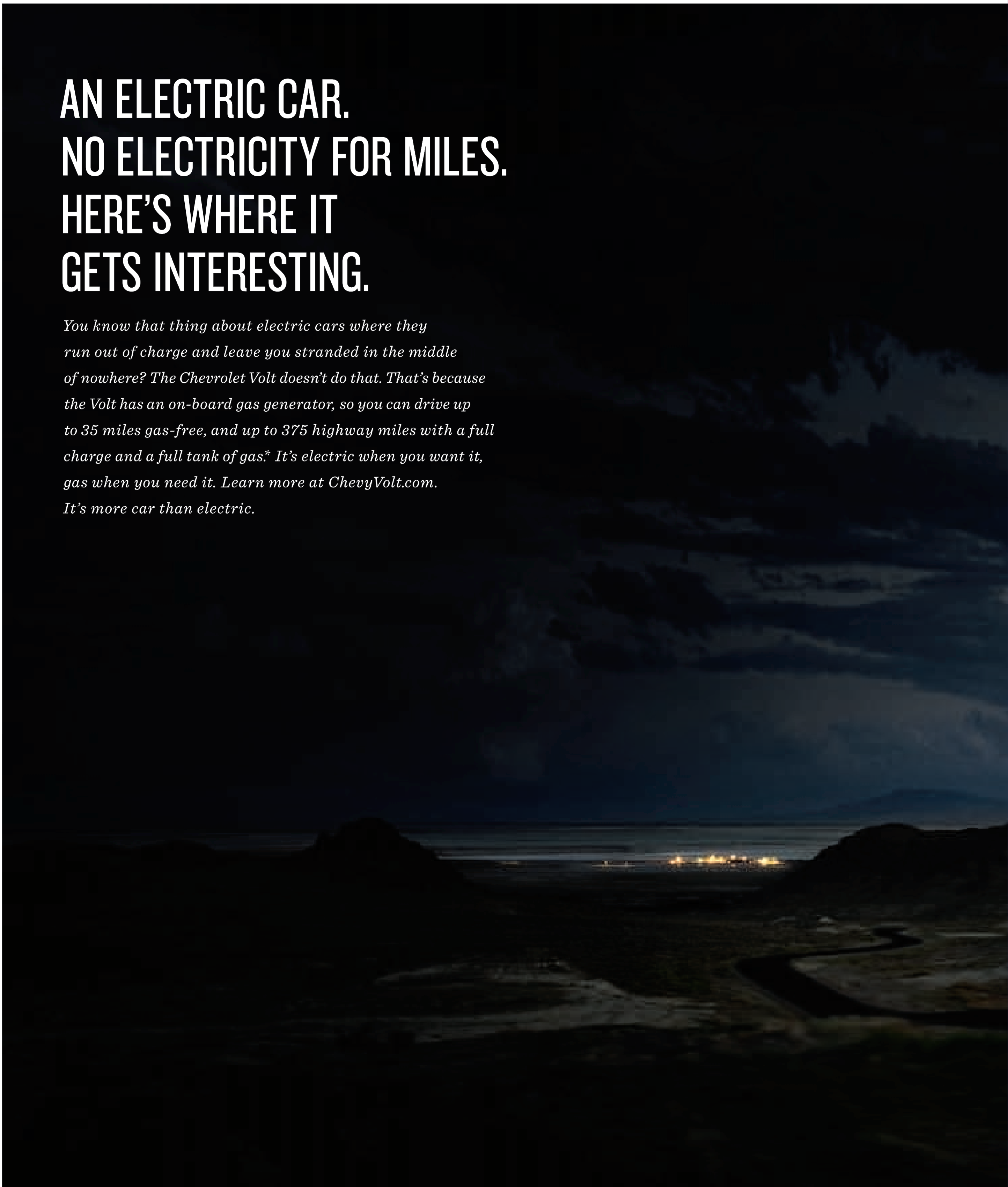
SPECIAL ISSUE

SCIENTIFIC AMERICAN

SEPTEMBER 2012

Beyond the Limits of Science

How we will transcend today's barriers to get smarter, live longer and expand the power of human innovation



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SCIENTIFIC AMERICAN

September 2012 Volume 307, Number 3

ON THE COVER

For science, limits don't mark what is forbidden. Rather they are guideposts to the edges of understanding—the signs demarcating the darkness beyond—and thus a smart place to aim the flashlights. In this special issue, we celebrate the quest to break beyond everyday limits—the most human quest of all.

