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Sentence and Word Complexity
Jeffrey Heinz and William Idsardi
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the fruit fly intestine, the hindgut, starts out as a simple tube along the embryo's midline. Through a process that occurs without cell division, this tube first dips ventrally (toward the fly's "belly"), and then rotates leftward by 90° to create a net rightward bend. Seeking a cellular basis for the rotation, Taniguchi *et al*. make the key observation of a small statistical bias in hindgut cell shapes with respect to the embryo's left-right axis. Cell-cell boundaries that make angles between −90° and 0° with the tube's long axis (left boundaries) appear more frequently than boundaries that make angles between 0° and 90° (right boundaries). The authors call this pattern planar cell-shape chirality (PCC). They identify the cell-cell adhesion molecule *Drosophila* E-cadherin (*D*E-cadherin) as a factor required for both PCC and gut rotation, showing that it is preferentially enriched on left boundaries. Mutations in a motor protein involved in intracellular movement, known as unconventional myosin ID (*MyoID*), reverse the polarity of *D*E-cadherin accumulation and PCC. This is consistent with *MyoID*'s previously identified role in setting the direction of gut rotation (*5*, *6*).

Because mutations in *D*E-cadherin cause all cell boundaries to expand, Taniguchi *et al*. suggest that *D*E-cadherin limits boundary expansion by increasing boundary tension. They propose that left-biased tension is sufficient to produce a leftward tissue rotation. Indeed, computer simulations identify one possible mechanism by which this might work. First, left-biased tension drives cell shape change and rearrangement while the endpoints of the tube remain fixed. Then, rotation occurs in the absence of asymmetric tension, and the tube twists as the cells relax back toward more regular shapes.

Together, Tang *et al*. and Taniguchi *et al*. highlight how statistical differences in cell behavior across a large population can lead to stereotyped, tissue-level morphogenesis. They also highlight several key ways in which mathematical models provide an essential predictive bridge between cell- and tissue-level dynamics. In the mouse lung, it is intuitively clear that biases in cell division orientations could cause differential increases in tube length versus circumference, and previous work had shown that oriented cell divisions can contribute to tube shape (*7*–*10*). A model, however, was essential to show quantitative sufficiency. In the case of the fruit fly hindgut, it is far from obvious how biasing tension on left boundaries will produce a leftward twist. Here, mathematical models step in when intuition fails, and provide plausible testable hypotheses.

For both systems, the mathematical models provide a framework for exploring the molecular mechanisms that control local cell polarity and coordinate its tissue-wide effects. One obvious candidate in both cases is the signaling pathway known as the planar cell polarity (PCP) pathway, which controls cell division orientations and cellular polarities in many other contexts (*11*, *12*). In the experiments conducted by Tang *et al*. and Taniguchi *et al*., however, disrupting PCP function had no effect on these developmental processes, suggesting that other mechanisms are at work.

In the mouse lung, a key question is: How does ERK signaling shape the distribution of cell division angles? The nature of the wild-type distribution suggests that cells partition between two qualitatively distinct orientation states: strictly longitudinal or random. Tang *et al*. hypothesize that the longitudinal state is the default, that ERK signaling overrides this default to randomize division axes, and that *Spry1/2* tune ERK signaling to achieve a balance between longitudinal and random divisions. But how does a graded change in ERK levels control the fraction of cells that inhabit these two states? Does ERK signaling merely gate the response to a longitudinal cue, or does it directly control a transition between distinct phenotypic states?

Likewise, the Taniguchi *et al*. study provides a starting point for thinking about how local left-right asymmetries in force generation could drive chiral rotation, but how do these asymmetries arise? The observation that *MyoID* mutants exhibit reversed PCC and gut rotation implies an intrinsic mechanism for breaking chiral symmetry that can be biased in either direction. The genetic requirements for *D*E-cadherin and MyoID suggest that symmetry breaking occurs shortly before hindgut rotation and requires local interaction across cell-cell boundaries. By contrast, in vertebrates, establishment of left-right asymmetry occurs far in space and time from the organs undergoing chiral morphogenesis, which suggests that it may be easier to identify the mechanisms involved.

