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Complex System View on Natural Language

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Abstract—**The study of complex systems in many sciences such as physics, chemistry, biology, engineering, economics, psychology, among others, has demonstrated itself as a powerful approach to resolve many hard issues and to contribute to a fuller and more realistic description of various phenomena. As different to other types of systems, complex systems are characterized by such properties as self-organization, emergence, openness, dynamic nature, chaoticity, fractality, catastrophism, nonlinearity, and fuzziness. It turns out that natural language as a system possess many indispensable properties of complex systems, so it can be viewed and studied as a complex adaptive system. We show that the complex system view on natural language is powerful not only to incorporate knowledge of language accumulated by traditional linguistics, but further make significant discoveries on many open issues in phonetics, grammar, lexicon, language origin and evolution, first language acquisition and development, simulating language functionalities by computational models.**

Index Terms—**Adaptive dynamic complex systems, agent-based model, cognitive model, emergence, usage-based grammar.**

I. Introduction

IT has been a long and well-grounded scientific approach to study a human, or natural, language as a system comprised of several layers: phonetic, phonological, morphological, syntactic, semantic, and pragmatic. In its turn, each layer is also a system of its proper interrelated elements, so the layers are subsystems within the system. Traditionally, these subsystems are objects of research in the respective fundamental linguistic subdisciplines: phonetics, phonology, morphology, syntax, semantics, and pragmatics. There are many other branches in linguistics focusing on specific language elements or aspects, giving a closer look at selected finer language details; examples of such branches are articulatory and acoustic phonetics, lexicology, conversation analysis, text linguistics, stylistics, among others.

There are also other dimensions of our interest in language: we desire to explore its diversity in language typology, its variation and change over time in historical linguistics and evolutionary linguistics, its usage in different locations in dialectology and by different social groups in sociolinguistics and ethnolinguistics. Language is analyzed with its relation to culture in linguistic anthropology, to brain/mind activities in neurolinguistics and psycholinguistics, to human cognition in cognitive linguistics, its acquisition as first or second language is another area of linguistics.

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Many interesting discoveries have been made in all these disciplines, many language facets and properties have been described and analyzed, indeed, an enormous amount of knowledge have been gained and applied in miscellaneous tasks. However, the knowledge we have is segmental and uncoordinated, each linguistic branch seems to be separate and isolated to some degree from the other branches, and still little is understood how all the branches interconnect and interact to explain and represent language in its totality and wholeness. The accumulated evidence and facts still remain in detached "storehouses" whose walls prevent them all from composing the complete picture.

Nowadays, a promising approach which can lead to a solution of the above issue is adopting the view on language as a complex system. Complex system framework has been proven successful in many other sciences: physics, chemistry, biology, engineering, computer science, economics, psychology, health studies, education. In this article we explain the concept of a complex system, its properties, and review recent works on modeling a natural language as a complex system mentioning some applications this model might have.

A. Systems and their Types

The study of complex systems is an area of systems theory where a system is defined as a construct with "the following characteristics: it consists of a set of objects, a set of relations between the objects, and a structure of layers, and it interacts with its environment" [1, p. 25].

There are many types of systems distinguished depending on their properties. Systems can be open or closed: an open system interacts with its environment, it has input/output and reacts to events occurring in its surroundings, and the opposite is a closed or isolated system (see http://pespmc1.vub.ac.be). According to their time-related behavior, systems can be static or dynamic: a static system is not time-dependent, dynamic systems evolve over time exhibiting continuous, discrete, or hybrid change; such systems can be stable or unstable, and an extreme case of an unstable system is a chaotic system [2]. Depending on the characteristics of output with respect to input, dynamic systems can be linear or non-linear, in a non-linear system output is not directly proportional to input [3]. With respect to system's reaction to environmental stimuli, it can be adaptive, customizing its structure and comportment to its changing context, otherwise it is non-adaptive [4].

B. Complex Systems

In what way does a complex system differ from any other kind of system? While there has not yet been developed a single answer to this question accepted by the whole research

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community, specialists in physics, biology and social sciences—three research fields from which this new science of complex systems has emerged [5]—come up with their own vision on what makes a system complex.

For instance, the physicists Amaral and Ottino [6] distinguish among simple, complicated, and complex systems in the following way. A system is simple if it contains a small number of components which act according to well-understood laws, giving a prototypic example of a pendulum. Then, a system with a large number of components which have well-defined roles and are governed by well-understood rules is defined as complicated, for example, a Boeing 747-400. For a complex system, the authors give an example of a migrating geese flock, which at first glance looks much simpler than the Boeing, however, it is different from the Boeing in the sense that it is an adaptive system, i.e., its behavior is emergent, it changes depending on the environment, and the flock is also self-organizing, i.e., the roles of the components (geese) may also change.

To summarize the considerations in [6], a complex system, as different from the other types of systems, is characterized by self-organization and emergence: it is a set of components (agents) whose roles may be fluid and the relations between the components may be plastic, it means that the rules that govern the behavior and connectivity of the components as well as their roles may change over time. Besides, complex systems also possess other properties which may be not unique to them but can be observed in other types of systems: openness, dynamic nature, chaoticity, fractality, catastrophism, nonlinearity, and fuzziness [7].

II. Complex System View vs. Traditional View on Natural Language

Knowing that a complex system is a structure with the properties mentioned in Section 1.2, and that in a complex system the components and rules of their interaction and behavior may change, can we observe such features in natural language? The researchers who call themselves the "Five Graces Group" [8] affirm that natural language has characteristics allowing to consider it as a complex adaptive system (CAS):

"Language as a CAS involves the following key features: The system consists of multiple agents (the speakers in the speech community) interacting with one another. The system is adaptive; that is, speakers' behavior is based on their past interactions, and current and past interactions together feed forward into future behavior. A speaker's behavior is the consequence of competing factors ranging from perceptual constraints to social motivations. The structures of language emerge from interrelated patterns of experience, social interaction, and cognitive mechanisms. The CAS approach reveals commonalities in many areas of language research, including first and second language acquisition, historical linguistics, psycholinguistics, language evolution, and computational modeling." [8, p. 1–2]

The authors go on to say that the processes involved in language acquisition, language use and change, although studied separately in different areas of linguistics and viewed as different systems, in fact are elements of only one complex system. This system is comprised of interacting speakers (system's agents) whose language behavior is adaptive as it depends on their experience of interaction among themselves and with the real world. The complex system of language also exhibits such characteristics as distributed control and collective emergence, intrinsic diversity, perpetual dynamics, adaptation through amplification and competition of factors, nonlinearity and phase transitions, sensitivity to and dependence on network structure, and local change [8].