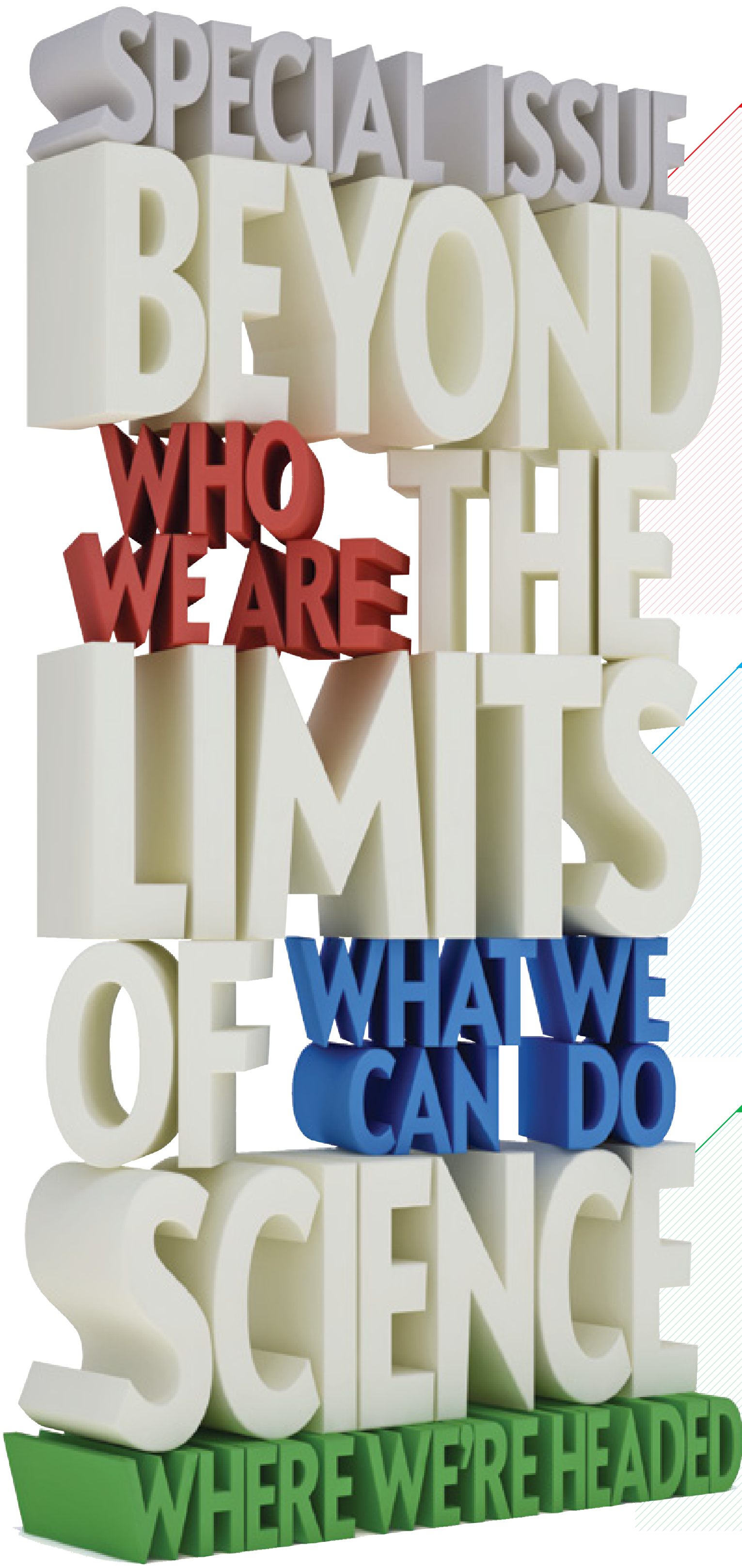

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Illustration by Benjamin Simon

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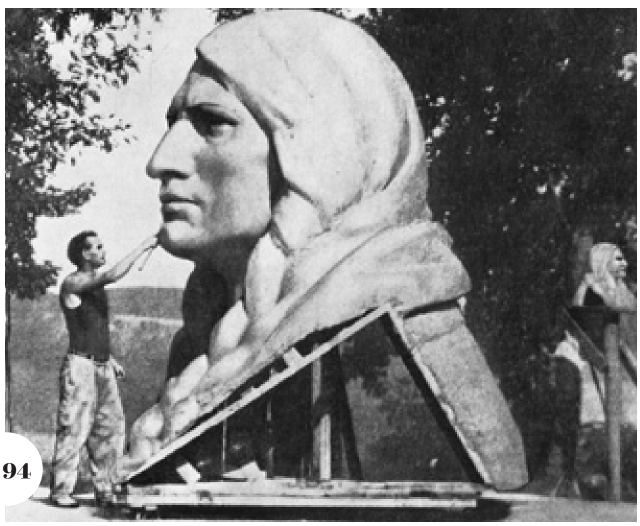