These studies signal a growing trend in which classical molecular and genetic approaches merge with quantitative microscopy, image analysis, and modeling to provide new insights into the cellular dynamics of tissue morphogenesis. It is likely, however, that we are seeing just the tip of an iceberg.

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PSYCHOLOGY

Sentence and Word Complexity

Jeffrey Heinz[1] and William Idsardi[2]

Do humans learn the sentence and sound patterns of natural languages through distinct learning mechanisms?

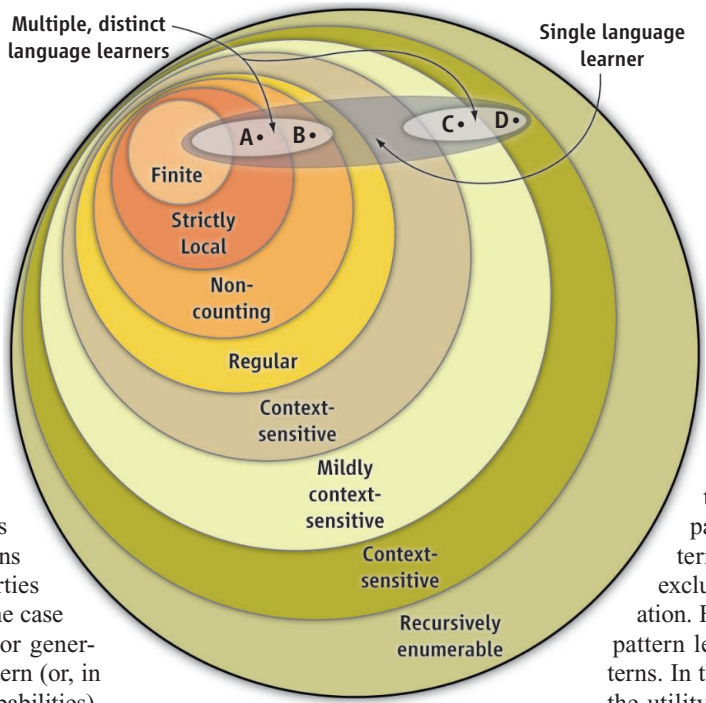
Our understanding of human learning is increasingly informed by findings from multiple fields—psychology, neuroscience, computer science, linguistics, and education. A convergence of insights is forging a "new science of learning" within cognitive science, which promises to play a key role in developing intelligent machines (*1*, *2*). A long-standing fundamental issue in theories of human learning is whether there are specialized learning mechanisms for certain tasks or spheres of activity (domains). For example, is learning how to open a door (turning the handle before pulling) the same kind of "learning" as putting up and taking down scaffolding (where disassembly must be done in the reverse order of assembly)? Surprisingly, this issue plays out within the domain of human language.

Language perception is organized at different levels, each with its own internal organizing principles: the organization of sounds into words (phonology), the organization of roots and affixes into words (morphology), and the organization of words into phrases into sentences (syntax). Are there any differences among the patterns observed at each level? And if there are, are specialized or

[1]Department of Linguistics and Cognitive Science, University of Delaware, 42 East Delaware Avenue, Newark, DE 19716, USA. [2]Department of Linguistics and Program in Neuroscience and Cognitive Science, University of Maryland, 1401 Marie Mount Hall, College Park, MD 20742, USA. E-mail: heinz@udel.edu

nonspecialized learning mechanisms better or worse at explaining them?

Theoretical computer science provides a mathematically rigorous way to characterize patterns in terms of strings, i.e., sequences of more basic units. For example, sentences are sequences of words; words are sequences of sounds. Patterns in any domain can be described as a set of strings or a probability distribution over strings. The Subregular and Chomsky hierarchies (*3*) arrange all logically possible patterns into nested regions of complexity (see the figure). These regions have multiple, convergent definitions which distill the necessary properties of devices (such as grammar, in the case of language) that can recognize or generate the strings comprising the pattern (or, in the case of distributions, their probabilities). This mathematical framework permits the comparison of patterns and their complexity across different levels or domains, linguistic or otherwise.



