NATURAL HISTORY Centennial

Homo Grammaticus

Mathematics has a say about how human language evolved.

By Martin A. Nowak

Whenever I tell my four-year-old a dream, he also tells me a dream. His is often similar to mine. He doesn't distinguish between a story and a dream. Both my four- and my six-year-old have their own fantasy realms. Sometimes, when a fact proves contrary to their expectation, they hold comfortably to their version of reality in a different world. Their language is limited neither to actual experience nor to the context of this world. We can talk about everything.

Producing the sounds we use in an ordinary conversation is an anatomical feat. The motions of various parts of our vocal tract are coordinated within millimeters and timed within hundredths of a second. On the receptive end, a listener must process a stream of sounds instantaneously. When it comes to words, a six-year-old has a lexicon, or word store, of about 13,000. The rate of word learning in humans comes to about one word every ninety waking minutes from age one to age seventeen. This leaves a seventeen-year-old with about 50,000 words stored in her mental lexicon. When it comes to grammar, a four-year-old knows how to avoid 95 percent of the mistakes he could make. Children acquire the grammatical rules of their native language spontaneously and without formal education. All they need is the opportunity to talk to someone and to hear examples of sentences.

I could prove to you mathematically that what children do in acquiring language is not possible unless we add a further assumption: children must have a built-in sense of what grammar is. The linguist Noam Chomsky called this innate mechanism universal grammar. It is written in our genes and generated by neuronal circuitry in our brain.

Grammar is the computational system of human language. As used by linguists, the term "grammar" encompasses the patterns inherent in speech sounds, in word forms, and in sentence structures (syntax). All human languages use complex grammar. Grammar is what enables us to produce an infinite number of meaningful sentences, and it is what allows a child to speak sentences he has never heard before. The computations that are necessary for formulating or interpreting sentences cannot, so far, be performed by any computer, but they flow through our brain's language processor without conscious effort on our part. We can talk and listen without thinking about it.

The aim of my own work on language is to outline the fundamental principles that determine how natural