Discourse
Pragmatics
Semantics
Syntax
Morphology
Phonology
Phonetics

Fig. 1. Linguistic subdisciplines respective to the levels of language they study Magnetization as a function of applied field.

Different from the traditional view on language as a system of layers abstracted from individual language users (Fig. 1), the complex system approach sees language as adaptive and self-organizing communication behavior of agents (speakers), emerging from interaction among them as well as with environment and developing according to cultural selection and structural coupling [9]. Compare Fig.1 with Fig. 2, where basic components, processes, and relations in a complex system are presented [10][1]. Although this diagram is general and represent a "skeleton" of any CAS, not developed specifically for language, it conveys fundamental principles of complexity and adaptivity found in any domain of reality. The vision of CAS expressed by Massip-Bonet [2] supplements the diagram in Fig. 2:

"Complex adaptive systems are systems that learn or evolve in the same manner as living beings. They seek patterns. They interact with the environment, they "learn" from experience and, as a result, they adapt. They contain information on the environment; in a special sense, they "know" it. The common trait of complex adaptive systems is that they all process information in some way" [2, p. 40].

[1] https://www.innovationlabs.com/summit/discovery1/

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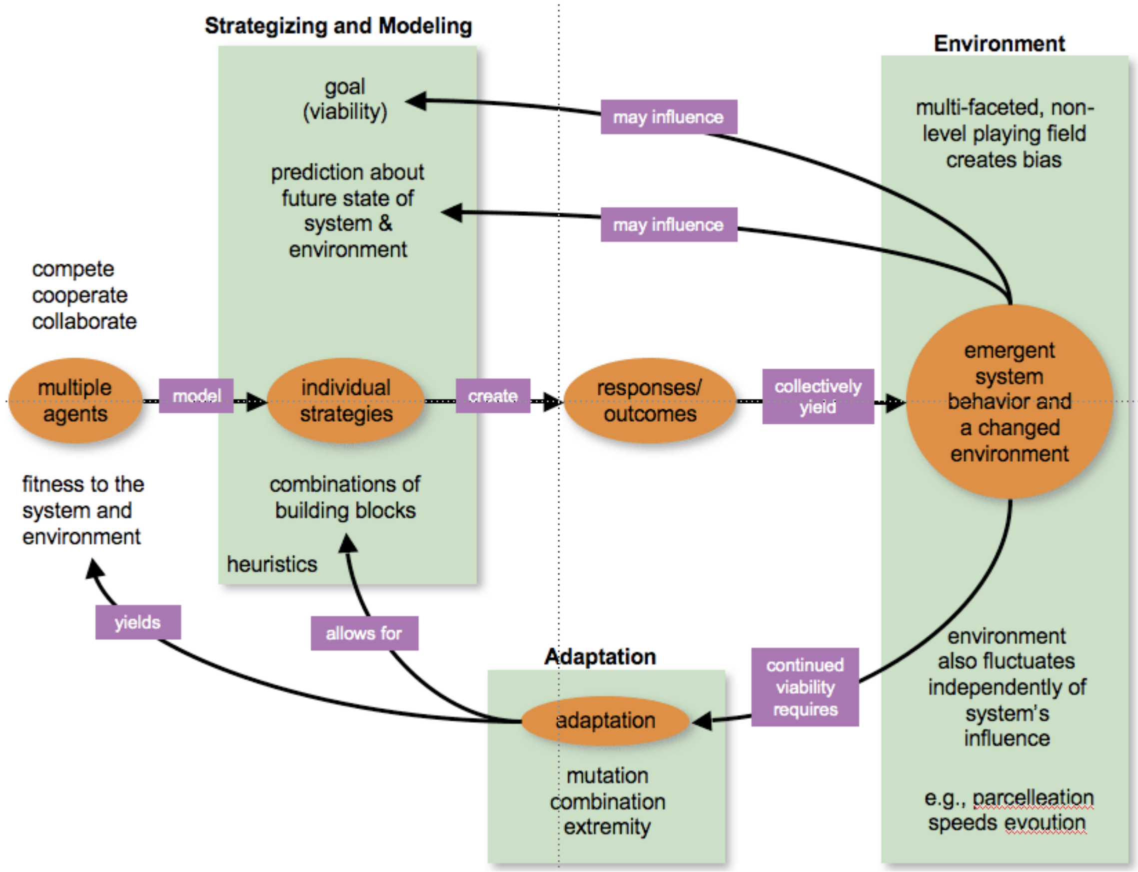

Fig. 2. Complex adaptive systems.

The traditional structural language modeling follows the strategy "divide and conquer" by segmenting its object of study into smaller thus more manageable parts, further analyzing their elements and relations. It seeks generalizations and comes up with well-defined concepts and categories [11]. Categories can be defined in terms of characteristic features or resemblance to a prototype. However, not all linguistic phenomena fit perfectly into elaborated categories, there are cases difficult to resolve and assign to a specific category.

As an example, let us consider the concept of collocation usually defined as a combination of words whose meaning cannot be derived from the meaning of its constituent words. Therefore, the distinctive feature of collocations is their semantic non-compositionality. Here are some examples of collocations with their meaning in parenthesis: *have breakfast* (consume a morning meal), *break a habit* (stop doing something that you do regularly, especially something that you should not do), *dead-end job* (a job in which there is no chance of progressing to a better, more important job), *call it a day* (bring something to an end), *find one's feet* (become more comfortable in whatever one is doing), *under the weather* (sick), *hit the sack* (go to sleep)[2].

