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excerpt from **Chapter 1**

Computer Simulation: A New Scientific Approach to the Study of Language Evolution

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Introduction

Language is such an important human characteristics that we would like to know how it first came into existence and how it managed to reach its present form. If we could go back in time for a sufficient number of generations we would encounter human ancestors that did not have language. In a succession of generations the descendants of those non-linguistic ancestors came to possess the ability to speak and to understand the speech of others. What made the transition possible? How did the transition occur? Were there intermediate forms of language in the sense of communication systems different from known animal communication systems but also different from language as we know it and as is spoken today by all humans?

These questions constitute the scientific study of language origins and language evolution. The study of language origins does not directly include historical linguistics since this focuses on how human languages change historically and how new languages emerge from pre-existing languages, nor does it directly include the study of how language is acquired by children since they learn in an environment in which language already exists. The study of language origins and evolution is the study of how language emerges from a situation in which there is no language. However, both historical linguistics and the developmental psychology of language are concerned with causes, mechanisms, and processes of language change and with primitive forms of language such as pidgin, creole, and children's languages. These disciplines can indirectly contribute to the study of language origins and evolution.

The study of language origins and evolution clearly is an interdisciplinary field

(Knight, Studdert-Kennedy and Hurford, 2000; Hurford, Studdert-Kennedy and Knight, 1998; Harnad, Steklis and Lancaster, 1976). Evolutionary biology and the neurosciences are involved in this study because the human capacity of language has a genetic and a neural basis. Furthermore, as we have seen, historical linguistics and developmental psycholinguistics and, more generally, linguistics and psychology, may have something to say about language evolution. Finally, paleoanthropology and cultural anthropology are clearly relevant since language has evolved in human ancestors and, although it can have an evolved genetic basis, is culturally transmitted, i.e., learned from others, and it changes culturally (historically) from one generation to the next.

The rich interdisciplinary basis of the study of language evolution can be an asset but also a liability since the various disciplines that contribute to this study tend to have different theoretical and methodological orientations and practices which are difficult to reconcile. But the real problem that makes the study of language origins and evolution a difficult and even problematic research field is that it is a field with a multitude of theories but a very limited, or even non-existent, empirical basis. Language has emerged from non-language in the distant past and there is no direct trace of the event. Furthermore, the origin of language is an event that does not repeat itself and therefore cannot be observed. We can observe a child's first acquisition of language and the emergence of pidgin/creole languages but these are different events, although somewhat related.

How can we reconstruct the origin and evolutionary stages of human language given these difficulties? Since language is so important for defining what a human being is, human beings have a natural tendency to propose theories and evolutionary scenarios for its origin and evolution. But these theories inevitably tend to remain speculative because we don't have the empirical evidence to confirm or disconfirm them or to choose among them. In the nineteenth century this situation persuaded the *Société Linguistique de Paris* to emit its famous ban on research and publication on the subject. Today we know much more about language, about mind and the brain, and about human ancestors than was known in the nineteenth century. But still the variety of different theories and interpretations of language origin and evolution that have at least initial plausibility is so great and the empirical basis for choosing among these different theories and interpretations so restricted that the study of language origins and evolution remains a somewhat dubious research field. Science is the production of theories about causes, mechanisms, and processes underlying the phenomena of reality and explaining them but a mature science cannot stop at theories. To be called scientific a theory must generate specific empirical predictions and these predictions must be compared with directly or indirectly observed facts.

Theories of language origins and evolution not only are difficult to test empirically but they tend to be stated in such vague and general terms that these theories are unable to generate specific and detailed empirical predictions. Empirical predictions are the "interface" between theories and empirical reality. Science makes progress when this "interface" is extended and detailed. This is not the case for theories of language evolution. Hence, the problem of the objective scarcity of empirical evidence for such theories becomes even more serious because the theories do not generate specific and detailed empirical predictions and they do not help the researcher to look for empirical evidence.

It is this very problematic aspect of the study of language evolution which computer simulations can help us to overcome. Computer simulations are theories of the empirical phenomena that are simulated. Traditionally, scientific theories are expressed verbally or with the help of formal and mathematical symbols. Simulations are a novel way to express theories in science. Simulations are scientific theories expressed as computer programs. The program incorporates a set of hypotheses on the causes, mechanisms, and processes underlying the simulated phenomena and, when the program runs in the computer, the results of the simulations are the empirical predictions derived from the theory incorporated in the simulation. All this contributes to the development of a new approach to the study of the origins and evolution of language.

A New Approach to the Study of Language Evolution: Computer Simulation

The use of computer modeling and simulation in the natural and human sciences has greatly progressed in recent decades. This progress has been possible because of the availability of very efficient and low cost computers. The new methodological approach has also facilitated interdisciplinary research because the great memory and processing speed of computers make it possible to incorporate in one and the same simulation data and ideas from a variety of disciplines. For example, in cognitive science and artificial life the computer simulation methodology plays a major role in bringing together scientists from different disciplines. In the specific field of language evolution, simulation provides a complementary methodology that can help researchers to develop detailed and precise hypotheses on language origins and evolution and to test these hypotheses in the virtual experimental laboratory of the simulation. Various bits of empirical evidence such as observations and experiments on animal communication, fossil record analysis, genetics studies, and experimental psycholinguistic data can lead to the formulation of theories and predictions that can be verified through computer simulations.