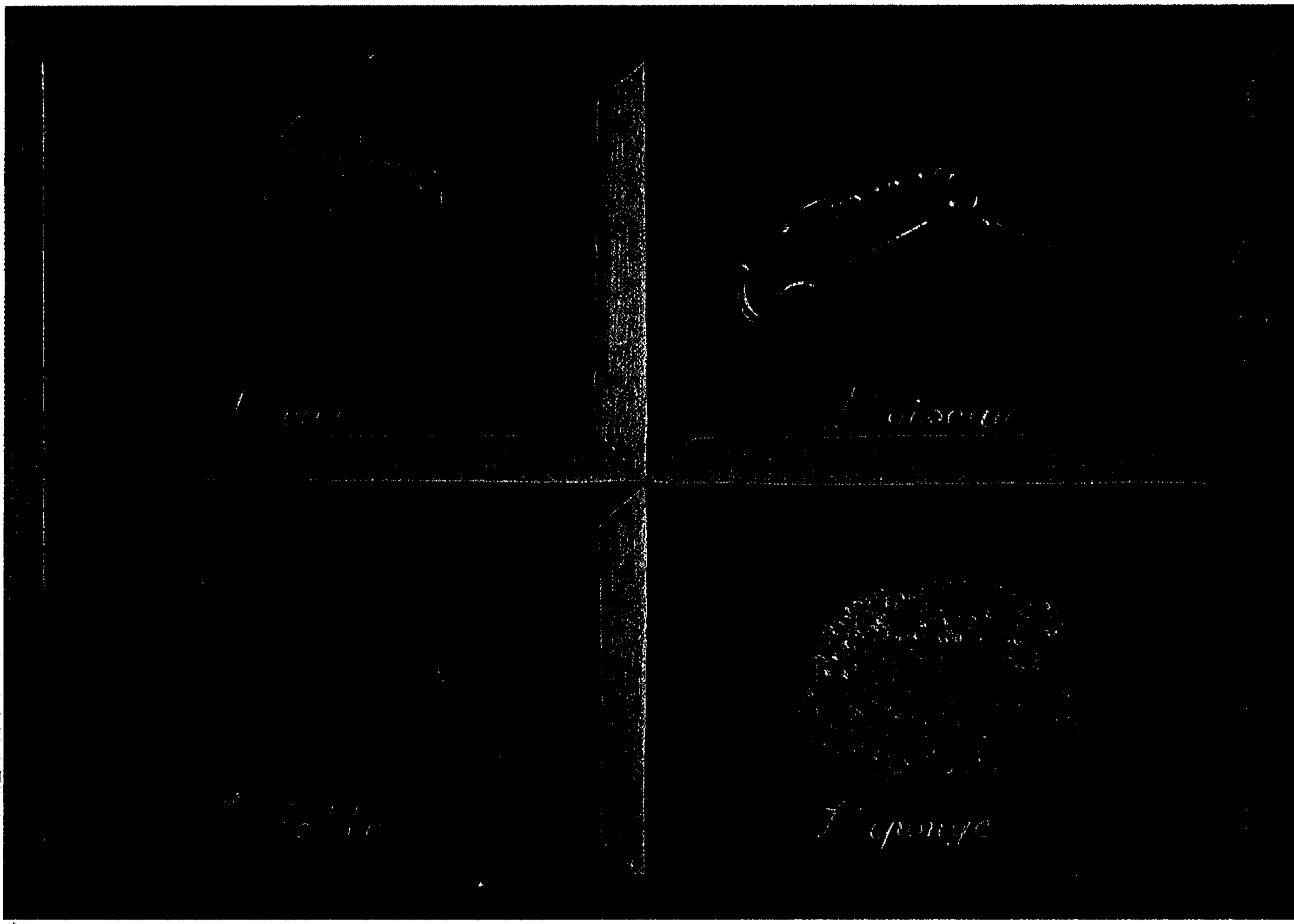
> No computer, as yet, can perform the computations that flow through our brain's language processor effortlessly. We can talk and listen without thinking about it.

selection shaped animal communication and led from there to human language. The main forces of evolution—mutation and natural selection—can be described by precise mathematical equations. As early as 1906, Oxford zoologist Walter Weldon remarked that "Darwinian evolution is intrinsically a mathematical theory and can only be tested by mathematical and statistical techniques." Hence, I and my colleagues at the Institute for Advanced Studies in Princeton are using mathematics to find out how language evolved.

Language was the most important evolutionary event in the history of the human species. Indeed, grammatical language defines humanity. The complex vocalizations of mammals such as dolphins and primates have been the subject of many studies, but so far, no natural animal communication appears to have a power of expression that is in any way close to human language. Animal communication can be based on a limited repertoire of calls (for example, warning or territorial calls) or consist of variations on a theme (such as birdsongs) or be a continuous, analog signal (the honeybee's dance, which transmits information on food sources). But the grammar inherent in human language enables us, in the words of Wilhelm von Humboldt, to "make infinite use of finite means." Language has changed us and the appearance of the planet and is responsible for the acceleration of cultural evolution during the last few millennia.

Human language originated after our human ancestors diverged from our closest relatives, the chimpanzees, about 5 to 7 million years ago. Since all currently living *Homo sapiens* have the same language ability, the most recent date for the origin of language would be the time of our last common ancestors, who lived in Africa perhaps 150,000 to 200,000 years ago. Evolution would not have had enough time to build our language ability from scratch but must instead have used existing structures that may originally have been employed for other purposes. Neuroanatomists describe certain areas in the brains of monkeys, for instance, that correspond to the human language areas but that are apparently not involved in producing calls or gestures. Monkeys use these brain regions to interpret sounds and control facial muscles. Evolution may have had an easy game here in adopting these structures to generate the neuronal circuits that control speech production and speech interpretation in humans.

