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Self-organization and language evolution

Language can be considered from two perspectives. It can be considered as behavior and knowledge of an individual, and it can also be considered as a system of conventions in a language community. In fact, these two perspectives can be said to define two levels at which language can be observed. One is the individual level, where detailed individual behavior is studied. The other is the population level, where individual behavior is averaged and abstracted and more general trends and processes are studied. Examples of subfields of linguistics at the two levels will be given below. Of course, both levels are intertwined and depend on each other. Individuals' behavior is determined by conventions in the group, but at the same time, the group conventions are created and maintained through individual behavior. Such interaction between two levels can lead to a phenomenon called self-organization.

Self-organization in its contemporary meaning is the spontaneous emergence of order in a system. Generally this involves repeated interaction between elements on a microscopic scale that results in organization on a macroscopic scale. The macroscopic scale can then be described with far fewer parameters than would be necessary to describe the behavior on the microscopic scale. In language the individual level corresponds to the microscopic scale, while the population level corresponds to the macroscopic scale.

The term self-organization appears to have been coined by W. Ross Ashby (1947) with a slightly different meaning in the context of cybernetics and the nervous system. Ashby intended the term self-organization to refer to the possibility of a system to control its own behavior. However, in his mathematical formulation the notion of two interacting levels is already present. The notion of self-organization as the spontaneous emergence of order stems more from physics and chemistry, such as for example the work of Prigogine (Nicolis & Prigogine, 1977).

A classical example from biology is the honeycomb. Through interaction between individual bees, and *only* through such interaction a regular structure is formed that is much larger than the bees themselves. There is no need for a central controlling force, or for precise behavioral programs in the individual bees. Flocking of birds, schooling of fish and trail formation by ants (or university students on campus lawns) are other basic examples of self-organization.

A system in which self-organization can occur must consist of a (large) number of interacting elements. In language these elements could for example be speakers in a population, different sounds or words in the language itself, or (if one looks at the neural level) neurons interacting in the brain[1].

Emergence of order means that the system evolves towards a macroscopic state that can be described with fewer parameters (or in terms of information theory, with fewer bits of information) than the possible states at the microscopic level. This means that the behavior of the individuals must become coupled: an individual's behavior is no longer independent of the behavior of the other members of the population. In the example of language in a population of speakers, this means that the language of individuals cannot be arbitrarily different from that of the rest of the population.

A final requirement on self organization is that the emergence of order must be spontaneous. This excludes systems that are controlled by an outside force, or a system that is structured beforehand in a way that imposes order on the elements of the system. An example of a system that is controlled by an outside force is the solar system: the motion of the planets is orderly, but only because of solar gravitation that acts as a global force. An example of a structured system is any hierarchical system: behavior of elements on a lower level is directly controlled by elements at higher levels. Self-organization must really be the result of the interaction between the elements of the system. No small subclass of elements in the system should have complete control over other elements of the system.

The above implies that there must be feedback between the individual (microscopic) level and the population (macroscopic) level. Individuals must be able to sense the population behavior somehow, and adapt their behavior accordingly. In order to allow one macroscopic state to dominate the population, this must be a self-amplifying effect, in that once a certain state begins to dominate, more and more individuals will conform to

[1] In this article we will focus on the first two levels. Although self-organization at the neural level is important in for example development of sensory capacities, and plausibly in learning of speech, it falls in the domain of neurology, rather than linguistics.

this state. This is called *positive feedback*. In language the interaction between the two levels can be illustrated by the emergence of new words for new objects. At first, several words will be coined by different individual speakers. However, as for successful communication shared words are necessary, individuals will adapt words that are also used by other speakers. This process will start a positive feedback loop: more frequent words will be more successful in spreading. Eventually all speakers may come to perceive that there is one "correct" word at the population level, and they will adopt this word.

The above-mentioned processes are quite basic, and therefore natural examples of self-organization abound. They can be found in physical, chemical, biological and neurological systems. It is even likely that self-organization occurs in social and economical systems, but in these contexts, the term self-organization is often applied in an imprecise way and therefore uncontroversial examples are more difficult to identify.