As we have said, a simulation is the implementation of a theory in a computer. A theory is a set of formal definitions and general assertions that describe and explain a class of phenomena. Examples of language evolution theories are those that identify a specific ability as the major factor explaining the origins of language, such as gestural communication (Armstrong, Stokoe and Wilcox, 1998), tool making (Parker and Gibson, 1979), vocalization and speech (Lieberman, 1994), or symbol acquisition abilities (Deacon, 1997).

Theories expressed as simulations possess three characteristics that may be crucial for progress in the study of language origins and evolution[1]. First, if one

[1] Some of these characteristics will be discussed in more detail in the section on the advantages of simulation.

expresses one's theory as a computer program the theory cannot but be explicit, detailed, consistent, and complete because, if it lacks these properties, the theory/program would not run in the computer and would not generate results. This is crucial for theories of language evolution because, as we have said, these theories tend to be stated in vague and general terms and, therefore, it is virtually impossible to determine if they are internally consistent and complete, that is, sufficient to explain the phenomena. Second, a theory expressed as a computer program necessarily generates a large number of detailed predictions because, as we have said, when the program runs in the computer, the simulation results are the predictions (even predictions not thought of by the researcher) derived from the theory. This is important for theories of language evolution because a large and diverse set of empirical predictions broadens and strengthens the usually restricted and weak interface between theory and data which characterizes these theories. Third, simulations are not only theories but also virtual experimental laboratories. As in a real experimental laboratory, a simulation, once constructed, will allow the researcher to observe phenomena under controlled conditions, to manipulate the conditions and variables that control the phenomena, and to determine the consequences of these manipulations. This is crucial for the study of language evolution not only because experimental manipulations yield a richer and more detailed set of observed empirical phenomena but because these manipulations allow the researcher to test hypotheses and ideas experimentally, which is otherwise entirely impossible if one is interested in long past events and phenomena such as those concerning the origins and evolution of language.

Simulations not only implement general theories but they can implement a specific model derived from a theory, or some specific hypothesis. A model is a simplification of a general theory, or focuses on a specific aspect of the phenomena of interest. For example, there are formal models that seek to explain the necessary conditions for the evolution of syntactic communication (Nowak, Plotkin and Jansen, 2000), or that focus on the role of imitation of motor skills and the development and specialization of Broca cortical areas for language (Rizzolatti and Arbib, 1998). A computer simulation is a clearer and more *practical* way of expressing what a theory or a model says. This makes a theory or model more verifiable, because the execution of a computer program can easily identify the problems, inconsistencies, and incompleteness of the theory or model. Simulations also permit the discovery of new predictions that can (and must) be derived from a theory and the search of new (real) empirical data that can verify these predictions.

Computer simulations are also important because they tend to be inherently quantitative research tools. Quantitative predictions derived from theories, quantitative descriptions of the empirical data, quantitative manipulations of variable and parameters controlling the observed phenomena, are critical features of a mature science. The natural sciences have made great progress in the last 3-4 centuries not only because they have created an intense and detailed dialogue between theories and experiments but because empirical observations, predictions derived from theories, and experimental manipulations are all expressed in precise, quantitative terms. Quantification makes ideas and observations more objective and makes it possible for other people to replicate observations and experiments. Computer simulations tend to be quantitative. The simulated phenomena tend to be described and analyzed in quantitative terms and the parameters and conditions controlling the phenomena that are manipulated by the researcher also tend to be quantitative. Furthermore, simulations can be repeated ad libitum, varying the initial conditions, and they make possible all sorts of statistical and reliability analyses.

But simulations are not only a novel way of expressing scientific theories and not only virtual experimental laboratories. Simulations re-create reality, they *are* artificial reality. This is a property of simulations which can be very important for the study of language origins and evolution. The study of language origins and evolution is the study of long past and non-repeating phenomena that it is impossible for us to observe today. There is some empirical evidence available from which we can reconstruct these past events but it is only very indirect. From archeological evidence about ancient stone tools we can learn about the tool-making skills of our ancestors (Davidson, 2000) and from the study of cranial bones we can speculate on their vocalization abilities (Lieberman, 1994). From observations of the communicative behavior of species that are closely related to humans, we can hypothesize about the communicative abilities of our ancestors (Savage-Rumbaugh, 1998) and reflect on the differences between human language and animal communication systems (Hauser, 1996). But as we have said, this is all indirect empirical evidence. The phenomena and events of language origin and evolution elude us. Computer simulations allow us to *re-create* these phenomena and events. To some extent, we can simulate the process of natural selection (Holland, 1975) and re-create possible evolutionary scenarios (natural environments, social groups, survival strategies) to directly test the validity of possible evolutionary explanations of the origins of language. We can observe the primitive form that this simulated language tends initially to assume and the changes which occur in successive forms due to both biological and cultural evolution. We can systematically study the adaptive advantages of different communication systems and the pre-conditions that make the evolutionary emergence of these communicative systems possible.