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SCIENTIFIC AMERICAN

DEPARTMENTS

ON THE WEB

Particle Prospectors Hit Higgs Pay Dirt
The long-sought Higgs boson, which helps to explain why elementary particles have mass, finally seems to have revealed itself. What does the Higgs mean for science, and which particles do physicists hope to find next?
Go to www.ScientificAmerican.com/sep2012/higgs

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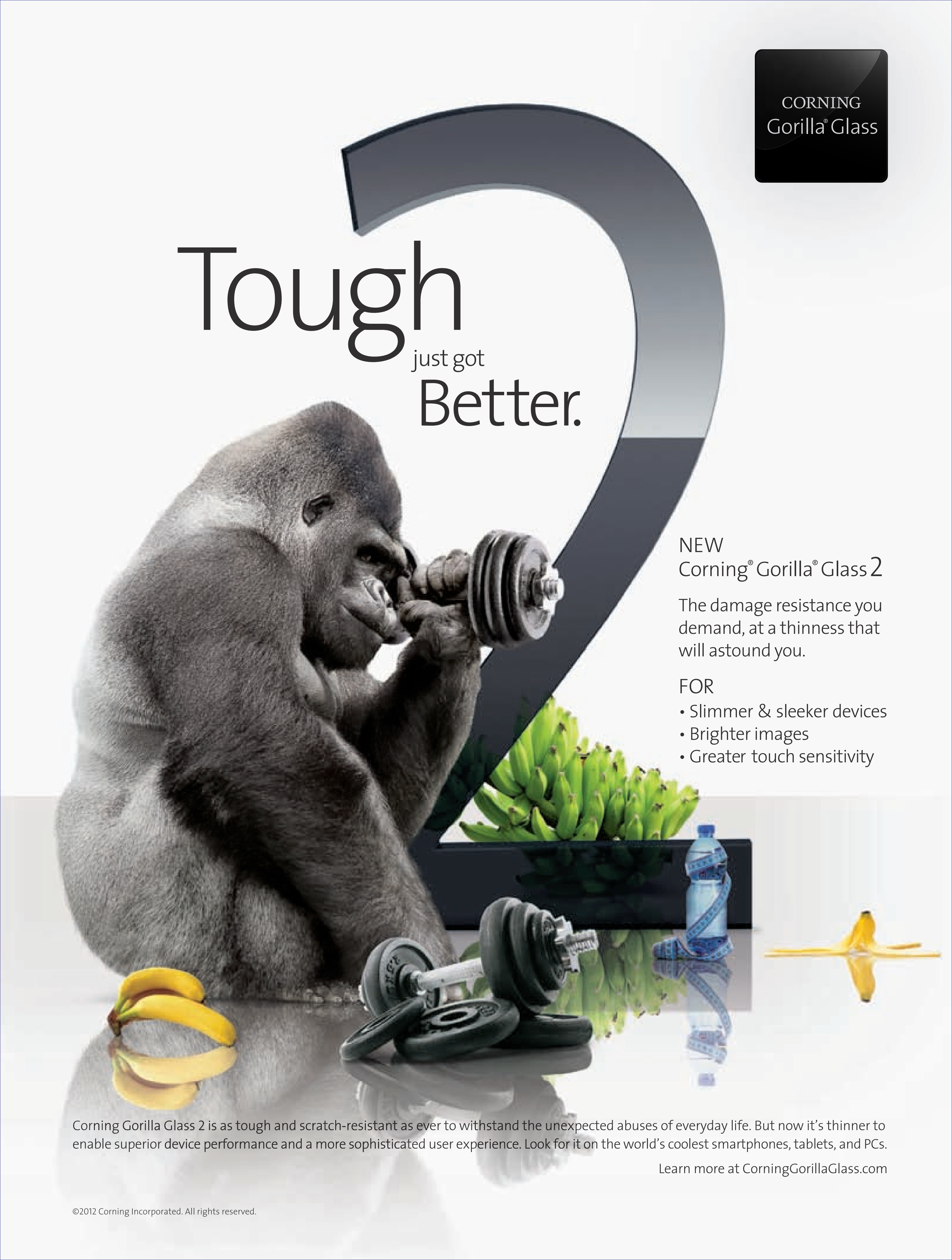