> Adding signals to a repertoire increases the number of things that can be described but also increases the likelihood of errors.



Key of Dreams, **René Magritte, 1927**

Language evolved as a means of communicating information between individuals. In order to communicate on a basic level, a population of individual animals or hominids must discover that specific signals can be associated with specific referents—things being referred to—such as people, objects, actions, places, times, and events. A wolf, for example, may whine, growl, or howl, and this sound (along with extensive body language) can convey certain information to the members of its pack. We can imagine early hominids—perhaps Lucy and her fellow *Australopithecus afarensis,* who lived 4 million years ago—being capable of making a variety of sounds and transferring information about their world. If a wolf cub fails to learn the sounds and signals of its society, its life may be short. Similarly, hominids that were best able to transmit—and to hear and interpret—specific signals presumably benefited from this trait. They were fitter in the evolutionary sense, surviving longer and having offspring that knew how to communicate.

The computer simulation that I and

my colleagues have been working on moves us from the realm of the presumed to the realm of mathematical analysis. The equations take into account mutation, forces of natural selection, and learning behavior. In the simulation, each individual in a group is characterized by what we call a lexical matrix, which links specific signals to specific referents. In the beginning of our simulation, all individuals are assigned very different, randomly chosen lexical matrices. Then individuals "talk" to each other. Whenever a simulated speaker uses a certain signal to denote a particular referent and the hearer interprets the signal as denoting that referent, they communicate correctly. As the simulation continues, the individuals that are able to communicate well prosper and produce offspring who in turn inherit the genetically encoded mechanism for learning the language. The offspring will use this mechanism to learn the lexical matrix from their parents and others in the population or community. As a consequence of heterogeneity in the group and some errors occurring during language learning, children will not acquire the exact lexical matrix of their parents. Over time, the matrices will change and those individuals that communicate well will increase in abundance.


NAT FARBMAN; TIMEPIX

Bechuanaland (now Republic of Botswana), 1947

We have found that over a few generations, each signal tends to become associated with a single referent and that most individuals in the group will use the same signal for the same referent. But to be successful, this evolutionary process depends on conditions that we have quantified and that can also be expressed verbally: communication must contribute to biological fitness, and learners must have a sufficiently reliable lexicon-learning mechanism. Under these conditions, evolution can construct a communication system—but only a simple one.

Our model shows that while adding new signals or sounds to the repertoire may increase the number of things that can be described, such additions also carry a significant cost: a greater possibility of errors. What happens when a signal is misinterpreted, when a hearer misses the message? One monkey shouts "lion," but the other one understands "banana" and is attacked by the lion. We stretched our basic model by including the possibility of such perceptual errors into our equations. The mathematical analysis revealed an "error limit," a point at which having too many signals and referents creates confusion and becomes a liability rather than an evolutionary asset. In other words, the monkey might have been better off without a signal for banana that could be mistaken for the signal for lion.

Natural selection, then, prefers limited repertoires of signals. But how did human language overcome the error limit and come to be so vast? Our vocal apparatus can produce a large diversity of sounds. The roughly 6,000 languages on Earth have a total of about 1,000 phonemes—basic sound units, such as the English pronunciation of the letters g, d, p, or t. Still, any one language uses only about 40 phonemes on average, with a range of about 10 to 100. So we use only a small fraction of all possible signals. We generally avoid mistakes among the phonemes that make up our native language but have a hard time with those of other languages.

How do we humans get such linguistic mileage from a small stock of sounds? In something of an evolutionary leap, we have combined them into words. Snippets of sound are spun out and blended into different configurations: the words "God" and "dog" or "top" and "pot" contain the same phonemes but have different referents. Word formation marks a transition from something like an analog (continuous) system to a digital (discrete and combinatorial) system of communication. Our equations show that for a simulated digital language, the error limit is much higher than for a simple analog signal system. Most animal communication, based on a simple system, must operate with a limited repertoire of signals, while human languages consist of more than 10,000 words (English has about 100,000 words).