With computer simulations researchers tend to adopt a synthetic strategy (Steels, 1997), which is quite different from classical scientific methodologies based on the analytic approach. In the natural sciences such as biology a top-down approach is often used. The organism is analyzed, i.e., divided up, into organs: brain, heart, lungs, etc. An organ is then divided up into different tissues, tissues are divided into cell types, and so on until the molecular and purely physical level is reached. In linguistics, language is analyzed, i.e., decomposed, into lexicon and syntactic principles, then lexical entries are divided up into morphemes and phonemes, and so on. A synthetic strategy uses a bottom-up and constructive approach. The researcher decides the basic components of a system, the rules by which these components interact and, possibly, the environment in which the components interact with each other or with the environment itself. The computer program will then simulate the interactions among the components and as a result of these interactions the researcher should be able of observing the emergence of the various higher-level entities with their properties and the different phenomena that involve these entities. With a simulation, the feasibility and validity of assumptions regarding components, their interaction rules, and the environment can be tested. Wrong, incomplete, or inadequate assumptions will make it impossible to observe the emergence of higher-level entities or of entities that do not have realistic properties and do not exhibit realistic phenomena. The bottom-up approach of synthetic simulations also permits the study of problems and phenomena that are analytically intractable, such as those of complex and non-linear systems – and language and evolution are typical complex systems (De Jong, 1999).

The synthetic methodologies that can be used to study the origins and evolution of language include evolutionary computation (Goldberg, 1989), neural networks (Rumelhart and McClelland, 1986; Levine, 2000), artificial life and synthetic ethology (Langton, 1995; Parisi, 1997) and rule-based agents (Kirby, 1999). In this book we are not restricting the use of the term simulation only to software implementation of models. We also include *embodied* simulations, which are hardware-based models such as robots. In fact, various robotic models for studying the evolution of communication and language have been developed (Steels and Vogt, 1997; Steels and Kaplan, 1998; Billard and Dautenhahn, 1999). All these methods will be described in detail in Chapter 2. In the next paragraph we look at the advantages and limitations of simulation.

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Advantages of simulation

1. Simulations as virtual experimental laboratories

2. Simulations as tools for testing the internal validity of theories

3. Simulations as tools for studying language as a complex system

Limits of simulation

1. Simplification

2. Arbitrariness of assumptions and details

3. Difficult external validation

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Simulation Approaches to the Evolution of Language

The study of the origins and evolution of language and communication has a broad range of issues to address. These research questions spread along different continua. First, the differentiation between language and communication can be used to stress different levels of complexity in the communication medium. The study of the evolution of *communication* mostly focuses on simple animal communication systems, such as monkeys' calls or honeybees' dance. It investigates, for example, the adaptive role of communication in groups of animals. The evolution of *language* mainly refers to human languages, and focuses on their inherent complexity, such as syntax. However, this distinction is not always a very significant one, because of the large overlap between research aims in the evolution of language and of communication. Indeed, the study of language is inherently connected to the evolution of animal communication. Language/communication issues lie along the same continuum.

Secondly, some differences exist between the study of the origins of language and that of the evolution of language. Research on the *origins* of language concentrates on the particular spatial (e.g., geographical), temporal (e.g., historical), individual (e.g., neural, cognitive) and social conditions that might have favored the beginning of language. The issue of the *evolution* of language is a broader one, and deals with the continuity in animal communication systems and human language, the historical changes of languages and differentiation of language families, and the adaptive, behavioral, neural, and social aspects of language. In fact, evolution includes the study of the origins of language, along with all other evolutionary and historical aspects.

Current simulation models of language evolution have dealt with various research issues along these continua. This book presents a variety of approaches that focus on these issues. The volume is organized into seven parts. The first part, which includes this chapter, gives a general introduction to computer simulation in the study of language evolution and to the various methods and techniques. The various research questions will be addressed in the following five parts: (Part II) the evolution of simple signaling systems; (Part III) the emergence of syntax and syntactic universals; (Part IV) the sensorimotor grounding of symbols in evolving language systems; (Part V) the neural and behavioral factors in language use, evolution, and origins; (Part VI) the role of auto-organization and dynamical factors in the emergence of linguistic systems. In the final part, the concluding chapter suggests ways in which current studies of primate communication, including humans, may broaden the empirical base for future simulation approaches to language evolution.

Introduction to simulation methods

In Chapter 2 Huck Turner introduces the reader not familiar with computational methods to the different simulation techniques used in language evolution. Methods are grouped into two sections, one for the representation of the individual agents, and one for the learning and interaction algorithms. The agent representation methods serve to control the behavior of the agents. These include symbolic rules and neural networks. The interaction amongst agents is implemented through learning techniques (rule generalization, obverter, imitation, self-understanding), evolutionary algorithms (genetic algorithms, game theory, synthetic ethology) and robotics. In the second part of the chapter the author gives some comments on the implications of these methods for language evolution issues such as innateness and adaptive benefits.