Complexity hierarchies for patterns. The Subregular and Chomsky hierarchies divide all logically possible patterns into nested regions (*4*). A is a pattern of permissible consonant clusters in English (*14*); B is the long-distance sound pattern of Samala (*9*); C is the recursive pattern of sentences within sentences in English; D is a particular sentence pattern in Swiss German (*5*).

Every natural language distinguishes well-formed and ill-formed sentences and words. Every sentence in this article is well-formed; ill-formed sentences are obtained by shifting every period one word to the left. Likewise, English words must contain proper sequences of English sounds (*4*). For example, "gdansk" and "srem" are not possible native English words, though they are possible words in other languages. English speakers can readily assent to new coinages ("bling") while avoiding others ("gding").

An important, but perhaps overlooked, difference is that sound patterns are less complex than sentence patterns according to the Subregular and Chomsky hierarchies. Capturing which patterns of words are well-formed sentences can require context-free or even mildly context-sensitive computations (*5*). Thus, similar to the assembly and disassembly of scaffolding, English exhibits recursion, because sentences ("The mouse ran away") can be contained in larger ones ("The mouse that the cat chased ran away"). The recursive nature of sentence patterns is a defining characteristic of natural language (*6*), and demonstrably makes such sentence patterns at least context-free.

By contrast, sound patterns are measurably simpler because identifying well-formed patterns of sounds does not require context-free computations (*7*). One kind of sound pattern restricts adjacent sounds (such as "gding"). Another kind of sound pattern restricts sounds over long distances (*8*). For example, Samala, a language native to California, does not allow words containing both "s" and "sh." Consequently, there are words such as "shtoyonowonowash" (which means "it stood upright") but none like "shtoyonowonowas" (*9*). Moreover, all sound patterns fall into the "regular" region (less restricted) of the Chomsky hierarchy (*7*), and probably belong to even less complex regions (*10*).

What are the possible explanations for this computationally measurable difference between sentence patterns and sound patterns? One possibility is that sound patterns are constrained by the human nervous, motor, and auditory systems in ways that sentence patterns are not. That is, the moment-to-moment configurations of the vocal tract constrain the moment-to-moment articulation of sounds. However, long-distance sound patterns cannot be due to articulation alone because the tongue does not retain the "sh" posture throughout "shtoyonowonowash."

Because humans do learn languages, another possibility is that the properties of sentence patterns and sound patterns reflect properties of how they do this. It follows that if humans employ distinct learning mechanisms for phonology and syntax, the complexity differential could be explained. There is a convergence of results from philosophy, psychology, and computer science (*1*, *11*–*13*), showing that learning is only possible if learners (humans or machines) are restricted in the generalizations they are allowed to consider. Indeed, the successes in the "new science of learning" carefully tailor hypothesis spaces so that learners succeed with reasonable amounts of data and effort. In fact, recent, distinct computational models for learning sound patterns (*10*, *14*) and sentence patterns (*15*, *16*) succeed because they exclude certain patterns from consideration. For instance, algorithms for sound-pattern learning exclude context-free patterns. In this way, these results demonstrate the utility of multiple, differentiated algorithms for language learning.

Task-specific knowledge and its acquisition are familiar in robotics (*17*) and biology (*18*). Human and robot locomotion, for example, are often modeled with systems with less than context-free power (*19*). Thus, modular learning proposals may be based not on the content of the domains (language versus locomotion), but rather on the informational complexity of the patterns in each domain.

Although single, general-purpose language-learning models (*20*) cannot be ruled out, they face a series of challenges. Such models predict that no complexity differential between sound patterns and sentence patterns should exist: Any sentence pattern ought to be a possible sound pattern and vice versa. Moreover, such unitary algorithms must enable the learning of both sound patterns and sentence patterns from reasonable amounts of data. Finally, these models should also offer some explanation for the observed difference in complexity between sentence and sound patterns (or disprove it).

