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 detected 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 milliseconds 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 constists to about one word every ninety-six 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 calls this innate mechanism universal grammar. It is written in our genes and encoded by neuronal circuitry in our brain.

Grammar is the compositional 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 languages evolve.

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.

The 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 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 limited repertoire of calls (for example, warning or territorial calls) or consists of variations on a theme (such as birdsong) or be a continuous, analog signal (the “sleepytime’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 ex-
Adding signals to a repertoire increases the number of things that can be described but also increases the likelihood of errors.

have had an easy game here in adopting these structures to generate the neuronal circuits that control speech production and speech interpretation in humans.

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 other members of its pack. We can imagine an early hominid—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 shows us from the realms of the pre-
formed to the realm of mathematical
analysis. The equations take into ac-
count mutation, forces of natural selec-
tion, and learning behavior. In the

As the simulation continues, the indi-
viduals that are able to communicate
well prosper and produce offspring
who in turn inherit the genetically en-
coded mechanism for learning the lan-
guage. The offspring will use this

mechanism to learn the lexical matrix
from their parents and others in the
population or community. As a conse-
quence of heterogeneity in the group
and some errors occurring during lan-
guage learning, children will not ac-
sue the exact lexical ma-
trix of their parents. Over-
time, the matrices will
change and those individ-
uals that communicate
good will increase in abun-
dance.

We have found that over a few generations
each signal tends to be-
come associated with a
single referent and that most individuals in the
group will use the same
signal for the same refer-
ent. But to be successful,
this evolutionary process
depends on conditions
that we have quantified
and that can also be ex-
pressed verbally: commu-
nication must contribute
to biological fitness, and
learners must have a su-
ficiently reliable lexical
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 de-
scribed, such addition
also carry a significant
cost: a greater possibility
of errors. What happens when a signal
is misinterpreted, when a hearer miss-
the message? One monkey should
“lion,” but the other one understands
“banana” and is attacked by the lion.
We stretched our basic model by li-
chiding the possibility of such percep-
tual 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 ba-
nana that could be mistaken for the
signal for lion.

Natural selection, then, prefers lim-
ited 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, 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 sounds. We gen-
erally avoid mistakes among the
phonemes that make up our native lan-
guage but have a hard time with those
of other languages.

How do we humans get such lin-
guistic mileage from a small stock of
sounds? In something of an evolution-
ary leap, we have combined them into
words. Soprops of sound are spun out
and blended into different configura-
tions: the word "dog" and "dog" or
"top" and "pot" contain the same
phonemes but have different referents.
Word formation marks a transition
from something like an analog (conti-
uous) system to a digital (discrete and
combinatorial) system of communica-
tion. 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 sys-
tem, must operate with a limited rep-
ertoire of signals, while human language
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
Language enables
humans to generate
messages that can
contain information
about new tools,
faraway happenings,
customs, and history.

can be put into sentences governed by
the rules of syntax. Mathematically put,
the lexicon of a population cannot ex-
ceed the total number of chances an in-
dividual has to learn a new word. Syn-
tax makes it possible to generate more
sentences than the total number of sen-
tences encountered by a learner. A
child, for example, has to memorize
the meaning of words but does not
have to memorize the meaning of sen-
tences. Syntax enables us to construct
and understand an unlimited number of
novel sentences.

What we know about animal com-
unication suggests that it is largely
nonsyntactic: signals refer to whole
events. In contrast, human language
syntactic signals consist of components
that have independent meanings. To
find out whether the latter situation
confers more of an evolutionary advan-
tage than the former, we built a math-
ematical model to analyze difference
between the two kinds of communica-
tion in terms of natural selection. The
resulting equations from our mathemat-
ical model indicated, fortunately,
that syntactic communication is
not at all a bright idea, and for two main
reasons. Unlike nonsyntactic communica-

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(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 "max bites dog."

Nevertheless, the equations reveal some limits: natural selection favors syntax only if there exist large enough numbers 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

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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, art, 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.

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 rewrite 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.*
As a child, Jared Diamond ("Theodore and Ten," page 24) assumed he would become a physician like his father. The toyhood 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 fellow 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 Geometricus," 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 his 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, atmospheric 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 Astronomer* (Doubleday, 2000).

Ian Tattersall ("A Hundred Years of Missing Links," page 62) does not trace his current interest in human evolution to a childhood spier 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 redate 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 Korad Lorenz had but that, unlike Lorenz, he never enters it. Although he staved out as a child, he is still a fellow of 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, cooperation, and cooperation. His favorite species for this work are chimpanzees, bonobos, and capuchin monkeys. De Waal is C. H. Candler Professor of Primatc 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 sabatical in China and Japan, he explored differences in attitudes toward Africa between Eastern and Western cultures. This 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.