The evolution of signaling systems: adaptive, phonetic, and diversity factors

The chapters in Part I focus on the evolution of simple signaling systems. The emergence of shared communication in animal-like groups can be seen as a preliminary stage towards the emergence of more complex human languages. The simulation of simple signaling systems can help the understanding of various factors in language evolution. In particular, the three chapters look (a) at the adaptive factors in signaling systems, (b) at the emergence of a shared speech systems, and (c) at the formation of dialects.

Chapter 3 investigates the selective pressures which affect the origin, organization, and maintenance of shared signaling systems. Jason Noble, Ezequiel Di Paolo and Seth Bullock present a series of simulations which model the evolution of populations of individuals interacting in shared environments. This evolutionary simulation modeling approach is presented as a way of augmenting conventional game theoretic and mathematical models, allowing modelers to explore aspects of signaling system evolution that would otherwise remain cryptic. First, evolutionary simulation models address *trajectories* of evolutionary change, revealing how model populations change over evolutionary time, perhaps reaching one equilibrium or another, perhaps cycling endlessly, etc. Second, these models help us to understand the relationship between the high-level phenomena exhibited by signaling systems and the low-level behaviors of the individual signalers and receivers that constitute these systems.

The three main questions addressed by Noble *et al*. are the role of ecological feedback, the handicap principle in honest signaling, and the use of communication in animal contests. Ecological factors such as the spatial distribution of individuals and the presence of noise are shown to have non-trivial implications for the evolution of altruistic communication. In a first model, action-response games in which signalers and receivers suffer a conflict of interest are simulated. Results show that evolutionary pressures bring about a spatial organization of the population which itself alters the selective pressures of the model such that altruism is supported. A second simulation investigates Zahavi's (1975) handicap principle, where extravagant displays such as colorful tail feathers are thought to be adaptive because their costliness guarantees trustworthiness. In particular, the authors investigate the evolutionary attainability of handicap signaling equilibria from appropriate initial conditions. Simulations suggest that although there exist scenarios in which signaling systems with any degree of exaggeration are evolutionarily *stable*, only those signaling systems which exhibit high degrees of exaggeration are likely to be evolutionarily *attainable* by populations evolving from reasonable initial conditions. In a final model, Noble *et al*. describe a continuous-time simulation of animal contests. This tests Enquist's hypothesis (1985) that weak animals cannot afford to risk commencing a fight and communicate this honestly. Simulation results reject Enquist's explanation because it is based on an implausible discrete model of animal contests.

A quite different aspect of the evolution of signaling systems is investigated in Chapter 4. Bart de Boer focuses on the *form* of signaling systems, i.e., speech sounds, rather than on the content and reliability of communication. He first reviews the different approaches to modeling speech systems and discusses the advantages of a modeling approach that combines genetic algorithms and language games. Subsequently, de Boer presents a population-based language game model of the emergence of a shared vowel system. Simulation results show that there is a significant bias towards the emergence of optimal vowel systems that closely reflects the frequency and structure of human language vowel systems.

The author favors an explanation of the evolution of language speech universals based on the functional optimizations of communication over noisy channels. For example, it is shown that the frequency of vowel occurrence in human language reflects the optimization of acoustic distinctiveness. This functional explanation is proposed as an alternative to the view that speech universals are a reflection of innate human linguistic abilities, and to the historical explanation of relatedness between human languages.

The evolution of dialect and linguistic diversity is presented in Chapter 5. Daniel Livingstone uses simulation models to inform the debate on the two existing opposite explanations of the role of dialect diversity. The first hypothesis is that dialects cannot be an accident of natural selection and, therefore, must have a purpose. The second explanation argues that the processes of language learning and transmission provide sufficient means to explain language diversity.

Livingstone first reviews the different modeling approaches to the development of linguistic diversity, including both mathematical and computer simulation models. In particular, he criticizes Nettle's models of dialect formation (Nettle, 1999; Nettle and Dunbar, 1997) for the use of language acquisition rules based on explicit averaging and thresholding processes. Livingstone argues that these explicit mechanisms bias Nettle's results on the evolution of diversity and its explanation based on social status influences.

The author describes simulations in which communicating agents are spatially organized, but no social relationships exist between them. In a first simulation, agents learn an abstract signaling system. This model shows that dialect continua form depending on the patterns of spatial organization of individuals. For instance, larger neighboring sizes reduce the number of distinct dialects. The second model is an extension of de Boer's simulation of evolving vowel system (see Chapter 4). This new simulation again shows the emergence of vowel dialect continua, due to the geographically limited interactions allowed between agents. It supports the general view that language diversity arises as part of the auto-organization process of language evolution and transmission.

The emergence of syntax and syntactic universals

The three chapters in Part II investigate the emergence and use of syntactic structures. Most of the chapters in this book deal with the emergence of syntax and syntactic structures, along with other aspects of the evolution of language such as lexicon formation. The three included in this section mainly focus on the emergence of syntactic universals such as compositionality, the population dynamics of grammar acquisition, and the role of sequential learning. Moreover, the authors employ a variety of simulation approaches also in conjunction with other formal and experimental methods.