While complexity differentials do not entail distinct learning mechanisms, the hypothesis that humans learn sound patterns separately from sentence patterns provides a viable explanation for the difference in complexity observed between them. The utility of specialized or general learning mechanisms (or perhaps even both) for language learning will become clearer through further empirical collaborations. Indeed, psychologists and linguists are currently testing these hypotheses with artificial language-learning experiments (*21*), an approach that can determine

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whether people make the same kind of generalizations when they encounter both words and sentences.

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CHEMISTRY

Pores Within Pores—How to Craft Ordered Hierarchical Zeolites

Thin walls of crystalline zeolites can be assembled into hexagonal nanopore networks, which expands the range of their catalytic reactions to larger molecules.

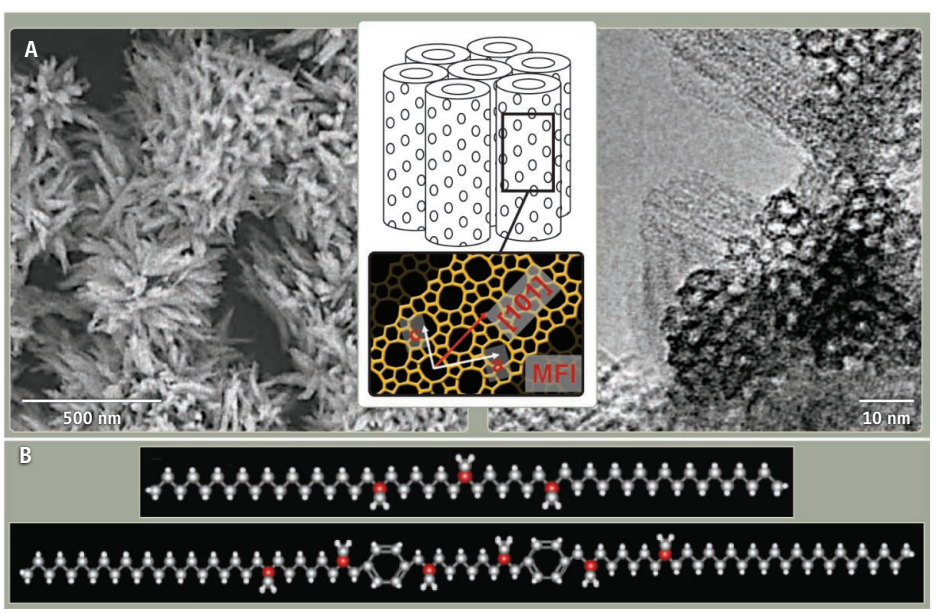
Karin Möller and Thomas Bein

Zeolites are aluminosilicate crystals that have internal networks of angstrom-size pores, similar to the dimensions of small molecules. They are among the most widely used materials in heterogeneous catalysis (*1*, *2*) because of their defined structure and composition. Although zeolites are very potent solid-acid catalysts, their catalytic applications have been limited to processing smaller molecules; their internal pores are not readily accessed by molecules exceeding 1 nm in size. Major efforts have been directed to overcoming this limitation. On page 328 of this issue, Na *et al*. (*3*) present a new strategy for creating thin zeolite walls, containing small pores, that grow into structures forming larger pores that can catalyze reactions with larger molecules.

To date, two major synthesis strategies have been explored to create zeolites with additional larger pores. One is to form a secondary pore system of larger size than the zeolitic micropores within the zeolite crystal, thereby allowing faster diffusion of larger molecules into the zeolite particles. In many zeolite synthesis routes, molecular "templates" are added to aid the growth of the aluminosilicate crystals; when the synthesis is completed and the template molecules are removed, zeolitic pore spaces remain. Traditional methods in zeolite synthesis use a single molecular template with a size similar to or smaller than the micropore dimensions. This micropore size barrier was broken in the early 1990s with the synthesis of mesoporous oxides by using larger amphiphilic surfactant templates (*4*). However, the local order in the resulting (alumino-)silicates was lost, and with it their strong acidity. Efforts to recrystallize these amorphous walls into zeolitic structures were usually unsuccessful.