Observing these examples, it can be noticed that the meaning of some collocations is closer to the composition of the meaning of their constituents (*have breakfast*, *break* a *habit*), while the meaning of others cannot be analyzed compositionally (*under the weather*, *hit the sack*). The remaining collocations (*dead-end job*, *call it a day*, *find one's feet*) can be situated within the range given by these two extremes: compositional semantics and completely fused semantics. It looks like non-compositionality is graded, it varies within an interval starting from zero non-compositionality in free word combinations with fully compositional semantics (*write a letter*, *buy a dress*) to maximum non-compositionality in idioms: *pull someone's leg* (joke with someone), *beat around the bush* (avoid saying what you mean because it is uncomfortable)[3]. Reddy *et al*. [12] studied compound nouns like *climate change*, *crash course*, *spelling bee*, *cash cow* and proved that their compositionality varied over a continuum of values, see Fig. 3 [12].

It means that linguistic categories are fuzzy rather than crisp sets, Fig. 4 [7]. To study fuzzy sets, we need tools not available within the traditional linguistic paradigm analysis but well suited for complex system approach [13].

[2] Examples from Merriam-Webster Dictionary https://www.merriam-webster.com and Cambridge Dictionary https://dictionary.cambridge.org.

[3] Examples from https://www.ef.com/wwen/english-resources/english-idioms.

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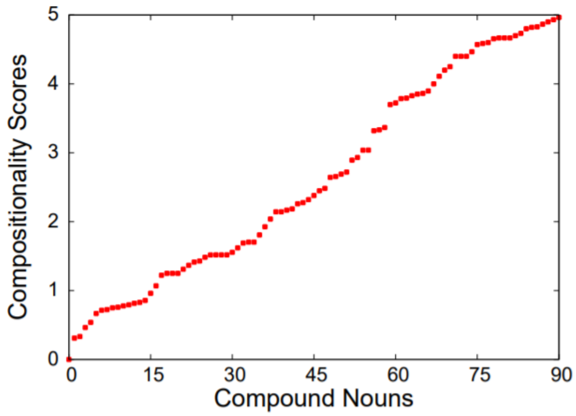

Fig. 3. Mean values of compositionality scores.

Fig. 4. Fuzzy vs. crisp set.

In theory, taking into account the above said, it can be expected that the complex system approach would allow for a more realistic description of natural language. We hope that it is able to assist in discovering previously unknown regularities and patterns useful in various tasks where spoken or written texts have to be interpreted manually or automatically. Besides, the complex system view can open a new perspective on observations and knowledge accumulated within the traditional linguistics, incorporating them into a wider linguistic map. This is how Cameron and Larsen-Freeman [14] put it: "Analysis or investigation of discourse from a complex systems perspective does not require us to throw away other approaches and their techniques. Indeed, multiple types of analysis are needed to work with information from systems at different scales, and new ways of blending methods are needed to explore simultaneous activity on several scales" [14, p. 236].

In the next section, we discuss some results achieved in fields of language study, where complex system strategies have begun to unfold their potential in helping researchers to acquire more insight and understanding.

III. Complex Models of Language

To model language as a complex adaptive system, we are to study not only its discrete constituents but also their interactions as they produce self-organized behaviors. Such interactions are difficult to describe using the traditional conceptual apparatus, so computational simulation and robotic applications come to rescue in this case [15].

Machine learning algorithms assist in finding and evaluating inter-dependency relations among system's constituents, artificial neural networks are used to model the brain activities of the system's agents, their interactions and collective performance. Cellular automata simulate emergence and evolvement of language components, robotic systems allow us to experiment with language phenomena which involve embodiment: perception and action of speakers. In the following sections we will consider complex models developed in scientific endeavors aimed to advance in resolving some interesting issues and challenges posed in language studies.

A. *Language Origin and Evolution*

Since long ago, researchers have been interested in how natural language emerged as a means of communication among human agents, why and how it undergoes changes and evolves over time. Recently, swarm robotic complex systems have been used to investigate the emergence of language intercourse. The objective of such systems is to model collective self-organizing communication through interactions of multiple simple robots. A tool proposed by Cambier *et al.* [16] to simulate the evolvement of language communication among robots is language games. The authors describe several language games such as imitation games, guessing games, and category games, further emphasizing that a best suited game for robotic swarms to develop communication activities is the minimal naming game explored earlier by other researches in different environments [17–20].

The minimal naming game is played by two or more robots; initiating the game, each robot is provided with a set of artificially generated words and then, in the course of the game, it takes the role of a transmitter/speaker or a recipient/hearer in turns. In each step of the game, the goal for the robots is to reach an agreement on the choice of a word from their sets of words, which is to be associated with a given object; selecting words in this way, the robots create a vocabulary of objects' names. Fig. 5 is an illustration of the game in its simple version of two participating robots [16].

First, the robot-transmitter selects a random word from its vocabulary and messages it to the robot-recipient. Then, if the recipient also has this word in its vocabulary, the agreement on the object's name is reached and the game is success; otherwise the game is failure, in such case the recipient has to insert the word in its vocabulary. Cambier *et al.* [16] argue that the minimal naming game possesses a big latent capability to generate an emergent language in systems of robotic swarms aiming at collectively fulfilling a specific task.

The language game approach has been shown productive in another work on language evolution, the research done by Vera *et al.* [21]. The authors focused on the emergence of the fundamental property of any natural language, namely, Zipfian distribution of words in vocabulary. They modeled human communicative decentralized interactions with a bipartite graph where words were mapped to their meaning. Phase transitions in numerical simulations executed on the model

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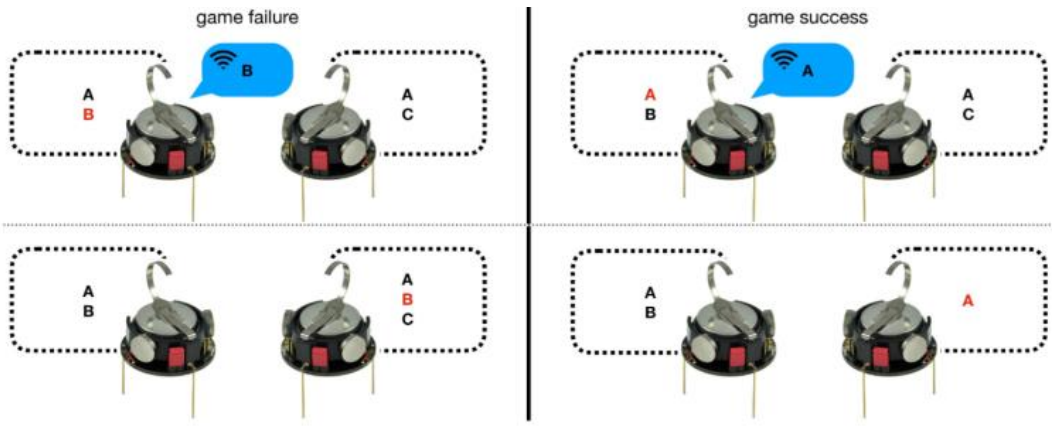

Fig. 5. The minimal naming game played by two robots.

converged to the state where the vocabulary revealed a word distribution in accordance with the Zipf's law, thus demonstrating how such distinctive lexicon property might have originated.