The emergent properties of syntactic universals such as compositionality are explored in Chapter 6. Simon Kirby and Jim Hurford give an overview of the Iterated Learning Model (ILM) that they have used with other collaborators to simulate the emergence of linguistic structure. The ILM is presented as a general approach to simulate the process of glossogenesis, i.e., the cultural transmission of language in populations of interacting agents. Each agent is able to learn a meaning-signal mapping (1) from being exposed to the training data (E-language) produced by other agents and (2) through its ability to identify regularities in the language via neural networks or rule inference systems. In ILM simulations the agents are initialized without any linguistic system whatsoever and after many (thousands) learning iterations a stable (but potentially dynamic) language system is reached

The authors present various simulations of the ILM. In a first model neural network learning agents are used for the emergence of expressive and stable meaning-signal mappings. Symbolic rule-based agents are used to simulate the emergence of compositionality and recursion "out of learning". A final simulation studies the interaction between the process of glossogenesis and that of phylogeny and shows that functional pressures bias the initial setting of grammatical Principles. Overall all these simulations show that much of the structure of language is emergent. In particular, most fundamental features of human language can be explained as by-products of the pressures on language transmission, without necessary reference to communication.

A mathematical model of the population dynamics of the acquisition of grammar is presented in Chapter 7. Natalia Komarova and Martin Nowak use a rigorous definition of grammar and formalize the process of grammar learning in evolving populations. Three factors are manipulated to study the evolution of shared coherent grammars: search space, learning mechanism, and learning examples. The search space refers to the "pre-formed linguistic theory" of a child, or the "universal grammar" that, according to Chomsky, specifies the form of possible human grammars. The learning mechanism is the algorithm that children use to evaluate the available linguistic data in order to deduce the appropriate grammatical rules; since the actual learning mechanism in humans is unknown, two model grammar learning mechanisms are used, namely memoryless and batch learning; they provide the lower and the upper bound on the efficiency of the mechanism used by children. The effects of varying the number of learning interactions are also studied.

The key result of this model is the finding of a "coherence threshold". It turns out that in order to facilitate successful communication, i.e., to maintain grammatical coherence, the learning accuracy of children must be sufficiently high. Below this threshold no common grammar can evolve in a population. Above the threshold, coherent grammatical systems manifest themselves as stable equilibria.

The analyses of the threshold condition relate the maximum complexity of the grammars' search space to the number of learning interactions and the performance of the learning mechanism. Only a universal grammar that operates above this threshold can induce and maintain successful communication in a population. Komarova and Nowak also extend their model to include variants of universal grammars and natural selection amongst them.

The interaction between general cognitive limitations in sequential learning and their resulting linguistic by-products, such as word order constraints, is discussed in Chapter 8. Morten Christiansen and collaborators present a multi-methodological approach to the investigation of the role of sequential learning in language acquisition and evolution. Sequential learning is defined as the acquisition of hierarchically organized structure in which combinations of primitive elements can themselves become primitives for further higher-level combinations. The authors propose artificial language learning as a complementary paradigm for testing hypothesis about language evolution. This method permits the investigation of language learning abilities in infants, children, adults, and also computational models such as artificial neural networks. Subjects are trained on artificial language with particular structural constraints on word order, and then their knowledge of language is tested.

The results of these experimental and modeling studies demonstrate how constraints on basic word order and complex question formation are a by-product of underlying general cognitive limitations on sequential learning. In general this suggests how many constraints on language development are a consequence of limitations on cognitive abilities. This view is further supported by converging evidence from studies with aphasic patients, literature on primate cognition, and other computational models.

The grounding of symbols in evolving languages

The issue of the sensorimotor grounding of symbols is of central interest in language evolution research. It involves questions such as: How do symbols acquire their meaning? How do different individuals autonomously ground sufficiently similar representations that allow them to share a common lexicon? Is there a single mechanism for the symbol grounding, whereby all symbols are directly grounded to object in the world during language acquisition? Or are there other others complementary mechanisms for the transfer of grounding?

Language evolution models differ in the way they approach (or avoid) the problem of grounding symbols into sensorimotor representations and objects in the world. Some simulations do not include any direct grounding of evolving symbols, and assume symbols are virtually grounded. The modeler has the interpretative power of linking the symbols of an evolving language with external objects. Other simulations have directly confronted symbol grounding. In these models the strategy for grounding symbols in reality is an integral part of the system and becomes one of the various factors in how language evolves. Two models that directly deal with the problem of symbol grounding in evolving language systems are included in the book. They show the importance of sensorimotor grounding and its potential contribution to the explanation of the origins of language.