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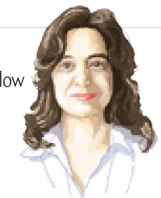
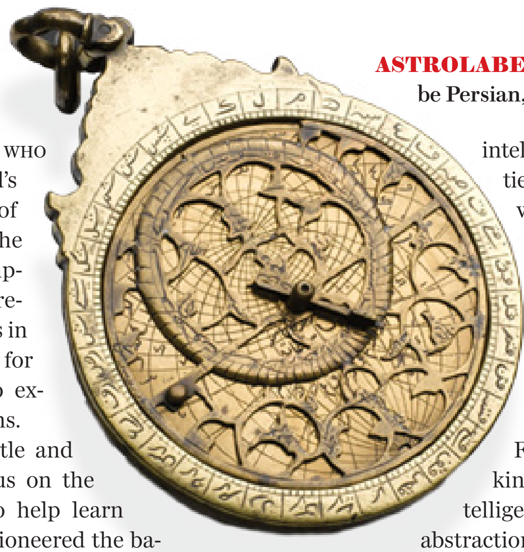


Mariette DiChristina is editor in chief of *Scientific American.* Follow her on Twitter @mdichristina

Out of Bounds



ASTROLABE, thought to be Persian, circa 1650

IT ISN'T POSSIBLE TO PINPOINT EXACTLY WHO is most responsible for humankind's best invention of all time. I am, of course, talking about science—the process that lets us test our assumptions, gather evidence and analyze the results. That process has propelled advances in basic research and practical applications for everything from extending our lives to expanding our physical and mental horizons.

Around the third century B.C. Aristotle and other ancient Greek philosophers put us on the right track, employing measurement to help learn about the world. Muslim scholars later pioneered the basics of testing and observation, the foundations of the scientific method, perhaps more than 1,000 years ago. Among the others who helped to refine the process were Roger Bacon, who fostered the use of inductive reasoning in the 1200s; Galileo, who put Bacon's ideas into practice in the late 1500s and early 1600s; and René Descartes, Francis Bacon and Isaac Newton, who built on the method shortly before and during the Enlightenment of the 1700s—to name a mere handful.

In our single-topic issue, "Beyond the Limits of Science," we celebrate just how far we have come as a species using that rational system. A series of apparent barriers now stands before us in our current life span: the physical body's performance, individual intellectual capacity, engineering capabilities and even collective knowledge. How will we move past them? In this special edition, we promise a mind-expanding armchair journey, with leading scientists and expert journalists as guides, to the edges—and beyond—of what is and will be possible.

For instance, in "Can We Keep Getting Smarter?" journalist Tim Folger writes about the Flynn effect, a kind of Moore's law for measures of intelligence. In a world that prizes logic and abstraction, a positive feedback loop has led to our continuous progress in mental adaptation and the invention of new technologies. "How We All Will Live to Be 100," by staff editor Katherine Harmon, examines efforts to lead longer, healthier lives by attacking our ancient enemies of illness and decrepitude. Casting aside the idea of mortality altogether, contributing editor Davide Castelvecchi describes "Questions for the Next Million Years"—research we could do if an individual's career or life span were no obstacle.

As Newton famously put it: "If I have seen further, it is by standing on the shoulders of giants." Following his model, we can use the process of science to exceed today's boundaries. Perhaps our only true limit is the human imagination itself. SA

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Illustration by Nick Higgins


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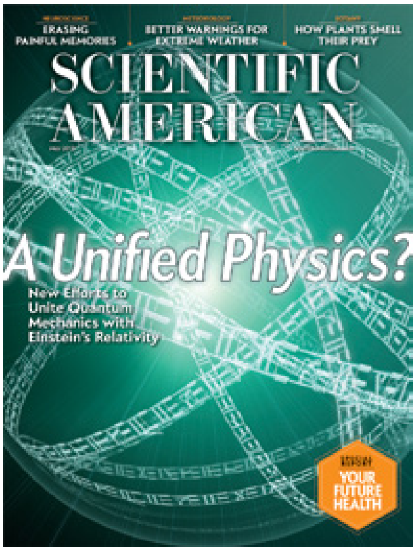

May 2012

"Guests in more expensive hotels are more willing to accept charges for Wi-Fi."

BJORN HANSON *NEW YORK UNIVERSITY*

FLASHY FOSSILS

Dinosaurs have certainly become a lot prettier in the decades since I was a child. But I wonder if these splashes of color, such as seen in the images in "Triumph of the Titans," by Kristina A. Curry Rogers and Michael D. D'Emic, have gone too far. Among living creatures today, none of the larger land animals sport elaborate color schemes. And in the smaller critters, color has evolved as a camouflage, something that would have little or no success on an animal the size of an elephant—or an *Apatosaurus!*

John Byrne
via e-mail

THE AUTHORS REPLY: We chose to "spruce up" our depictions of sauropods with some color to reflect our new understanding of these animals as fast-growing and dynamic, with a unique mix of birdlike and reptilelike biology. Although most large-bodied animals today could be construed as drab, some are indeed colorful (giraffes and orcas come to mind). As for camouflage, the bright colors of many small animals have not evolved for that function but for the purposes of attracting a mate or signaling kin or a predator.