Self-organization and evolution

Self-organization can help simplify biological and genetic accounts of evolution. If complex structures can be explained as the result of self-organization, this means that such structures need not to be genetically coded. Only the much simpler behaviors that lead to self-organization need to be coded. This tends to simplify the account of how these complex structures evolved. In the case of linguistic structures, explanations based on self-organization usually depend on general cognitive mechanisms that are already present to some degree in other animals, as well as on functional constraints that are due to imperfect articulation, perception and processing. Such mechanisms and constraints entail more continuity with evolutionary ancestors than language-specific adaptations. Language-specific adaptations are for example the principles and parameters model (e. g. Baker, 2002), or the capacity for recursion as proposed by Hauser et al. (2002). Such language-specific adaptations would require more complex and therefore vulnerable genetic coding, and this makes it more problematic to explain how language evolved relatively rapidly. Self-organization, in providing an alternative to biological evolution for complexity to emerge, helps to reduce the amount of adaptation that needs to be explained by genetic, biological evolution.

The interaction between self-organization and biological evolution is fundamental to understanding the evolution of language. Biological evolution determines the dynamics and the boundary conditions of the self-organizing process. Self-organization causes the language to converge to a limited number of states. The properties of these states then determine the fitness of the language-using agents. Biological evolution then selects for adaptations that help to cope with the properties of the states that are the result of self-organization. For example, Zuidema and de Boer (2009) have shown that systems of utterances under pressure of acoustic distinctiveness tend to self-organize towards having combinatorial structure, even though the agents that use these utterances are not aware of this structure. However, once combinatorial structure is present, biological adaptations for using this combinatorial structure increase fitness. This solves part of the riddle of how ape vocalizations evolved into human speech. Ape vocalizations are holistic in the sense that utterances generally consist of single articulatory gestures (possibly repeated multiple times) and that the apes do not make any use of the internal structure of signals. Human speech makes extensive and productive use of the internal structure of utterances, and is therefore combinatorial. The riddle is that if all agents in the population use a holistic system, then how could an evolutionary adaptation for using combinatorial structure ever increase fitness? Self-organization here provides a means for a system of signals with combinatorial properties to be present in a population of language users before the language users are aware of this structure.

The example above illustrates a general point about language evolution: fitness of adaptations for language is in general frequency-dependent, meaning that a single agent with the adaptation does not have increased fitness, but that multiple agents with the adaptation have. However, self-organization can move a population of agents towards states where a single individual with a mutation for language does have increased fitness. Self-organization thus helps to solve the apparent paradox of how innovative adaptations for language can have increased fitness, even if only one agent in the population has this adaptation.

Investigating self-organization in language

Although the idea of self-organization is reasonably intuitive, it nevertheless requires interaction between large numbers of individuals as well as feedback between the population and the individuals. Especially in the case of human behavior, this can become complex. This complexity is most likely the reason why self-organization in language has only relatively recently become a subject of study in linguistics. Although the individual and collective levels of language clearly influence each other, modern linguists generally choose to study them separately. Subfields like historical and descriptive linguistics study language at the collective level (even though descriptions of dialects are often based on single informants, they are nevertheless taken to be representative of a whole language population). Subfields like the study of speech errors, of language acquisition or of psycholinguistics on the other hand are based on individual behavior. Both de Saussure (De Saussure, 1987) and Chomsky (Chomsky, 1965), in defining theoretical frameworks for studying language, have abstracted away from the interaction between individual and collective levels. They either defined idealizations of the collective language (de Saussure's *langue*) or assumed that in the ideal case individual knowledge and collective language are the same (Chomsky's *competence*). Such idealizations are generally in order when making descriptive grammars of a given dialect at a given time, but are inadequate when the processes of language change and language emergence become the subjects of study. Sociolinguistics and the studies of language birth, change and death, as well as the study of the evolution of our linguistic abilities are therefore the prime fields within modern linguistics that study the interaction between individual and collective behavior. It is therefore not surprising that these are also the fields where the idea of self-organization is most influential. Probably the first linguistics paper to use the term self-organization explicitly was Lindblom, MacNeilage and Studdert-Kennedy's (1984) paper on the emergence of syllable systems. Since then, much work has been done that links self-organization, language and language evolution. Most of this work has in some way made use of computer models, as these have no difficulties dealing with the repeated complex interactions inherent to self-organizing systems. Overviews can be found in (Cangelosi & Parisi, 2002; de Boer, 2005; Kirby, 2002; Kirby *et al.*, 2008).