In Chapter 9, Angelo Cangelosi, Alberto Greco and Stevan Harnad discuss the different definitions of a symbol and explain their implications for the symbol grounding problem in cognitive and linguistic models. The authors propose categorical perception (the compression of perceived similarities within categories and the expansion of perceived differences between categories as a side-effect of learning) as a unifying theoretical and computational framework for understanding the cognitive mechanisms of category learning and the acquisition of grounded symbols. Category learning and symbol grounding are based on a series of processes by which individuals (i) first transform categorical representations (i.e., filtered features of internal sensorimotor projections of objects) into grounded low-level symbols (i.e., the names of basic categories), and (ii) subsequently learn new higher-level symbols through Boolean combination of already-grounded symbols. All these processes are shown to be possible in a neural network model for the categorization and naming of geometrical shapes.

A simulation model that tests the "symbolic theft" hypothesis of the origins of language is also presented. The "symbolic theft" strategy refers to the linguistic acquisition of new categories by hearsay. New categories are defined as propositions consisting of Boolean combination of already-grounded categories. In contrast, the "sensorimotor toil" strategy for acquiring new categories is based on direct, real-time trial-and-error experience with the objects, guided by corrective feedback from the consequences of categorization and miscategorization. In competition, symbolic theft is always found to outperform sensorimotor toil. The picture of language origins and evolution that emerges from this hypothesis is that of a powerful hybrid symbolic/sensorimotor capacity. Initially, organisms evolved an ability to detect some categories of the world through direct sensorimotor toil. Category "names" were, originally, whatever differential instrumental action it was adaptive to perform on them (e.g., eat, mate, attack, carry, nurse, etc.). These analog actions may then have done some double duty in communication and been simplified by social convention into arbitrary names. Subsequently, some organisms may have experimented with stringing combinations of the names of those categories and discovered the advantage of this new way of acquiring and conveying categories: "stealing" them via hearsay instead of doing it the hard way. This hypothesis is tested in a computational model where two populations of organisms can learn new categories through sensorimotor toil or symbolic theft. The results clearly show the adaptive superiority of category learning by theft over toil, as well as the effect of categorical perception phenomena in language learning. This helps to explain the adaptive advantage of symbolic theft over direct sensorimotor toil and its role in the origins of language.

A slightly different approach to the evolution of grounded symbols is proposed by Luc Steels in Chapter 10. He presents a complex and innovative approach to the problem of sensorimotor symbol grounding in groups of robots and Internet agents. The robotic setup consists of a set of "Talking Heads" connected through the Internet. Each Talking Head features a rotating video camera, a computer for the cognitive processing of perception, categorization, and language, and devices for audio input and output. Agents can load themselves in a physical Talking Head and teleport themselves to another Head by traveling through the Internet.

Steels stresses the importance of representations used by a cognitive agent that are directly grounded in external reality through a sensorimotor apparatus. These representations need to be sufficiently similar to those used by other agents in the group. They will enable coordinated actions and shared communication. In this system, each agent autonomously acquires internally grounded representations. Steels argues that language plays a crucial role in the learning of similar grounded representations because it is a source of feedback and constrains the degrees of freedom of the representations used in the group. Evolutionary language games are introduced as a framework for concretizing the structural coupling between concept formation and symbol acquisition. An example experiment with physical robots is discussed in detail to show how grounded representations emerge.

Behavioral and neural factors in language use, evolution, and origins

Some theories and models of the evolution of language focus on the interaction between linguistic abilities and other behavioral and cognitive skills. For example, it has been hypothesized that there is a strict interdependence between the origins of language and those of other motor skills, such as hand signing, or the ability to imitate motor actions from others. Moreover, in these motor theories of language origins great importance is given to the neural control of motor behavior. In other theories, the evolution of language and cognitive skills are hypothesized to be strictly interdependent. The chapters in this section will present two of these theories that show the strict interaction between the evolution of language and other behavioral abilities, and the neural control of both systems.

In Chapter 11 Michael Arbib proposes the view that the human brain and body have been evolutionarily shaped to be language-ready. As a consequence, the variety of human languages evolved culturally, as a more or less cumulative set of inventions. In particular, the author proposes the Mirror System hypothesis of the evolution of language. That is, speech derived from an ancient gestural system based on the mirror mechanism: the link between observer and actor became, in speech, a link between the sender and the receiver of messages.

Arbib introduces computational models of monkey mechanisms for the control of grasping and for the mirror system of grasping. The proposed FARS model of visually-directed grasping in monkeys is used to ground the study of the evolution of the human brain upon a detailed understanding of the brain of monkeys and of our common ancestors. The chapter offers a very detailed exposition of the mirror system hypothesis. Arbib has postulated that the progression from grasp to language through primate and hominid evolution proceeded via seven stages: grasping, a mirror system for grasping, a “simple” imitation system, a “complex” imitation system, a manual-based communication system, protospeech, and language. During the discussion of such transitions between stages the author goes “beyond the mirror” to offer more detailed hypotheses about the evolution of the language-ready brain.