Notwithstanding, it is important to remember that sauropods did not start off life large (baby sauropods were about half a meter in length), so predation was a factor in a young sauropod's life. Ultimately the coloration of most dinosaurs remains speculative, although recent research has indicated complex patterns and colors on some feathered dinosaurs.

WI-FI FOR THE WEALTHY

In "The Trouble with Wi-Fi," by David Pogue [TechnoFiles], Don Millman of Point of Presence Technologies responds that the reason high-end hotels charge for Wi-Fi is that they "attract business travelers who expense their stays." While this is not incorrect, the answer is more complex. For example, most high-end resorts serve more leisure travelers than business guests but charge for Wi-Fi. High-end hotels are mostly operated by brand management companies with fees based on a percentage of total revenue; most less expensive hotels are franchised, and their fees are based on room revenue only. Thus, there is an incentive for brand management companies to maximize their revenue—for example, by charging for Wi-Fi—and an incentive for less expensive franchised hotels to have higher room rates—for example, by including Wi-Fi in the rate.

But the most correct answer is that guests in more expensive hotels are more willing to accept charges for Wi-Fi. A reason to charge separately for Wi-Fi is that if it were included in the room rate, municipal occupancy taxes would be based on the higher room rate, and therefore the rate would be more costly for guests.

Bjorn Hanson
Dean, Tisch Center for Hospitality, Tourism, and Sports Management
New York University

SIMPLIFYING PHYSICS

The new unitarity approach, a method of analyzing quantum-particle processes less complex than the Feynman diagrams that have been the standard, proposed by Zvi Bern, Lance J. Dixon and David A. Kosower in "Loops, Trees and the Search for New Physics," doesn't seem new. Applying estimates of probabilities to beginning and prior events in a causal chain to determine the final outcome's probability (adjusting as new results are available) simply describes Bayes' rule, doesn't it?

Duncan Byers
Norfolk, Va.

THE AUTHORS REPLY: If the quantities we were interested in were really probabilities, then one could assemble them as Byers suggests and it would not be particularly novel. As we mentioned in the article, they are really square roots of probabilities. These are complex numbers, although for simplicity we usually referred to them as probabilities. One combines them according to the usual rules of quantum mechanics, wherein the phases associated with them are essential. They capture quantum-interference phenomena that prevent the application of the usual probability rules. Another obstruction to simply multiplying probabilities in Feynman diagrams is the presence of the spurious contributions we had described in the article, which disallow a simple probabilistic interpretation of an individual diagram.

There are useful approximations where the interference terms can be neglected. These have been implemented as products of sequential probabilities in computer programs, widely used by particle physics experimenters, that produce realistic-looking jets of particles. But their overall accuracy is not as good as the loop calculations described in the article. Combining the best features of both techniques is a very active area of current research.

WEATHER WARNINGS

The lack of low-altitude radar coverage as a factor in tornado-warning lead times was not mentioned in "A Better Eye on the Storm," by Jane Lubchenco and Jack Hayes. Even with improvements in signal processing and phased-array radars, the unobservability of the zone where tornadoes form will limit the ability to forecast. Not all urban areas have or will have radars close enough to observe the bottom 5,000 feet of highly active weather

systems when tornadoes pose the greatest threat. Very small short-range radars might be co-located with cell-phone towers to provide the density, power, communications and required altitude.

Doc Dougherty
Playa del Rey, Calif.

The authors speak of new, higher-resolution weather models that use horizontal grids. Wouldn't it be better to concentrate computing power where it would be most valuable? Model designers might take a cue from image-compression software that uses fine resolution for only those areas in an image where changes occur. It should result in horizontal and vertical grids that fluctuate in fineness in response to actual and predicted conditions—lowering the number of data points in areas where weather is fairly uniform and increasing them where conditions are changing rapidly.

Ralph McLain
Colorado Springs, Colo.

WHISPERING WOODS

The poplar and sugar maple experiment by Ian Baldwin and Jack Schultz, described in Daniel Chamovitz's "What a Plant Smells," doesn't actually demonstrate signaling between plants. As told, undamaged leaves on trees having two damaged leaves were the ones to respond to that damage by making caterpillar deterrents. Nothing is said of the behavior of the intact trees of the same population.

Dov Elyada
Haifa, Israel

CHAMOVITZ REPLIES: The confusion comes from editing that shortened the excerpt from chapter 2 of my book, What a Plant Knows. *Indeed, Baldwin and Schultz detected insecticidal chemicals not only in the intact leaves of the trees that had torn leaves but also in the intact leaves of trees that neighbored them. This was the basis of their volatile communication hypothesis.*

ERRATUM

"Erasing Painful Memories," by Jerry Adler, incorrectly refers to a foot shock causing a rat to avoid a particular area as a negative reinforcement. It is more accurately described as a positive punishment.