Words still have to be memorized. Once we have them, however, words can be put into sentences governed by the rules of syntax. Mathematically put, the lexicon of a population cannot exceed the total number of chances an individual has to learn a new word. Syntax makes it possible to generate more sentences than the total number of sentences encountered by a learner. A child, for example, has to memorize the meaning of words but does not have to memorize the meaning of sentences. Syntax enables us to construct and understand an unlimited number of novel sentences.

Language enables humans to generate messages that can contain information about new tools, faraway happenings, customs, and history.

What we know about animal communication suggests that it is largely nonsyntactic: signals refer to whole events. In contrast, human language is syntactic: signals consist of components that have independent meanings. To find out whether the latter situation confers more of an evolutionary advantage than the former, we built a mathematical model to analyze differences between the two kinds of communication in terms of natural selection. The equations resulting from our mathematical model indicated, fortunately, that syntactic communication is a bright idea, and for two main reasons. Unlike nonsyntactic communication (for example, the simple system obtained in the beginning of our simulation), syntactic communication not only allows the number of things that can be said to be larger than the number of things that have to be memorized but also enables us to generate messages that refer to novel and rare events—not just "dog bites man" but also "man bites dog."

Nevertheless, the equations reveal some limits: natural selection favors syntax only if there exist a large enough number of events that need to be communicated and only if these events can be broken down efficiently into components with meanings of their own, such as places, times, objects, and actions. We call this point the syntax threshold. Below it, nonsyntactic communication works well; above it, syntactic communication stands the users in better stead. We believe that many animal species have the capacity for a syntactic understanding of the world—monkeys and dogs, for example, perceive that the world consists of components, and they are able to relate the components to one another—but animals did not evolve syntactic communication, because the syntax threshold was not reached.

We can envision the savannas and forests of Africa where, some 100,000 years ago, our young species lived among other mammals, all using their respective ways of transmitting information. For example, vervet monkeys (as shown by biologists Dorothy Cheney and Robert Seyfarth) have a handful of calls they use to denote the presence of potential predators. The call for "leopard" makes the monkeys jump up into a tree, where they can move faster than the cat. The call for "eagle" sends them running under a bush, where they can hide. However, a resident *Homo sapiens,* armed with syntax, can call out—give voice to objects and actions in a sequence—and indicate that a leopard is stalking ominously or that a leopard is sleeping benignly. A hearer may be warned of a danger approaching from a particular direction or be advised of a course of action. And the participants may one day recount to others the story of how they escaped from or killed a leopard.

The humans may also pass on information about new tools, faraway happenings, customs, and the history of the tribe. They may have names for one another, greatly facilitating social interactions, including planning and politicking, within the group. Syntax then gives rise to new and complex possibilities of cooperation and fairness, deception and manipulation.

Selected for and shaped by evolution, language has, most importantly, led to a new mode of evolution. Information drives evolution. For most of the 4 billion years of life on Earth, the only information that could be used for evolutionary purposes was encoded in gene sequences. Human language gave evolution a new playground. Relatively suddenly, vast amounts of information (at first in the form of orally transmitted ideas, stories, and legends, and later printed in books and journals and transmitted via Internet pages) could be exchanged between individuals and passed on to subsequent generations. Language lit the fuse that exploded the "big bang" of cultural evolution. In this sense, language, more than any other invention since the emergence of the nervous system some 500 million years ago, has affected and continues to affect the rules of evolution itself.