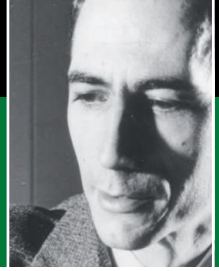
Dual-templating approaches are now being explored that combine the advantages of zeolites and the mesoporous oxides. In addition to the molecular zeolite templates, larger assemblies such as the above surfactant micelles (*5*), polymers (*6*), or objects such as carbon beads or fibers (*7*) were used to create mesoporosity. Alternative approaches include chemical treatments that partially dissolve the crystalline zeolite lattice and create larger intraparticle cavities (*8*). The need for a secondary template can also be avoided by the direct assembly of nanosized zeolite particles, thus creating mesoporous interparticle voids (*9*).

The other approach for allowing access of larger molecules to zeolite pores is to pre-



Ordering the walls. Na *et al*. have used large molecular templates to grow thin walls of zeolites into morphologies that create ordered mesopores. (**A**) Two electron microscopy images of the hexagonally grown mesoporous MFI-type zeolite with extremely high surface area. The inset shows a schematic of the hierarchical structure and the MFI pore framework of the zeolite walls. (**B**) Examples of the bifunctional templating molecules used in the synthesis that bear ammonium groups and long alkyl chains (white spheres, hydrogen; gray spheres, carbon; red spheres, nitrogen).

Department of Chemistry, Ludwig-Maximilians University, 81377 Munich, Germany. E-mail: karin.moeller@cup.uni-muenchen.de; bein@lmu.de



A chronicle of information 1826

Wildlife as public trust 1828

LETTERS

edited by Jennifer Sills

Retraction

IN OUR 2006 REPORT, "DESORPTION OF H FROM SI(111) BY RESONANT EXCITATION OF THE Si-H vibrational stretch mode" (*1*), we reported resonant photodesorption of hydrogen from a Si(111) surface using tunable infrared radiation that corresponded to the Si-H vibrational stretch mode. Our recent attempts to reproduce these experiments have been unsuccessful, and the free electron laser facility at Vanderbilt, a unique light source for this experiment, has shut down, prohibiting further research. Because our conclusions are now in question, we retract the Report.

ZHIHENG LIU,[1,2]* L. C. FELDMAN,[2,3]† N. H. TOLK,[2] ZHENYU ZHANG,[3,4] P. I. COHEN[1]‡

[1]Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN 55455, USA. [2]Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235, USA. [3]Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA. [4]Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA.

*Present address: Department of Physics, The City University of New York, Brooklyn, NY 11210, USA.

†Present address: Institute for Advanced Materials, Devices, and Nanotechnology, Rutgers University, Piscataway, NJ 08854–8065, USA.

‡To whom correspondence should be addressed. E-mail: picohen@umn.edu

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Editor's Note

IN THE REVIEW "CHINA'S DEMOGRAPHIC history and future challenges" in the 29 July special section on Population (*1*), Fig. 1 showed a map of the South China Sea. We have become aware that some readers are interpreting the publication of this map as a statement by *Science* on the maritime borders marked in the image. This is not the case.

Science's policy, found on the masthead page of each issue, states that "all articles published in *Science*—including editorials, news and comment, and book reviews—are signed and reflect the individual views of the authors and not official points of view adopted by AAAS or the institutions with which the authors are affiliated." *Science* does not have a position with regard to jurisdictional claims in the area of water included in the map. We are reviewing our map acceptance procedures to ensure that in the future *Science* does not appear to endorse or take a position on territorial/jurisdictional disputes.

MONICA BRADFORD

Executive Editor

Reference

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Tiger Conservation: Trust Tradition

IN THEIR LETTER "RESTORING TIGERS TO THE Caspian region" (12 August, p. 822), C. A. Driscoll *et al.* propose the reintroduction of tigers into the historic range of the extinct Caspian tiger. Driscoll *et al.* assert that new approaches such as this one are needed because "traditional conservation approaches are proving insufficient." We disagree.