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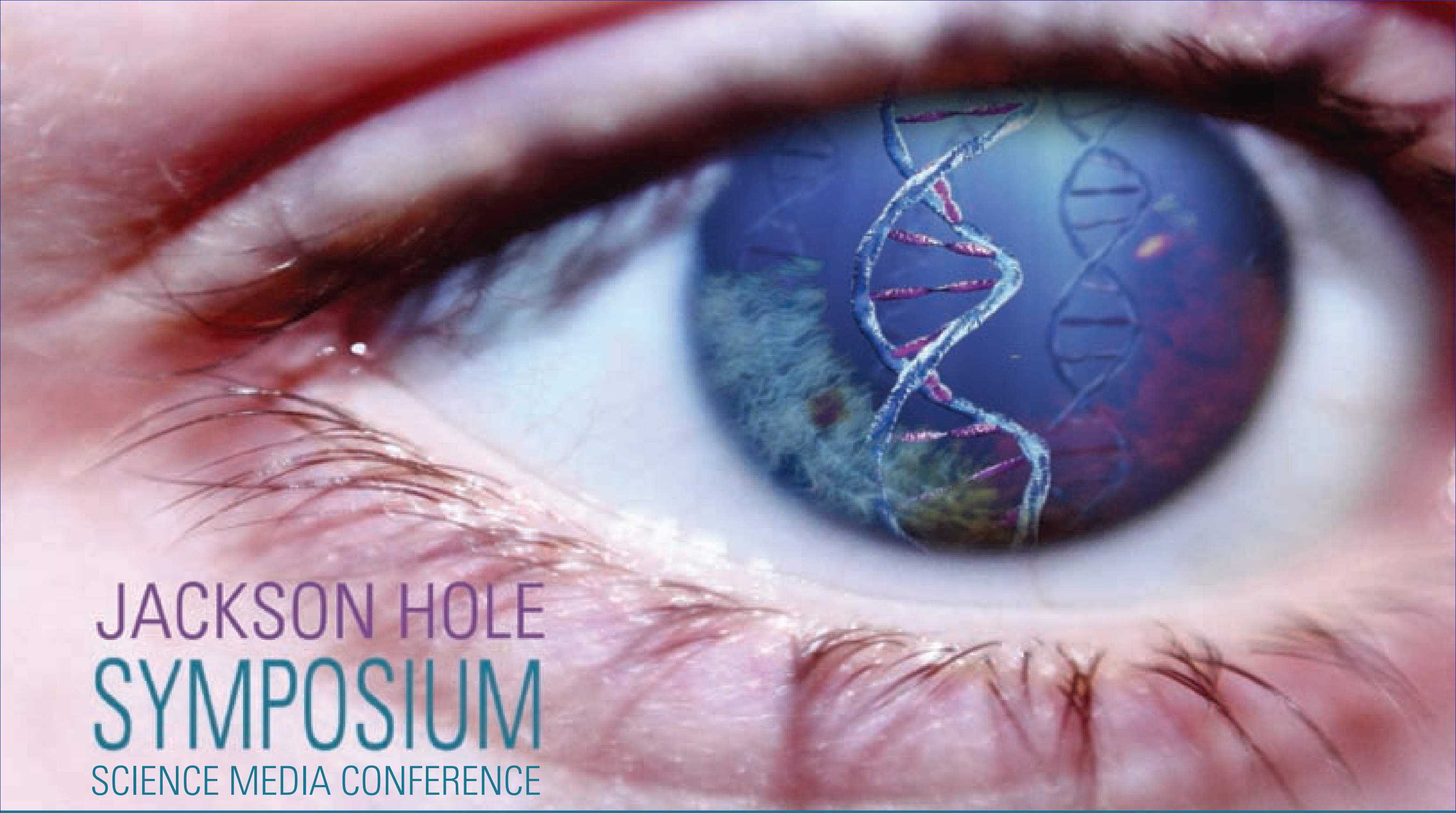
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Opinion and analysis from *Scientific American*'s Board of Editors

Safer Drugs for Kids

Many of the medicines children take have never been proven safe and effective for them. A new law will help change that

Parents assume that when a pediatrician prescribes a drug for their child, that drug has been tested and proven safe and effective. If only it were so. Only half of the medicines doctors prescribe to patients 18 and younger have been through the same rigorous trials as those drugs prescribed to adults. The other half are given off-label—that is, in circumstances for which they were never properly vetted, putting children at risk for overdoses, side effects and long-term health problems. For newborns, that fraction rises to 90 percent. In July the U.S. Congress gave the Food and Drug Administration new authority to compel companies to test their products for kids. The law should improve the situation, but it has worrying gaps.