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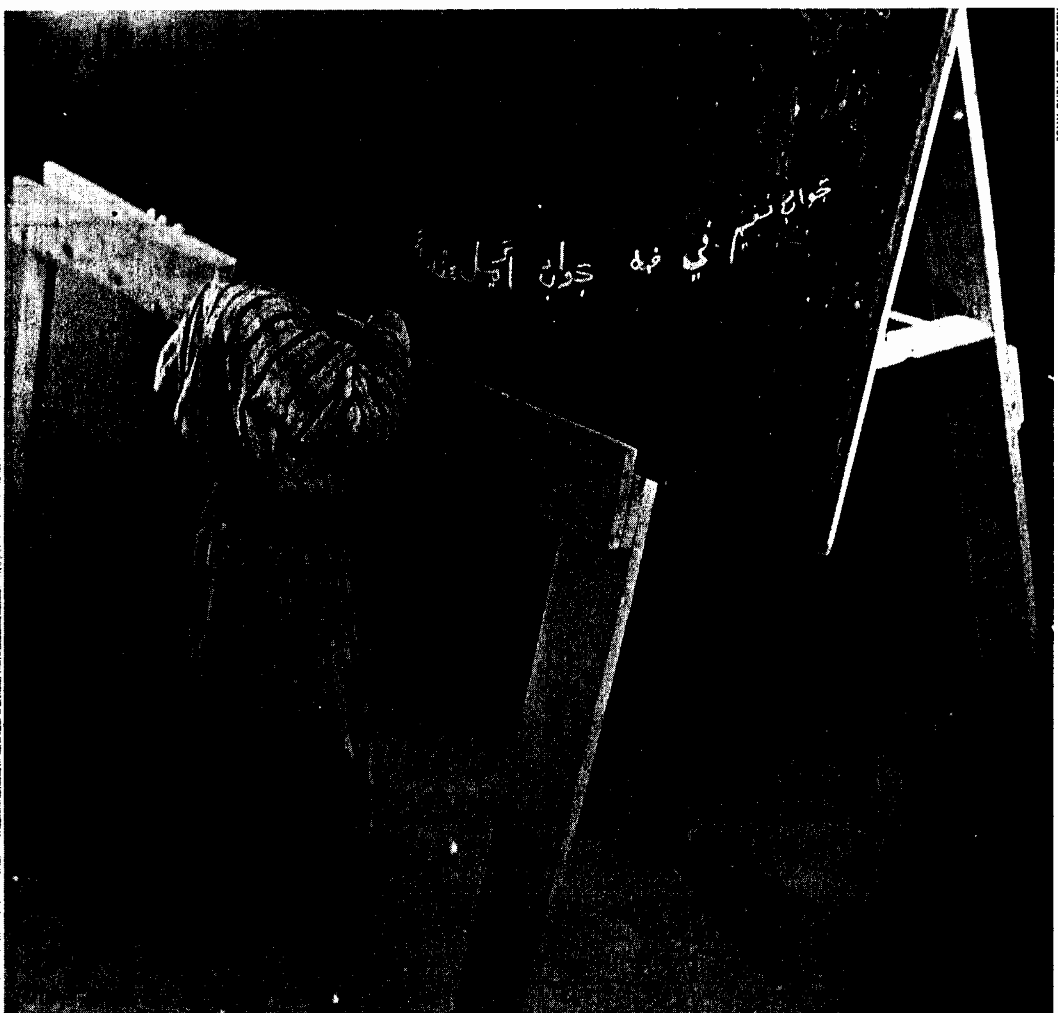
In the small redbrick building opposite my office window, where my four-year-old is at nursery, John von Neumann built the first programmable computer. The Hungarian-born mathematical genius realized that it was not a good idea to rewire a computer every time you wanted to calculate something different. The computer should be a general problem solver. Evolution had the same idea when it came up with a nervous system that allowed animals to learn. Not every task had to be solved by rewriting genetic code: a neuronal problem solver could be more efficient. Language was the next step. It provided an operating system, linked the neuronal problem solvers together, and enabled them to pass on solutions, to work on problems, and to exchange dreams. Language created *Homo sapiens.* □