Another important question we can pose considering language origin and evolution is related to speech sounds. How did speech sounds appear, and simultaneously, how did they acquire the ability to form meaningful structures, i.e., words? The first attempt most cited in the literature to answer this tough question within the complex systems framework was the experiments in [22]. Using robotic simulation, de Boer modeled the origins of vowels by means of imitation games. Each robotic agent was equipped with a sound feature analyzer and a sound synthesizer, imitating human acoustic and articulatory apparatus. The agents in turns produced and perceived random sounds. If an agent who received the sound produced by another agent was able to imitate it, the outcome in the game was count successful, if it could not reproduce it, it was a failure. After 4,000 games, the sounds evolved in the system showed features very close to those of human language vowels. This result is a strong evidence for evolution of language as a self-organizing system, opposite to other theories on this topic, see a substantial review of these in [23].

Another model of phonological system evolution is presented in [24], showing how local interactions among speakers can cause the emergence of a global system. The authors efficiently modeled basic motor, auditory, and sensory-motor factors in play in the process of language formation. However, there are other factors—cognitive, environmental, social, cultural—present in the context of language development. Due to this multi-causal scenario, it is rather complex to incorporate all factors into a single model; to our knowledge, such model has not yet been designed. Besides, some researchers assume that there exist still other driving forces influencing language evolution, and among them, curiosity as an intrinsic human capability.

Speaking of curiosity, we need to note here that there have already been made several contributions to the effort of integrating this human faculty into complex evolutionary models. An interesting suggestion is [25]. These researchers conducted an experiment with a system of robotic agents using a strategy of curiosity-driven learning, interpreting curiosity as "an epistemic motivational mechanism that pushes an organism to explore activities for the primary sake of *gaining information* (as opposed to searching for information in service of achieving an external goal like finding food or shelter)" [25, p. 493]. The authors implemented curiosity as a mechanism using which the robots, in an active learning environment, were acquiring skills allowing them to decrease uncertainty. In the course of the experiment, the emergence of more complex behaviors adapting to the constraints of the environment was observed.

In this section we reviewed some of the works on the issue of language origin and evolution in the light of the complex system view. These have been initial attempts to model and analyze sophisticated processes involved in language development, trying to account for factors commonly neglected in traditional linguistic studies for the sake of simplicity. The proposed models still need further improvement, and we hope that in future, more elaborated complex models will be proposed.

B. *Phonology*

In this section we continue the discussion of sound system emergence and evolvement started briefly in Section 3.1, where we focused more on language in its totality. Here we will speak specifically of the phonological system as viewed and studied within the complex system framework.

de Boyer's model of vowel system emergence [22], introduced shortly in Section 3.1, inspired other scientists to apply the complex system approach to studying phonology. In fact, de Boyer himself extended his robotic vowel model to the sound system as a whole [26], since the former was found to explain the emergence of language sounds in a very realistic way. Now we will give more details on de Boyer's simulation.

In de Boyer's model, the evolvement of sounds was simulated by means of an imitation game with the basic rules

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shown in Fig. 6 [26], reproduced in [27, p. 141] through self-organization of robotic agents' sound production and perception activities. The simulation included two mathematical models. The first model was responsible for generating sounds whose format frequency values were computed based on a number of equations designed for this purpose. This model imitated the human articulatory mechanism. The second model was developed for imitating the human auditory system. Using the second model, the robots perceived sounds.

Initiator (teacher)	**Imitator (learner)**
If $V = \emptyset$ then Add random vowel to V	
Pick random v from V, Increment count of uses of v Produce signal A_1 from v	

	Receive A_1
	If $V = \emptyset$ then
	    v_{new} = Find phoneme(A_1)
	    $V = V \cup v_{new}$
	Calculate $v_{received}$
	Produce signal A_2 from $v_{received}$

Receive A_2
Calculate $v_{received}$
If $v = v_{received}$ then
    Send non-verbal feedback: success
    Increment count of successful use of v
Else
    Send non-verbal feedback: failure	

Do other updates of V (see below)	Receive non-verbal feedback Update V according to feedback signal Do other updates of V (see below)

Fig. 6. Basic rules of imitation game.

The game was played as follows. At the beginning, each robot was equipped with a set of vowels. Then, in the course of interactions, robots, in turns, were emitting sounds and perceiving them, as well as reproducing them as an evidence of perception. After perceiving and reproducing a sound, a robot compared it with the sounds in its set. If it was similar to a sound in the set, it was merged with this sound, otherwise it was added as a new sound to the set. Thus, while the game proceeded, the sound systems of robots went through a continuous process of developing and updating. Fig. 7 [26], reproduced in [27, p. 141] presents a part of the emergent sound system obtained by aggregating the sound systems of all robots into a single structure. Comparing the emerged system with the human sound system, the former was found to be very similar to the latter.

The work of de Boyer [22], [26] was dedicated to the issue of the sound system origin as such system emerged resulting from self-organizing activities of speakers-hearers. Another interesting issue in phonology is sound change over time. The questions we may ask here are why sounds change, what the causes of sound change are, in what way sounds change, and how this change is preserved and becomes fixed thus turning into a conventional pattern accepted by all language speakers, i.e., how a changed sound becomes a phoneme.