As biologists have come to appreciate, drug metabolism is one of the many ways in which kids are not just small adults. When doctors downsize an adult dosage to suit a child's weight or body surface area, a drug can prove ineffective or harmful. Infants have immature livers and kidneys, so even a seemingly small dose of medicine can build up quickly in their bodies. As children mature, their organs can develop faster than their body size, so they need to take disproportionately *more* of the drug. For example, some recent pediatric clinical trials have found that the asthma medication albuterol does not work for children younger than four when taken through an inhaler. The seizure drug gabapentin (Neurontin) requires higher-than-expected doses for children under five.

The reason that drug companies neglect their youngest customers is simple. Children make up a small fraction of the world's drug recipients, so developing and testing new medicines for them is rarely worthwhile from a business perspective. Pediatric trials are especially expensive and complex, in part because of the difficulty of finding enough patients to enroll in them.

Congress began to address the issue in 1997, and its latest legislation, known as the FDA Safety and Innovation Act, strengthens those earlier efforts. The law requires pediatric studies for certain drugs and provides incentives to test others, such as a six-month patent extension. In addition, the law requires better advance planning of pediatric studies, improves the transparency of data and makes special provisions for newborns. The American Academy of Pediatrics praised the law: "The bill ensures that children will have a permanent seat at the table for drug research and development."

Still, the law leaves many children vulnerable. It does little for youngsters with cancer, who rely disproportionately on undocumented drugs. Earlier this year Genentech won FDA approval for the skin cancer drug vismodegib, which intervenes in the same molecular process thought to be involved in a childhood brain tumor, yet the company was under no obligation to test the drug in younger patients. Congress needs to close this loophole, and in the meantime the FDA should continue to work closely with pharmaceutical companies and pediatric oncologists to find new ways of identifying and testing promising cancer medicines in children.

LAUREN BURKE *Getty Images*

Another problem is that doctors are worryingly in the dark about the long-term health effects of pediatric drugs. Young people take medications for asthma, diabetes, arthritis and many other chronic conditions, yet rarely are side effects recorded and followed up on. In its February report "Safe and Effective Medicines for Children," the Institute of Medicine recommended that the FDA make greater use of its authority to require long-term safety studies when it approves a product for pediatric use.

That said, the FDA Safety and Innovation Act is an important achievement. Children's medications are safer now than at any time in history, and many doctors and children's health advocates are so elated by the act's passage that they are reluctant to talk about what still needs to be done. But now is not the time to let up on our drive to make drugs safe for all our citizens. We hope this legislative victory will breed even more success. SA

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Commentary on science in the news from the experts

Daniel T. Willingham is a professor of psychology at the University of Virginia and author of *When Can You Trust the Experts? How to Tell Good Science from Bad in Education* (Wiley, 2012).

Brain Science in the Classroom

Teachers need a trusted source to tell fads and fallacies from proved methods

Most teachers would agree that it is important that students remember much of what they read. Yet one of the most common sights on high school and college campuses across the land is that of students poring over textbooks, yellow marker in hand, highlighting pertinent passages—which often end up including most of the page. Later in the semester, to prepare for their exams, students hit the textbooks again, rereading the yellow blocks of text.

Studies have shown that highlighting and rereading text is among the least effective ways for students to remember the content of what they have read. A far better technique is for students to quiz themselves. In one study, students who read a text once and then tried to recall it on three occasions scored 50 percent higher on exams than students who read the text and then reread it three times. And yet many teachers persist in encouraging—or at least not discouraging—the techniques that science has proved to fall short.

This is just one symptom of a general failure to integrate scientific knowledge of the mind into schooling. Many commonly held ideas about education defy scientific principles of thinking and learning. For example, a common misconception is that teaching content is less important than teaching critical thinking skills or problem-solving strategies. Scientists have also long known that kids must be explicitly taught the connections between letters and sounds and that they benefit most when such instruction is planned and explicit. Yet some reading programs, even those used in large school districts, teach this information only if an instructor sees the need.

It is easy to argue that teachers ought to do a better job of keeping up with science, but teaching is already a labor-intensive profession. And it is difficult for the nonspecialist to separate scientific research from the usual flood of quackery and pseudoscience. Peddlers of expensive and supposedly research-based nostrums lobby school districts. Other products that may have scientific validity have not yet been thoroughly tested. For example, theories of mathematical learning suggest that linear (but not circular) board games may boost math preparedness in preschoolers, but the idea needs large-scale testing.