Tiger biologists and conservationists have shown how to save tigers. So-called traditional approaches—including law enforcement, scientific assessments, monitoring of tiger and prey populations, and community outreach—are demonstrably effective in reversing tiger declines when properly implemented by conservation nongovernmental organizations (NGOs) and government agencies (*1*–*6*). New approaches should always be considered in our efforts to save the tiger, but the focus must be on addressing the most critical threats to those remaining tigers that survive in little more than four dozen source populations throughout their range (*7*). The immediate solution lies in convincing NGOs, conservationists, donor agencies, and government authorities to properly implement the proven best practices of tiger conservation: the traditional approaches. If we are considering reconstructive surgery for the tiger, then let's stop the bleeding first.

ALAN RABINOWITZ,* LUKE HUNTER, JOSEPH SMITH

Panthera, 8 West 40th Street, 18th Floor, New York, NY 10018, USA.

*To whom correspondence should be addressed. E-mail: arabinowitz@panthera.org

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The Ant Who Learned to Be an Elephant

IN 1998, THE EUROPEAN AND DEVELOPING Countries Clinical Trials Partnership established regional networks of excellence in sub-Saharan Africa to strengthen research capacity for clinical trials on tuberculosis, HIV/AIDS, and malaria (*1*). Through this program, the Faculty of Health Sciences of the University Marien Ngouabi of Brazzaville, like a poor, tiny Ant in an African tale, prepared to partner with a magnificent Elephant: the University of Tübingen in Germany.

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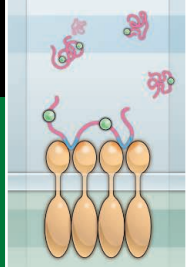

Stress sensor engagement
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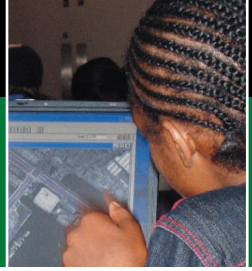

SPORE Prize Essay
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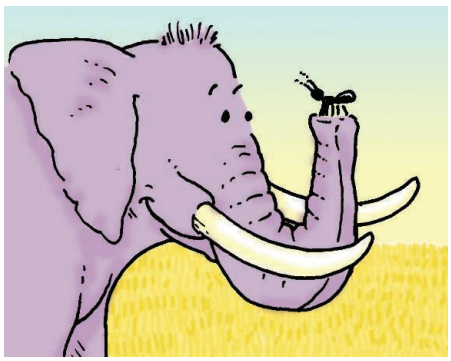

The Elephant is beautiful, muscular, and respected by all the animals in the jungle. The Ant is small and ignored. Could an Ant possibly build a strong relationship with an Elephant? This Ant was going to try.

First, the Ant sought national authorization to conduct a clinical research project that would develop baseline studies and collect baseline data necessary for future clinical trials. After submitting the research protocol, the Ant waited 15 long months for approval by Congo's only Institutional Ethics Committee, and two more months for authorization from the Ministry of Health. A 17-month delay could compromise the rest of the project, thought the Ant with alarm. The work plan was often misunderstood, and as the Ant explained again and again how the money would be used to address specific challenges, she worried that the Elephant would move on and leave her behind.

The Ant realized that a good research team must be multidisciplinary, consisting of junior and seniors scientists selected by an experienced panel from a list of qualified applicants. This would be a challenge in a place with limited postgraduate academic opportunities. To overcome this limitation, the Ant launched an open call for applications. The other animals in the jungle viewed the Ant's new approach with suspicion.

To invest in infrastructure, the Ant renovated an abandoned facility into the first molecular biology laboratory of the Faculty of Health Sciences, and then equipped it. Now the other animals started to appreciate the Ant's hard work. They congratulated her for the change and encouraged her to maintain the spirit.

To create a culture of research, the Ant had to be thoughtful and innovative. She stimulated scientific discussions by implementing regular scientific meetings. But how would she attract students and scientists to these meetings and foster interest and loyalty? The Ant formed brigades of students to urge others to participate. A year later, the seminar room was always filled with an enthusiastic audience.