One of the works aiming at answering these tough questions is [28]. The authors explained the sound change with a model of human speech processing, studying this phenomenon in the context of interaction between the speaker and hearer, analyzing the processes of speech production, transmission, and perception. The authors reviewed a number of cognitive-computational models of sound change and proposed two contributions which could improve the models and shed more light on how phonetic variation leads to phonologization, that is, when a diverge from a given phoneme results in fixing the new phonetic changes in a phonemic contrast. The first contribution was emphasizing the necessity to add the aspect of hyper- and hypoarticulation in relation to pragmatic meaning, and the second contribution was the proposal that a sound change model could take advantage of associations between perception and production if they are introduced mathematically, dynamically mapping articulatory patterns to acoustic aspects.

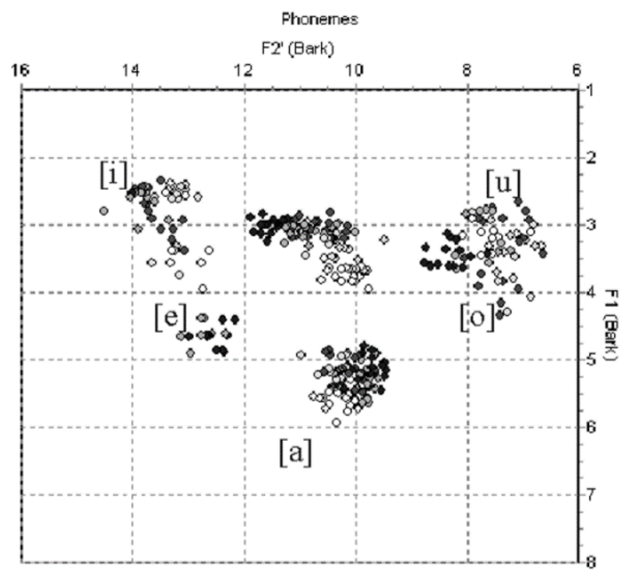

Fig. 7. Emergent vowel system: vowel phonemes are shown as clusters of similar vowels learnt by multiple robotic agents.

Latest achievements in attending to the phonological issues touched in this section as well as many others have resulted from neural networks. An interesting work where the neural network strategy was adopted to examine sound learning is [29]. The author implemented a Generative Adversarial Network (GAN) to learn aspirated and non-aspirated allophones of three English voiceless stop phonemes in an unsupervised fashion. The task was far from trivial as the network was trained on a corpus of continuous speech, i.e., the data was time-series. The basic principle of GAN is twofold: on the one hand, to learn phonetic features in the discriminator part of the network, and on the other hand, using such features, generalize various allophonic pronunciations to a single speech segment which corresponds to a phoneme, producing it in the generator part of the network. The author's experiments demonstrated a high potential of the network to learn allophonic distribution of phonemes. Alongside with other

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interesting contributions in [29], it is important to note that this is the first work where such distribution is uncovered in an unsupervised manner.

There have been other works done in the field of phonology, still there are many open issues left for future. However, as computer technologies are rapidly developing nowadays, we can expect a substantial progress in modeling the phonological layer of natural language as a complex system, which may lead to a richer and fuller representation and understanding of this phenomenon.

C. Grammar

The traditional approach to grammar consists in describing and categorizing language structures as well as formulating rules which generalize to as a broad range of language phenomena as possible; each rule is usually accompanied by a list of exceptions. Complexity theory does not neglect the knowledge accumulated by conventional grammars, but places it in the context of real-life experiences and interactions between humans as language users.

This usage-based approach looks at grammar as a dynamic adaptive network where grammatical constructs emerge through communicative experience of interrelating human agents. Thus, grammar is claimed to be “a cognitive organization of one’s experience with language” [30, p. 711], where the frequency of word usage and word associations plays a decisive role in forming grammar constructions. It turns out that frequencies and therefore probabilities of occurrence and co-occurrence of language constructions promote highly used forms turning them into conventionalized structures [8].

Going further in this direction of thought, one may ask a question of how and in what particular ways frequent usage gives shape to grammatical constructions, what mechanisms operate in the process of conventional pattern emergence. In other words, “what is the best model of constraint generalization”, as Dunn [31, p. 1] puts it, claiming that grammatical constructions are sequences of words that comply with some set of lexical, syntactic, and semantic constraints. So how these constraints emerge, that is, why some particular words and not others are combined to form structures accepted by a language community as grammatical or correct? With an intent to find an answer to this question, Dunn built two grammar generating models: one based on frequency and the other based on associations. Both models were applied to a corpus in order to encode it in a grammar, thus obtaining two grammars. The generalization capacity of the grammars was defined as the number of bits used to encode the corpus, and the quality of generalization was evaluated using the Minimum Description Length principle [32]. The association-based model was the winner, since the grammar it produced used a smaller number of bits.

Dunn’s work studied grammar as a whole; there have also been done studies of aspects or parts of grammar, focusing on their emergence as subsystems of the complex system of grammar. One of such works is [33] where the author studies the emergence of morphosyntactic patterns in complex words based on usage, proposing a theory called Construction Morphology, explaining that its basic idea “is that word formation patterns can be seen as abstract constructional schemas that generalize over sets of existing complex words with a systematic correlation between form and meaning” [33, p. 198]. An example of a constructional schema is derivation of nouns from verbs: *eat – eater, sing – singer, walk – walker*. All these deverbal nouns are formed according to the common pattern or constructional schema, which can be formalized in a simplified manner as verb + *er* = the verb’s agent. Analyzing many other examples as well as grounding on psycho- and neuro-linguistic evidence, Booij argues that schemas explain the relation between form and meaning of existing complex words and phrases on the one hand and on the other hand serve as a blueprint for creating novel words.