There are two perspectives on self-organization in language that will be discussed in this article. The first is the perspective of an individual's linguistic knowledge: linguistic items, such as words or speech sounds can be considered as the microscopic level and the complete linguistic system can be considered as the macroscopic level. The second perspective is that of language in a population of speakers, where individual language users constitute the microscopic level, and the whole language community constitutes the macroscopic level.

Work on explaining the structure of systems of speech sounds as the result of self-organization (Ke *et al.*, 2003; Liljencrants & Lindblom, 1972; Lindblom et al., 1984; Redford *et al.*, 2001; Schwartz *et al.*, 1997) fits with the perspective of self-organization at the level of an individual's knowledge. In this context, the micro-level consists of the individual speech sounds, and the macro-level is the sound system as a whole. Speech sounds have both perceptual and articulatory properties and these properties have continuous values. This means that some speech sounds can be close together in either articulatory or acoustic space, while others are further apart. At the level of the whole sound system, this can result in certain systems of speech sounds being more suitable for communication than others, either because they are easier to produce or because they are easier to distinguish, while most likely some systems are also easier to learn than others. This puts pressure on the individual sounds to be as distinct as possible, while at the same time to be easy to pronounce and to learn. This is a form of feedback (through use) from the macro-level (the whole system of speech sounds) to the micro-level (the individual speech sounds). This view abstracts away from how the feedback is implemented (this is investigated by the population view of self-organization explained below) and sees sound systems as the self-organized outcome of interactions within sets of speech sounds.

Using this perspective, acoustic distinctiveness turns out to be sufficient to explain the structure of small to medium vowel systems (Liljencrants & Lindblom, 1972; Schwartz et al., 1997). Ke et al. (2003) have shown that systems of tones can also be explained as the result of maximizing acoustic distinctiveness. For systems that include consonants, and for larger vowel systems, other factors also play a role. Articulatory ease can partly explain the structure of syllable systems (Lindblom et al., 1984; Redford et al., 2001). Syllable systems turn out to be a compromise between acoustic distinctiveness on the one hand, and articulatory ease on the other. However, learnability might also be important. Systems that reuse the same features are preferred over others and this has been investigated and modeled by Schwartz et al. (2007).

Because of the complexity of the interactions between the different elements of a system of speech sounds, a lot of calculation is involved in determining what the outcome would be of self-organization. This is especially true if multiple conflicting factors (such as articulatory ease and acoustic distinctiveness) are modeled. Most of this work was therefore done with the aid of computer simulations.

The models of self-organization at the level of the sound system address the question *why* sound systems are the way they are, but abstract away from the question of *how* linguistic systems came to be the way they are. This question is addressed by agent-based models of (cultural) language evolution. Such models (Batali, 1998; Hurford, 1987; Kirby, 2002; Steels, 1995, 1998) take the perspective of self-organization at the level of the population. These models directly investigate the link between individual behavior and emergence and change of language at the level of the population. In an agent-based model, individual behavior is modeled directly; the agents are generally small computer programs that model some aspect (languages use, language learning) of an individual's behavior. The model contains many of such agents, and all these agents interact repeatedly. Historically, there have been two main paradigms. One is called the iterated learning model, advocated by Hurford and Kirby while the other is called the language game model, advocated by Steels.

Iterated learning focuses on transmission from generation to generation. In a typical iterated learning model, each generation consists of one agent, while only two generations exist simultaneously (the parent and child generation). At each point in time the parent agent produces language, while the child agent learns. After a while the parent agent "dies", the child agent grows up and becomes adult, and a new child agent is born. This process is iterated. In this way, iterated learning models can focus precisely on which aspects of language structure can be explained by transmission from one generation to the next.

In the language game model on the other hand, typically transmission and emergence of language within one large population of agents is modeled. All agents simultaneously produce, perceive and learn language and even invent new language when the need arises. In this way the emergence and spread of language in an existing population of speakers can be investigated. Phenomena such as the emergence and spread of linguistic innovations, the effects of population structure or the emergence of linguistic diversity can be investigated.