In Chapter 12, Domenico Parisi and Angelo Cangelosi suggest that a unified computer simulation scenario can be used to try to answer three research questions: (i) What is the origin and past history of the ability to speak in the individual? (ii) What is the origin and past history of the ability to speak in the species? (iii) What is the origin and past history of the particular language spoken by the social group of which the individual is a member? That is, simulations should simultaneously include phenomena of language development, evolution, and historical changes. The proposed scenario is based on the interaction between the process of biological evolution and adaptation (simulated through evolutionary computation algorithms), the process of ontogenetic acquisition of language (through neural network learning), and the process of cultural transmission of linguistic knowledge (through cultural learning between organisms). This approach also permits investigation of the effects of behavioral, cognitive, and neural factors in the evolution, learning, and transmission of language.

To show how such a scenario can be used to study language evolution, the authors discuss three simulations that include lexicons of various complexity (from single-signal communication to compositional languages) and learning and interaction patterns of increasing complexity (from genetically-inherited signals to culturally-learned words). In particular, attention is placed on the interaction between behavioral and neural factors in the evolution of language. For example, results show that the evolution of good categorization abilities (to discriminate essential foraging stimuli) favors the emergence of optimal lexicons that discriminate between these categories. At the same time, language has a positive effect on categorization because it improves the neural network's categorization by optimizing its internal representation of categories. Moreover, in compositional languages using verb-noun structure, verbs have a larger positive effect on performance than nouns and this is reflected in their neural representation.

Auto-organization and dynamic factors

This part contains two chapters that discuss in depth the role of auto-organization and dynamical processes in the emergence of language structure. Language is seen as a complex dynamical system whose functioning depends on the interaction of autonomous individuals. The communicative behaviors of these individuals determine the dynamic auto-organization of complex linguistic phenomena. The communication between language users affects the concurrent and interlaced development of categories (meanings) and words (forms).

The processes of the auto-organization and emergence of shared language structure such as lexicons and grammars are thoroughly discussed in Chapter 13 by Ed Hutchins and Brian Hazlehurst. Emergent linguistic structures result from the organized interactions of patterns that are present in the initial conditions or are produced in the history of interactions within the models. Positive feedback loops control this process, which is capable of creating novel and complex structures. However, researchers can take different stances regarding the elements of language (Meanings, Referents and Forms) and the relations among those elements (e.g., arbitrariness in Forms-Referents associations). Hutchins and Hazlehurst consider three major frameworks for modeling the emergence of shared lexicons and grammars: (a) Expression/Induction, (b) Form-Tuning and (c) Embodied guessing games. For example, in models of the emergence of lexicons, researchers that use the Expression/Induction approach start with a closed set of forms and meanings to evolve shared form-meaning mappings. Following the Form-Tuning framework, employed by the same authors, the set of forms is not pre-determined and is made dependent on the organization and sharing of sensory-motor experiences. With the Embodied language game approach the most complex representation of meanings is used together with a set of closed and arbitrary forms.

Hutchins and Hazlehurst argue that Expression/Induction models are limited because these assume that complex structured meanings simply exist prior to the language phenomena that emerge later. This assumption is inherited from the physical symbol system hypothesis which posits that intelligent processes (including language) are realized through internal manipulation of language structure. The private language of thought (meanings) arises prior to, and independently of, the public language. In contraposition, the Form-Tuning and the Embodied frameworks view the evolutionary development of language and cognitive abilities to be strictly interdependent on each other. This supports a cultural symbol system hypothesis in which public symbols arise concurrently with the internal meaning structures with which they are coordinated.

Language is characterized as a complex system in the work of Takashi Hashimoto (Chapter 14). As such, language is regarded as an essentially dynamic system. There are four dynamic processes that are of interest in the study of language evolution: (a) the origin of first linguistic systems, (b) the evolution of various languages and language structures, (c) the development and acquisition of language in children and adults, and (d) the sense-making process of giving meanings to words during communication. In addition, the language dynamics depend on the subjectivity of individual language users. Complex linguistic structures will emerge from the interaction of such dynamical and subjective processes.

To understand such a complex dynamical system the constructive approach of computer simulation is proposed. This permits the modeling of the interaction of the individual activities of speaking, listening and understanding that contribute to the emergence of dynamical language structure. Hashimoto presents various simulations using this constructive approach. For example, he models the sense-making activity as the formation of a web of relationships between words through conversation between individuals. The analysis of the dynamics of the formation of word clusters (categories) shows the coexistence of global stability (closed categories with rigid links) and local adaptability (prototype categories with changeable, gradual links) depending on the use of words during communication. Subsequently, the integration of word-web categorizations into a system with evolving grammatical structures causes the emergence of a bigger variety of word-web categories. Hashimoto's work supports the view that the essence of language relies on a series of internal mental processes and on a series of conversations.

Simulation and empirical research

In the concluding chapter Michael Tomasello suggests a direction for computer simulations of language evolution. He acknowledges that there is not much directly comparable evidence on the ancient past *facts* of the origins and evolution of language. However, there are a number of *processes* that are currently ongoing in the real world that were very likely to have been involved in the evolution of language. These processes regard non-human primate communication, child language acquisition, imitation and cultural learning, and language change mechanisms such as pidginization and creolization. Most of these processes are studied empirically, with observational and experimental techniques. Some of the researchers using computer simulations have already attempted to benefit from recent research, sometimes by directly comparing simulation research with empirical data. Following this approach Tomasello suggests that computer simulations “can only make real progress with at least a little bit of back-propagation from facts about the way these processes operate in the real-world”. This can create a “virtuous circle”: research-informed simulations will produce new predictions and insight into the evolution of language; experimental studies will verify these predictions leading to new insights that will then produce better simulations, and so on.