JOHN PHILLIPS; TIMEPIX

Palestinian schoolboy, 1943

As a child, **Jared Diamond** ("Threescore and Ten," page 24) assumed he would become a physician like his father. The boyhood fantasy wasn't far off the mark; he eventually earned a Ph.D. in physiology from the University of Cambridge and since 1968 has been a professor of physiology at UCLA's School of Medicine. Also a research associate in ornithology at the American Museum of Natural History, Diamond spends part of each year doing fieldwork in New Guinea. Working with the "really smart people there, who traditionally only had stone tools," made him ponder why he was the only one who happened to be using steel implements. Ultimately, such thoughts about the effect of environment on culture resulted in his Pulitzer Prize–winning book *Guns, Germs, and Steel: The Fates of Human Societies* (W. W. Norton, 1997) and the recognition that "where you are born is the most important thing determining the outcome of your life."

Mathematical modeling is a rigorous tool for studying biology. **Martin A. Nowak** ("*Homo Grammaticus,*" page 36), head of the Program in Theoretical Biology at the Institute for Advanced Study in Princeton, New Jersey, has brought mathematics to bear on the question of how human language evolved. Nowak became interested in the topic after hearing a lecture on it by John Maynard Smith and reading Steven Pinker's *Language Instinct.* In 1998 he and theoretical biologist David Krakauer proposed a mathematical approach for language evolution. Nowak's other interests include the dynamics of infectious diseases, antiviral therapy, evolutionary genetics, and the evolution of cooperation and fairness. He is the author, with Robert M. May, of *Virus Dynamics: Mathematical Principles of Immunology and Virology* (Oxford University Press, 2000).

A columnist for this magazine since 1995, astrophysicist **Neil de Grasse Tyson** ("A Cosmic Muse," page 60) is the Frederick P. Rose director of the Hayden Planetarium at the American Museum of Natural History. A New Yorker by birth, he credits his career choice to his childhood visits to the Planetarium and an education at the Bronx High School of Science. Tyson's long-standing research interest has been the structure and chemical composition of the Milky Way galaxy. His most recent book is *The Sky Is Not the Limit: Adventures of an Urban Astrophysicist* (Doubleday, 2000).

Ian Tattersall ("A Hundred Years of Missing Links," page 62) does not trace his current interest in human evolution to a childhood spent in East Africa, even though it might make for a good story. Furthermore, his early research focused mainly on the biology of the lemurs of Madagascar (one of the most beautiful of these primates is named for him). But the understanding of animal diversity he gained in Madagascar eventually led him to the study of humanity's past. A curator in the American Museum of Natural History's Division of Anthropology for almost thirty years, he is collaborating with University of Pittsburgh professor Jeffrey H. Schwartz on a long-term project to scientifically redescribe the entire human fossil record, in order to provide a needed resource for students and researchers. Tattersall's latest books include *Becoming Human: Evolution and Human Uniqueness* (Harcourt Brace, 1998) and, with Schwartz, *Extinct Humans* (Westview Press, 2000).

Frans de Waal ("Reading Nature's Tea Leaves," page 66) says he has a fish tank almost as big as the one Konrad Lorenz had but that, unlike Lorenz, he never enters it. Although he started out as a child ethologist catching and observing stickleback fishes in the Netherlands, he later switched to the study of primate societies, with a special interest in conflict resolution, reciprocity, and cooperation. His favorite species for this work are chimpanzees, bonobos, and capuchin monkeys. De Waal is C. H. Candler Professor of Primate Behavior in the psychology department of Emory University and director of the Living Links Center for the advanced study of ape and human evolution (part of the Yerkes Regional Primate Research Center). In 1998, while on sabbatical in China and Japan, he explored differences in attitudes toward nature between Eastern and Western cultures. That research is the subject of *The Ape and the Sushi Master: Cultural Reflections of a Primatologist,* to be published by Basic Books early in 2001.