Once she had met these challenges, the Ant invited the Elephant to her home to share a cup of tea. She told him about all of her accomplishments, and showed him the new facilities. When the Elephant returned home, he was smiling and convinced. And he wondered, "What kind of Ant is this, this Ant who acts like an Elephant?"

It was just as the Ant had hoped. Next, the Ant hopes to sustain positive momentum and establish stable local research teams that will regularly publish in international scientific journals (*2*). The moral of the story: For young Congolese scientists wondering how to contribute scientifically to their country, the metamorphosis from tiny Ant to majestic Elephant is possible, but it will require time, cunning, and determination.

FRANCINE NTOUMI

Congolese Foundation for Medical Research/Faculty of Health Sciences, University Marien Ngouabi, Brazzaville, Congo, and Institute for Tropical Medicine, University of Tübingen, Germany. E-mail: fntoumi@fcrm-congo.com

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Letters to the Editor

Letters (~300 words) discuss material published in *Science* in the past 3 months or matters of general interest. Letters are not acknowledged upon receipt. Whether published in full or in part, Letters are subject to editing for clarity and space. Letters submitted, published, or posted elsewhere, in print or online, will be disqualified. To submit a Letter, go to www.submit2science.org.

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CORRECTIONS AND CLARIFICATIONS

Editors' Choice: "Loud enough?" by J. S. Yeston (12 August, p. 803). Dalian's location should have been specified as Northeast, rather than Northwest, China.

News Focus: "Climate change sparks battles in classroom" by S. Reardon (5 August, p. 688). The credit for the second image (bottom of page 688) was incorrect. The correct credit is Morgan Heim, Cooperative Institute for Research in Environmental Sciences. The credit has been corrected in the HTML version online.

Reports: "The plant cell wall–decomposing machinery underlies the functional diversity of forest fungi" by D. C. Eastwood *et al.* (5 August, p. 762). The second sentence of the caption for Fig. 2C should read, "Black trace, nitrogen-rich medium (+N); red trace, nitrogen-depleted minimal medium (–N)."

Perspectives: "Sentence and word complexity" by J. Heinz and W. Idsardi (15 July, p. 295). Due to a production error, the inner region in the figure was mislabeled "Context-sensitive." It should read "Context-free."

TECHNICAL COMMENT ABSTRACTS

Comment on "The Response of Vegetation on the Andean Flank in Western Amazonia to Pleistocene Climate Change"

Surangi W. Punyasena, James W. Dalling, Carlos Jaramillo, Benjamin L. Turner

Cárdenas *et al.* (Reports, 25 February 2011, p. 1055) used the presence of *Podocarpus* pollen and wood to infer ≥5°C cooling of Andean forests during Quaternary glacial periods. We show that (i) *Podocarpus* has a wide elevation range in the Neotropics and (ii) edaphic factors cannot be discounted as a factor governing its distribution. Paleoecologists should therefore reevaluate *Podocarpus* as a cool-temperature proxy.

Full text at www.sciencemag.org/cgi/content/full/333/6051/1825-b

Response to Comment on "The Response of Vegetation on the Andean Flank in Western Amazonia to Pleistocene Climate Change"

Macarena L. Cárdenas, William D. Gosling, Sarah C. Sherlock, Imogen Poole, R. Toby Pennington, Patricia Mothes

Punyasena *et al.* question our interpretation of climate-driven vegetation change on the Andean flank in western Amazonia during the middle Pleistocene and suggest that the use of *Podocarpus* spp. as a proxy of past climate change should be reassessed. We defend our assertion that vegetation change at the Erazo study site was predominantly driven by climate change due to concomitant changes recorded by multiple taxa in the fossil record.

Full text at www.sciencemag.org/cgi/content/full/333/6051/1825-c

Multiple, distinct language learners

Single language learner

A

B

C

D

Finite

Strictly Local

Non-counting

Regular

Context-Free

Mildly Context-Sensitive

Context-Sensitive

Recursively Enumerable