Aspects of both paradigms can be combined to form a continuum of possible models. One could for example increase population size in the iterated learning paradigm, or model agent birth and death in the language game model. In this way a complete spectrum of possible socio-linguistic situations can be modeled using agent-based models.

A typical example of iterated learning is Kirby and colleagues' (e. g. Kirby, 1999) work on the emergence of compositional syntax. In this model, a parent agent produces a set of sentences about a very simple world, involving an agent, an action and possibly a patient. The child agent learns the language on the basis of these sentences using a learning mechanism that detects regular correspondences between the intended meaning and the utterance used. Initially, agents just use random utterances to describe situations in the world. It turns out that compositional syntactic structure emerges after a number of generations. This happens only when the number of utterances observed is smaller than the number needed to describe all situations in the world (but large enough of course, so that all objects and actions occur in the examples). In this situation, accidental regularities in the initially random utterances are amplified, as fewer examples are needed to learn a regular language than a random language.

A typical example of a language game is the naming game, as described in (Steels, 1995). In the simplest version, a population of agents starts out without any linguistic knowledge at all, but is faced with the task of establishing names for each agent in the population. Agents engage in interactions with one other agent at a time, in which they try to identify a third agent by name. If an agent does not have a name for the third agent, it creates a random word. If it does have one or more candidate names, it selects one at random, with a probability proportional to the previous success of the name. If the agents agree on the identification, the success score of the name is increased, otherwise it is decreased. In this model, a population of agents rapidly converges to a unique set of names. Initially, different names will be coined for the same agent, but through positive feedback, names that are used more often will become more successful, and will end up being used even more often. In this way it has been shown that lexicons can emerge rapidly without central control.

When investigating the emergence of sound systems with agent-based models, it is possible to combine the two forms of self-organization. This has been done first at the Institut de Communication Parlée (Berrah & Laboissière, 1999; Glotin, 1995) and has been worked out in more detail by de Boer (2000). Oudeyer (2005) has combined all three levels of self-organization by including self-organizing neural maps in his models.

In de Boer's (2000) model, a population of agents develops a shared system of vowels that must be as large and as successful as possible. The setting is that of the language game: a large (but fixed) population starts out with empty vowel systems, and each agent develops a set of vowels through interaction with the other agents. Initially, vowels are generated randomly, but once signals are established, agents learn from each other. Successful vowels are kept, and unsuccessful ones are removed. Evaluation of vowels is done through imitation: one agent chooses a vowel from its repertoire and produces it (with noise). The second agent hears this vowel and finds the vowel in its repertoire that is closest to it. This amounts to categorical perception. Finally, the second agent produces the vowel it thinks it heard, and the first agent finds its closest vowel. If this is the same as the one it initially selected, the game is successful, otherwise it is a failure. This imitation game puts pressure on signals to be as distinct as possible, without the need of semantics (which would be necessary in a more realistic system). Through repeated interactions, vowel systems emerge that are very much like the ones found in human languages. Because of the randomness inherent in the imitation game, different vowel systems emerge for different runs. However, the frequency with which different vowel systems of a given number of vowels emerge is comparable to the frequency with which these systems are found in human languages.

The emergence of a range of different vowel systems (something which occurs in all these population-based models) indicates that not only optimal systems emerge. This is perhaps what one would expect if the only factor at play was self-organization within an individual – the type of self-organization described in the previous section. However, the fact that agents need to conform to what already exists in a population, tends to stabilize less-than-optimal vowel systems. Stability is of course relative; historical processes will have a higher probability of ending up with more optimal vowel systems (and therefore these will be more frequent) but there is always a small probability that a population will self-organize towards a suboptimal system.

Finally, a few papers have investigated models with self-organization from a mathematical perspective. For example, De Vylder and Tuyls (2006) have investigated convergence of naming games, while Kirby et al. (2007) have investigated properties of the states that iterated learning converges to. Other work, such as (Wang & Minett, 2005) investigated the actual trajectories with which language changes. Such mathematical analysis provides more fundamental insight than computer simulations alone. However, systems necessarily have to be simplified in order to do the mathematical analysis, but it is hard to determine which simplifications still result in interesting and realistic behavior without doing computer simulations. Therefore the combination of exploratory computer simulation and mathematical analysis is probably the best way to make progress in investigating the role of self-organization in language and its evolution.

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