There are a lot of other research questions related to grammar as a complex system, to various facets of grammar and their functions, to acquiring grammar, and Ibbotson *et al*. [34] are interested in finding an answer to one of such questions: how does the complex system of syntax emerge through interactions and dependencies between many simpler units such as words, when used in utterances by small children feedbacked by their caregivers? The authors aim at evaluating how distributional properties of words make their impact on emerging grammatical categories and their relations. Their model is a dynamic, evolving over time network, where weights are assigned to links and which grows incrementally in complexity, thus simulating cognitive processes in human brain. To develop and study the model, the authors took advantage of analytic tools, proposed for doing research on complex adaptive systems in general, especially of those tools developed for community detection in networks. A network community is defined as a set of network units or agents whose connections among themselves are stronger than their connections with the other units in the system. Ibbotson *et al*. [34] detected network communities by link density measures and further studied with respect to their grammatical structure. In the experiments, a corpus of child directed speech was used. When the caregivers pronounced a word for the first time, it was added as a node to the network, when two words were used together as a bigram in an utterance, they were linked by an edge. If such words were pronounced together more than one time, the weight on their link grew in proportion of usage frequency. Fig. 8 [34] shows how the network grows using as input the utterances *John liked Mary*, *John liked Bob*.

After inputting the corpus, Ibbotson *et al*. [34] identified network communities and discovered that they corresponded to some specific grammatical patterns, thus explaining how grammatical constructions can be learnt as self-organizing structures evolving through usage by language speakers. This discovery showed how emergence of grammatical structures is tightly related to real-world contexts, such fact contrasts with the conventional rigid system of highly abstracted rules.

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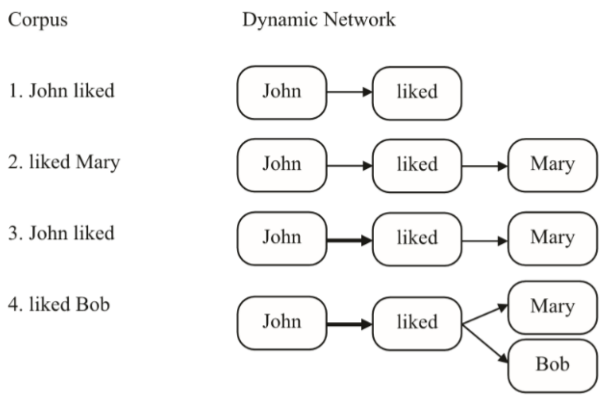

Fig. 8. The dynamic construction of network from speech '*John liked Mary. John liked Bob*.'

Another promising research line leading to a more realistic account of grammar than the conventional view is the theory of interactional linguistics. Its detailed review can be found in [35], here we will comment on it briefly. Interactional linguistics suggests to analyze grammar within a conversational setting, monitoring how grammatical constructions are used by speakers during their intercourse. The researchers, who adopted this approach, look for the ways grammar is shaped by human conversation and vice versa: how conversation is shaped by grammar. Therefore, grammar is examined within its real-world context; researchers observe the emergence and self-organization of linguistic structures and conversational traits when participants aim at understanding messages of each other. Moreover, during spoken discourse, language users may employ non-linguistic communication mechanisms such as sighs, sniffs, clicks, whistles, and the like, termed as liminal signs in [36]. In this research, the author stresses that the "language sciences need approaches that can deal just as well with the fluid, hybrid, and liminal aspects of language in interaction as they can deal with its better studied systematic, structural, and compositional aspects" [36, p. 194].

One more point of view on how grammar emerges is formulated by cognitive linguistics. This approach gives attention to a particular element of the context where language develops and operates, namely, general cognitive human abilities such as vision, attention, thinking, and reasoning, including categorization, analogy and entrenchment [37]. Cognitive linguistics is a challenge to generative (rule-based) grammarians who claim that a person is born with specific linguistic capacities, stipulations, and types, and their functioning results in grammatical competence. According to the cognitive approach, such competence emerges and develops through speakers' language experience by exercising general cognitive abilities mentioned above. During communicative practice of speakers, grammatical constructions come up through generalization of phrases that share structure and semantics. An example of such generalization in usage is given in [37] alongside with many other examples: the interrogative frame What AUX NP V? can be abstracted from the concrete questions used in child speech *What's Mommy doing? What's donkey doing? What's Mommy making?*

As we attempted to show in this section, there have been many fruitful trends in studying grammar as a complex dynamic system, functioning and developing within a wide context. In comparison with the traditional view on grammar, usage-based grammar and a complex view on grammar have been quite recent areas of research, where we can wait for many more works to appear.

D. Lexicon

Now speaking about grammar in Section 3.3. and lexicon in the present section may produce an impression that these aspects of language are separate but related strata, lexicon items being fillers in grammatical construction slots. In fact, much work has been done in this fashion. However, in real-world language interactions, grammar and lexicon function together in a tight coordination, so a better description of lexicon can be achieved when it is studied together with grammar. Indeed, the complex view on language suggests that all language elements as subsystems can be understood better within the whole complex system of language, which also include speakers as agents and all modalities of constantly changing contexts and environment. It means that the complex system approach can not only describe the existent lexicon in a more realistic way, but also account for its development and emergence of new words. Therefore, although this section is dedicated to lexicon, it will be considered in its relation with grammar and its usage by speakers.

One of many questions arising from such usage-based view on lexicon is how speakers choose words in each specific communicational context, or why a particular word is preferred to other words with similar meaning under certain circumstances.

Answering the above question, applied as a case study to four common Spanish verbs with the semantics of 'becoming', Bybee and Eddington [38] analyzed their 423 usage instances in spoken and written corpora representative enough of speakers' language experience. The verbs were *ponerse* 'to put (reflexive)', *volverse* 'to turn (reflexive)', *quedarse* 'to remain (reflexive)', and *hacerse* 'to make (reflexive)'. The typical frame in which these verbs were found is <an animate subject + verb + adjective>, for example, *El vecino se puso nervioso* ('The neighbor became nervous'). So, the question concerning the speaker's lexical choice would be the following: how does the speaker choose a particular verb out of these four verbs given their synonymy? How does she make the decision to use, for example, *hacerse* in some context, but not any of the other three verbs? Searching for a solution to this issue, Bybee and Eddington [38] fulfilled a comparative analysis based on verb frequencies and semantic similarity, discovering a number of interesting selection patterns, which can be consulted in their article as the space limits do not permit us to contemplate them here.