Tomasello also claims that experimental and simulation studies on the origins and evolution of language require attention to three distinct time frames: evolutionary, historical, and ontogenetic. For each of these dimensions, he proposes a series of ideas. In evolution, to investigate human ability to use language we must look at human ability to understand others as intentional agents. In historical terms, processes such as grammaticalization suggests that constructions of individual languages have been built up by groups of people communicating with one another under the general constraints of human cognition, communication, and vocal-auditory processing. In ontogeny, young children themselves create linguistic abstractions, such as word classes, by using general cognitive and social-cognitive skills.

Other approaches

This book contains a collection of some of the current simulative work in the evolution of language. However, it is not meant to cover *all simulation approaches* to the evolution of language and *all issues* addressed through computational modeling. The editors have tried to cover broadly the full range of simulation methodologies, and the range of different research issues. However, we want to acknowledge explicitly other work that has not been possible to include in the book. Among the many computational models, we would like to mention the early simulations on the evolution of communication by Hurford (1991), MacLennan (1992), Werner and Dyer (1994), Ackley and Littman (1994), more recent models by Saunders and Pollack (1996), Arita and Taylor (1996), Oliphant (1996; 1999), Wagner (2000), Grim, St Denis and Kokalis (2001), the recent models of the evolution of syntax (Briscoe, 2000; Teal and Taylor, 2000), the robotic approach of Billard and Dautenhahn (1999), the computational modeling of primate social intelligence (Worden, 1996), the connectionist simulation of historical changes in English morphology (Hare and Elman, 1995), and other models of language diversity (Nettle, 1999; Nettle and Dunbar, 1997). The reader will find references to such models in the various book chapters.

Conclusions

Among the advantages of computer simulation in language evolution research we have stressed the feasibility of synthetic methodologies as new scientific tools for studying language as a complex dynamical system. The theme that language is a complex system, whose functioning is due to bottom-up and non-linear interactions of local components, is common to the various chapters in this book.

Concepts typical of the study of complex systems, such as that of emergence, auto-organization, and interaction will be used over and over again. A first common thread that links the variety of approaches, models and theories presented in the chapters is that of the *emergence of language* (see also Knight *et al*., 2000). Most of the chapters claim and show that linguistic behaviors, structures and processes emerge due to the interaction between the components of complex systems. These components are constituted by interacting autonomous agents, their neural, sensorimotor, cognitive and communication abilities, and their social and physical environment. Computer simulation permits fine analyses for the investigation of the role of such components in the process of the evolutionary emergence of language. This volume, and in general the simulation research on the evolution of language, provide a long series of examples of the analysis of emergent linguistic behavior and structure. Shared vowel systems are shown to emerge because of their optimality and discriminatory features (Chapter 4), dialect continua emerge due to spatial organization of agents (Chapter 5), shared representations for sensorimotor grounding emerge through interacting language games between simulated and robotic agents (Chapters 9, 10 and 13), compositional linguistic structures emerge due to learning bottleneck (Chapter 6), and shared word categories emerge from internal mental processes and conversational games (Chapter 14).

A second common thread that connects most chapters in this volume is the strict *interaction and interdependence between language and the other non-linguistic abilities* and characteristics of the organisms and their environment. The study of the origins of language needs to look at the way other non-linguistic and non-communicative factors can have affected language evolution. Various chapters show that general cognitive constraints such as sequential learning can explain the evolution of word order constraints (Chapter 8), that our ancestors' behavioral and neural structures, such as the mirror system for grasping, can have shaped the evolution of the language-ready brain (Chapter 11), that sensorimotor and categorization abilities favor the evolution of language and contribute to the formation of word classes (Chapter 12). The interaction between language and general adaptive and population dynamics factors are analyzed in simulations on the evolution of simple signaling systems (Chapter 3) and in a mathematical model of the evolution of universal grammar (Chapter 7).

The final common theme of this volume is the *relation between simulation studies and empirical research*. At present, not many computer models make direct comparisons between simulation results and available empirical evidence, although simulations tend to be constrained on empirical research. In this volume, only few chapters systematically compare simulation and experimental data. For example, the evolved vowel system of simulations on the emergence of speech is compared with that of humans (Chapter 4), and the performance of neural networks in artificial language learning is directly compared with human subjects' data (Chapter 8). All other chapters look at available empirical evidence to define the parameters of models and to make some indirect comparisons between simulation results and published literature data. As Tomasello highlights in the final chapter, the simulation approach to language evolution can make real and significant progress if it directly looks at known facts related to language evolution, such as non-human primate communication, child language acquisition, imitation and cultural learning, and language change processes.

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