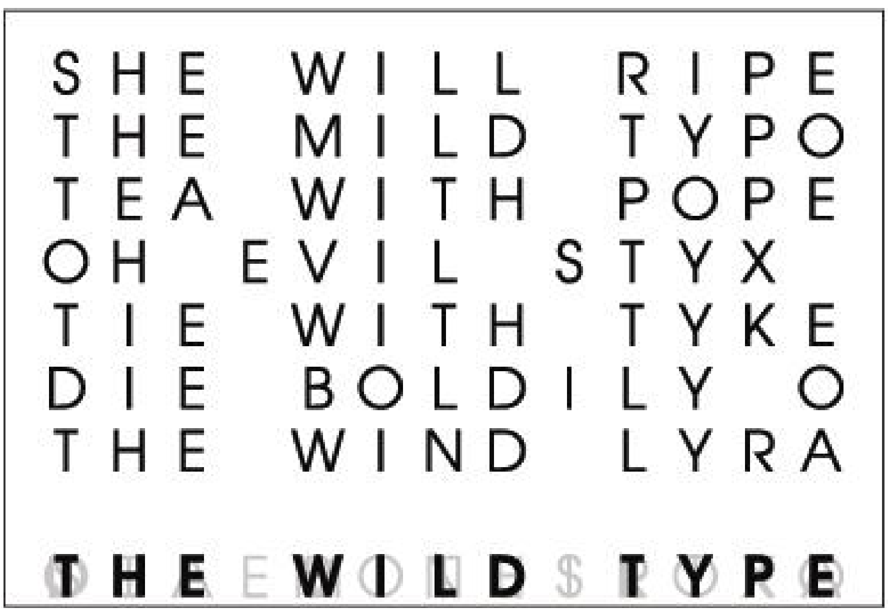

Figure 5: A simple illustration of the definition of the wild type in a cloud of mutants. Each "sentence" stands for a mutant with individual architecture and performance. But since each slot is predominantly occupied with one letter, the average, or rather the consensus sequence, is retrievable. In other words, the wild type defines the center of the population even though it might not exist itself. Of course, the illustration is a hopeless example of double loop thinking: It uses language to illustrate viral species that are used to illustrate a population of idiolects.

In contrast, language evolution is characterised by the opposite: the number of different mutants - in the sense of different language uses - is enormous, while the amount of each one of them is only one or just a few. This might sound like a technical detail, but it has important consequences. The fundamental assumption of the use of continuous differential equations is that of an infinitesimal difference in 'concentration change' over time, an assumption only usable when there is a very large number of identical entities (preferably somewhere around Avogadro's number). This is seldom the case in modeling of language evolution, especially for historical linguistics, where everybody competes with their personal idiolect. Therefore, it might be better to model language evolution by discrete cellular automata type of models, where each performance is assigned its own fitness value and is traced separately through the dynamics (Kauffman 1993).

Neutral language networks

From the viewpoint of historical linguistics, the dominant feature for language evolution is neutrality in the sense that most elements of a language have come into existence because of historical and contextual coincidences, none of which had any selective advantage or disadvantage in the first place. The neutral theory of evolution (Kimura 1983) stresses that this is also the case for the evolution of molecules and species. Thus, the neutral theory might be a good candidate for models for historical linguistics and for language origins and evolution in general. The main body of the neutral theory shows that selectively neutral variants (mutants) are prone to random drift and can create large networks of equally 'fit' mutants in sequence space. The neutral theory also shows that random drift can fixate one accidental mutant quite easily in a population (Kimura 1968). This may also be important for language evolution.

Random drift is an important contributor to evolutionary dynamics even when there is just a small degree of neutrality in the fitness landscape of possible language uses. Neutrality creates huge networks of equally fit variants of a language that can drift and percolate through all possible corners of language space, creating a new dynamics where they form superimposed structured spaces of flows, canals and intricately complex stream of neutral mutants, through which, as it can be shown, the process of adaptation and optimisation paradoxically can be speeded up and highly improved (Engelhardt 1998).

There are two additional consequences of neutrality: one is the fact that neutrality is a prerequisite of plasticity: it helps populations become more robust against environmental changes, because there is a probability that some initially neutral mutants can be immune against environmental perturbations, or even be more advantageous, so that the population as a result quickly amplifies around this mutant by normal adaptive selection. In this respect, phenotypic plasticity is a direct effect of neutrality. The other consequence is that variation and random drift might show more important than natural selection for the continuous evolution of new and diversified languages.

The neutral theory has only sporadically been used for models of language evolution (Lass 1997; Nettle 1999) and may still contain some interesting results for our us to find. For instance, modeling of neutrality with the use of genetic algorithms (Mitchell 1996; van Nimwegen 1997) has revealed the existence of metastability and epochal dynamics, where periods of stasis are interspersed by rapid increases in average fitness of the population. The effects of 'punctuated' evolution are also seen in a model of Kauffman's NK-landscapes (Kauffman 1991; Kauffman 1993) with tunable degree of neutrality, where large neutral networks of mutants become the key units of the dynamics. The model shows that the maximum fitness attained during the adaptive walk of a population evolving on such a fitness landscape increases with increasing degree of neutrality, and is directly related to the fitness of the most fit percolating network (Newman 1998). Finally, Komarova and Nowak (2003) have found that linguistic coherence can emerge in finite populations even in the absence of positive selection.

Conclusion

The story told here took departure in the assumption that communication errors and limited memory capacity among our human ancestors was, in fact, a necessary (but not sufficient) condition for the origin and evolution of language. Human fallibility was, in a sense, the accidental father of our powerful mastery of abstractions and conceptualisations and paved the way for the self-organisation of Saussurean signs, protowords, phonetics, words, syntax, sentences and grammar.

Using population dynamical models from theoretical biology and evolutionary game theory, it was shown that continuous selection pressures on primitive communication systems (the sound-meaning mapping and word-meaning mapping) were overcome by the dual use of a combinatorial trick, first by the recombination of simple sounds into protowords using morphological rules on meaningless phonemes (and syllables), and secondly, by the concatenation of protowords into lexical items (real words) and their endless combination and recombination into sentences by the use of syntax and generative grammar.

Next it was argued that this intricate linguistic system, which works on several hierarchical levels, also works on three different time scales – the evolutionary time scale of language construction and evolution, the historical time scale of language change, and the ontogenetic time scale of language acquisition. Language is therefore exposed to much faster dynamical processes than just natural selection. They include cultural learning, neutrality and random linguistic drift. These 'secondary' processes can nevertheless influence the large-scale structure of language through the mechanisms of genetic assimilation and the fixation of neutral variants. In fact, a coherent mathematical approach to language evolution should be able to integrate all time scales into one framework, which might make the modeling of populations moving on a discrete fitness landscapes a preferable option. Of special interest for this author is the role of neutrality in language evolution because neutrality not only seems important for understanding language plasticity and language drift, but also holds a promise of comparison to empirical data from historical linguistics at some day in the future.

Language was most likely favoured by natural selection because of its adaptive value. In matters of complex adaptive systems like the language faculty, however, many different mechanisms and secondary effects play a part in the actual design. The dynamics of self-organising systems is often counterintuitive and involves emergent features nobody could have foreseen. This text tried to take a look at these dynamical features from a modeling point of view.

From an evolutionary perspective, language research has just begun. Only with the arrival of writing and the computer – which themselves are yet other important steps for the evolution of human communication - scientists have been able to explain and simulate aspects of this general-purpose linguistic device, and have come quite far. But there is still a lot of work needed. The human brain is smart and inventive, though: If there is a communicative impasse, with time and good fortune it will be overcome.

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