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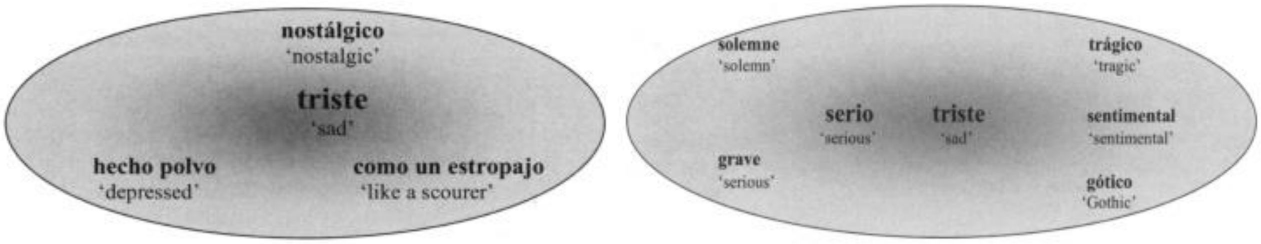

Fig. 9. Clusters centered on *quedarse triste* 'become sad' (left) and on *ponerse serio/triste* 'become serious/sad' (right).

Bybee and Eddington were not the first scientists to ask questions with regard to selectional decisions, there had been other research on this topic, mainly based on finding boundaries for each verb usage depending on semantic features. However, such boundaries resulted to be fuzzy, there is overlap among verb usage cases, moreover, it is hard to define semantic features formally and precisely.

A contribution of Bybee and Eddington [38] is their finding that verb choice does not depend on semantic features, but rather on the analogy to speaker's previous linguistic experience with verbal constructions. The authors formalized such choice by constructing a usage-based exemplar model. An exemplar is defined as a mental representation of an actual word or phrase usage; it differs from a prototype, which is a set of semantic features common in all realizations of the word or phrase. In [38], exemplars were retrieved by grouping semantically similar adjectives in all patterns <an animate subject + verb + adjective> found in corpora. In this manner, adjectives and, respectfully, verbs were categorized as clusters with adjectives of highest frequency as central members. As an example, Fig. 9 depicts clusters centered on *quedarse triste* 'become sad' and *ponerse serio/triste* 'become serious/sad'. These expressions are synonymous, so it is interesting to observe similarities and differences in adjectives used with the two verbs. All clusters found in the experiments formed a complex network representation of the section of Spanish lexicon that includes the four verbs mentioned previously.

Another important aspect of a complex system is its context. Jones *et al*. [39] studied the impact of diverse and distinctive contexts on mental lexicon organization posing the question: how do speakers arrive at similar organization of their mental lexicon which allows them to communicate and understand each other while having different individual linguistic experience? To answer this question, the authors used data on word recognition, semantic and episodic memory as general cognitive ability, and information retrieval for their analysis. It was found that not only word frequency is important in forming mental lexicon, but also the number of diverse contexts the word is encountered in. Words are learnt more rapidly and better if they are experienced by a learner as a constituent of other words or phrases, in a wide spectrum of combinations with other lexical items and in texts belonging to different domains. Such findings are important not only for enhancing language learning, development, and education, but also for developing more robust and precise mathematical and computational models and tools for more accurate text understanding and generation.

Speaking of lexicon, our language competence includes not only knowledge of individual words but also multiword expressions, various word combinations, and utterances. With such respect, Lieven *et al*. [40] studied how two-year-old children learn new multiword utterances relating them to known utterances. The research technique employed was the traceback method, in which a corpus of recorded utterances produced by four two-year-old children, two female and two male, was used and observations were made on the degree of relation between an utterance and previously produced utterances, which included it as a whole or as some segment of it. The analysis of observations revealed that what children said at the moment was closely related with the preceding speech. This discovery is in a complete accord with other research within usage-based approach; it was also confirmed that what children learn are multiword combinations, not just single words. Concerning grammatical schemas, the authors found that the slot for referents was most easily acquired by children when they compared it to other slots such as location, process, attribute, utterance or direction. This relation between speech and previously produced utterances showed that through such relations children develop schemas and their slots, starting with referring expressions and then, with further language experience, they develop more abstract slots in conventionalized constructions.

Usage-based approach to lexicon, which is the focus of this section, has been confirmed by many researchers, among them are Bruns *et al.* [41], who applied usage-based approach to familiar collocations (*I don't know*, *it's alright*, etc.) in non-fluent aphasia. The authors studied the frequency of producing such collocations by speakers with Broca's aphasia and their conversation partners in both dyadic and non-dyadic speech. Also, as a case study, the authors examined how one particular collocation *I don't know* was used in conversations. Their study showed that speakers with aphasia used much fewer word combinations then their conversational partners. However, the words within collocations were more strongly associated in the aphasic speech. Such stronger association confirm the usage-based view on language processing.

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Finally, the usage-based approach has been shown productive in studying artificial languages, for instance, sign language. Lepic [42] investigated how general-domain cognitive processes of chunking, entrenchment, and routinization were involved in lexicalization in American sign language. Particularly, the author studied multiword expressions, fingerspelled words, and morphologically complex signs. Analyzing sign language speech according to the usage-based position, the author demonstrated that conventionalized, or lexicalized, fixed multiword expressions, e.g. *interpreter bring-on* and *take-to hospital*, come from the ability to recognize and generalize relations between form and meaning while speakers exercise such ability in their individual experiences with language. Looking at fingerspelled words, e.g., *power* and *pen*, the author observed gradual and continuous processes of entrenchment and reduction, as these words were repeated in the same communication context. Concerning morphologically complex signs, e.g. *rent* and *hash-things-out*, Lepic found that they obtain their typical meaning by means of their contexts of use. In such contexts, complex signs gradually become related to additional senses by means of metonymy, diverging significantly from the original meaning of complex signs components.

The complex approach to lexicon, which claims that lexical constructions emerge through linguistic experience of speakers, has been successful in many other scientific works. Gradually, this approach has been forming a solid framework for analyzing lexicon, proposing effective formal language models, explaining development and function of lexical items. Such models further improve language analysis and processing, aiding in many aspects of human activities.

E. First Language Acquisition and Development

Another interesting but hard question to answer is how language is acquired, how it is transmitted from adult to infant, and how a child internalizes language as a global system, making its own individually distinctive version of this system.

In the course of time, there have been made several attempts to create theories explaining how a child develops her unique fashion of language. One of such theories is nativism, suggesting that the potential to acquire language is innate in the human nature and the ability to develop diverse language structures is genetically predetermined. The most prominent nativism advocate is Noam Chomsky [43]. In his opinion, specific neurophysiological attributes of human brain could be the only rationale accounting for the child amazing capacity of mastering such a sophisticated aggregate as language.

As opposed to nativism, behaviorism argued that linguistic forms like other stimuli are learnt through practice and repetition. This view was proposed by Skinner [44] and strongly criticized by Chomsky who claimed that the behaviorist approach cannot explain how the child develops adequate usage of irregular wordforms. The matter is that the process of acquiring such forms usage is not easily modeled with repetitive behavioral patterns: the child first utters these words correctly, however, in a while she starts to makes errors often giving no attention to adult corrections, eventually, this period terminates and the child attains to the proper usage.

Similar to behaviorism, empiricism (see, for instance, the classical work in [45]) criticizes nativism claiming that to acquire language, the child does not use genetically conditioned language-specific potential permitting to develop complex language forms, but instead, biologically inherited general cognitive abilities as in assimilating any kind of knowledge during the child's early lifetime. Researchers within this trend, ground their arguments in latest finding of neuroscience concerning the way children process information in different periods of their life [46].

Different from the previously mentioned theories, the emergentist approach to language acquisition [47] suggests that all factors—genetic, behavioral, and environmental—interplay in the learning process, leading to the continuous emergence and improvement of language proficiency in the child. Emergentism, allying with the complexity perspective, argues that language mastery results from local interactions between many factors and aspects embedded in the child-caregiver-real world complex system.

As a complex adaptive and dynamic system, language involves form, user, and usage [8]. Their relationships are difficult to study: it is practically impossible to make long-term observations of a child and her environment to investigate how she grows in language competence. Besides, learning takes its particular course in every child, so we have to observe continuously a representative sample of the children population which is also impracticable. These restrictions make computational models and simulation a valuable research tool on this complicated issue.

McCauley and Christiansen [48] suggested that language learning in fact is language use; they developed a computational model based on this assumption in a cross-linguistic ambient. Other underlying principles of the model design were incremental acquisition, memory constraints, and the child's ability to comprehend and produce language via discerning multiword units (chunks) rather than individual words, thus acquiring patterns of language structure. Incremental acquisition was modeled as a probabilistic word-by-word analysis in the phase of comprehension of adult speech directed to the child, and as chunk-by-chunk generation in the phase of language production based on immediate input rather on stored knowledge, thus modeling memory constraints, i.e., the word probabilities were computed over adjacent chunks. Multiword unit discovery was simulated by means of part-of-speech tagging and shallow parsing. Simulating child language acquisition, the model was learning language structure and producing utterances which were then compared to real children's real utterances in the corpus of English speech from CHILDES database [49] reaching the mean F-score of 74.5, thus successfully demonstrating the child's early linguistic comportment.

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Another side of language acquisition complexity was exposed by Ororbia *et al*. [50] who argued that early language learning takes place in multi-modal environment. The argument was underpinned by two experiments: first, learning was modeled by a neural network and, second, by the same network in conjunction with visual context. The model in the second experiment yielded better results than that in the first one, demonstrating that augmenting the predictive neural language model with images illustrating the sentences being learnt improved the model's predictive capacity. This result is supportive of the situated cognition theory [51], [52] whose claim is that language development goes in hand with learner's interaction with physical reality. Also, the results in [50] emphasized the significance of non-symbolic semantic representation combined with linguistic structures for language acquisition on the one hand, and on the other hand, served as an evidence of one of the principles of complex systems: the environment or context is to be taken into account as a part of the language system and not as its surroundings only, therefore, language cannot be abstracted from context without any loss of information.

In research community, there has been interest not only in modeling acquisition of the complex system of language as a whole, so to say, from the bird's eye view, but also in modeling the acquisition of language segments and subsystems. If we "take a loop" and give a closer look at language, we would observe further striking complexity in any language element we approach. One of such elements of the language development model is acquisition of verb inflections to express person, number, or gender. The computational model of verbal conjugation acquisition developed by Engelmann *et al*. [53] and applied to Finnish and Polish was built to test if rote storage and phonological analogy, two principles grounded in children's real-life linguistic activity, were sufficient for achieving verbal inflection mastery in contrast to traditional grammar rules. This assumption was verified in the experiments where the system reached almost adult-level expertise of six person/number forms in the verbal paradigm, chosen for the tests. The authors concluded that rote storage and phonological analogy were responsible not only for successful verbal form acquisition, but for attaining the knowledge of inflectional morphology in its totality and even for learning the whole body of language.

There are other works on complex modeling of morphology acquisition, different from [53]. However, the space for this article does not allow us to speak of them in detail, we will only make a brief mention of [54], where the researchers suggested that an end-to-end machine learning model based on a semantic vector space, linear transformation, and proportional analogy is potent enough for efficient lexicon management without the need of morphological analysis of words into phonemes and morphemes. In their experiments, the authors found that incremental implicit learning formalized by the proposed model, built as a two-layer linear network, explains quite well the fundamental aspects of understanding and producing words.

With the above survey of some recent papers on first language acquisition within the complex system modeling approach, we conclude our consideration of language as a complex system. We hope that all research works we reviewed in this article expose a high potential that the complex view on language, so different from traditional linguistic descriptions, has in exploring this multi-faceted and multi-dimensional phenomenon which is natural language.

IV. Conclusion

Human language possesses many features in common with complex systems: self-organization, emergence, dynamic and adaptive nature, fuzziness. This fact opens a new horizon in studying language since it can be viewed and investigated as a complex adaptive system. Traditional linguistics—also including methods in computational linguistics and natural language processing which develop models along the lines of the traditional approach—tries to avoid complexity by segmenting language into various layers (phonetics, phonology, lexicon, morphology, syntax, etc.) and studying or modeling them separately. In contrast, the complex view on language suggests to study language as a system of multiple agents-speakers involved in language interactions and relationships, where language structures emerge and develop. Research papers reviewed in this article present many significant discoveries in language studies made by using computational models and simulations within the complex system framework. We are convinced that in future we will witness many more contributions produced by the complex system approach to language.

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