How are educators supposed to know which practices to use? An institution that vets research and summarizes it for educators could solve the problem. Medicine provides a precedent. Practicing physicians do not have the time to keep up with the tens of thousands of research articles published annually that might suggest a change in treatment. Instead they rely on reputable summaries of research, published annually, that draw conclusions as to whether the accumulated evidence merits a change in medical practice. Teachers have nothing like these authoritative reviews. They are on their own.

The U.S. Department of Education has, in the past, tried to bring some scientific rigor to teaching. The What Works Clearinghouse, created in 2002 by the DOE's Institute of Education Sciences, evaluates classroom curricula, programs and materials, but its standards of evidence are overly stringent, and teachers play no role in the vetting process. Teachers also play no role in the evaluation, and their participation is crucial. Researchers can evaluate research, but teachers understand education. The purpose of this institution would be to produce information that can be used to shape teaching and learning.

It is also important that insights provided by a clearinghouse come from basic science. Many teachers, for instance, need to be disabused of the notions children have different "learning styles" and that boys' brains are hardwired to be better at spatial tasks than girls'. This job of bringing accurate scientific information about thinking and learning to teachers might arguably fall to schools of education, states, districts and teachers' professional organizations, but these institutions have shown little interest in the job. A neutral national review board would be the simplest and quickest answer to a problem that is a big obstacle to broad improvement across many schools. SA

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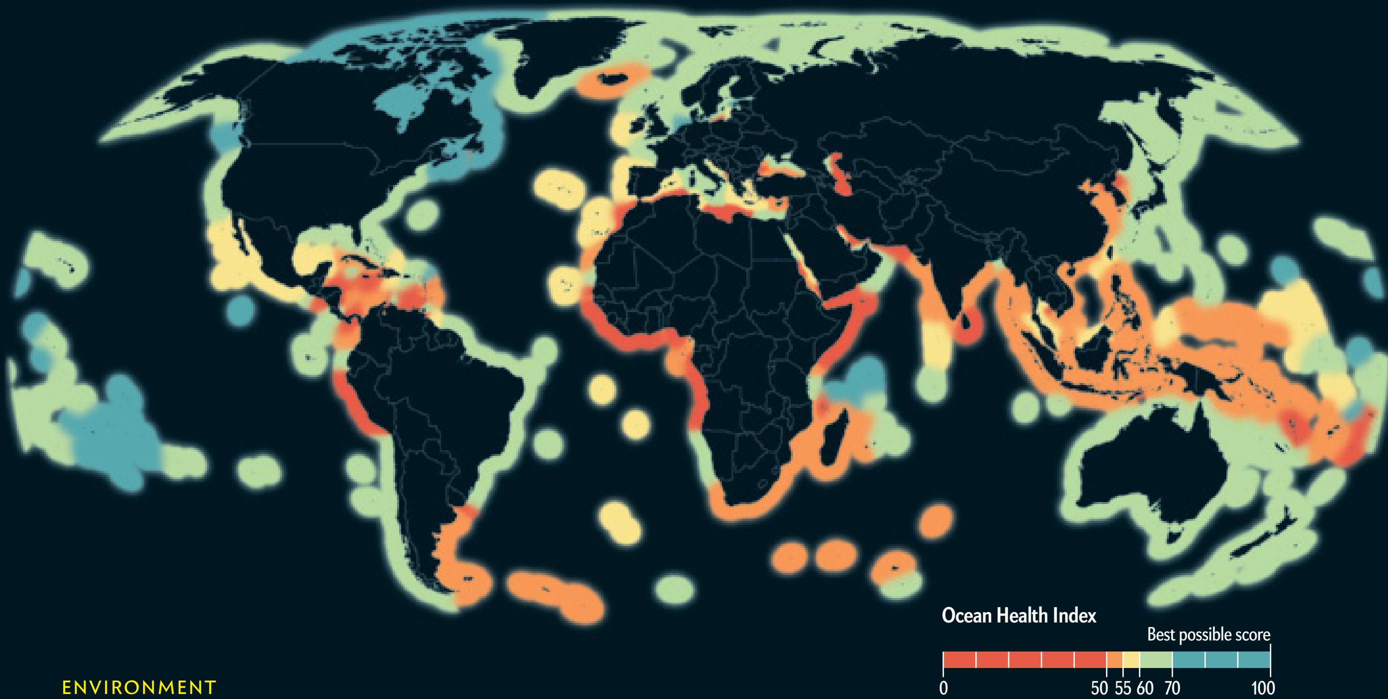
Illustration by Ross MacDonald

Dispatches from the frontiers of science, technology and medicine



ENVIRONMENT

How Healthy Is Your Ocean?

The first science-based assessment of the world's seas shows clean water but poor management

We regularly hear calls to improve "ocean health." Health is a powerful metaphor, but scientists have had no way to measure it and therefore no means to evaluate how the world's oceans are doing. More than 60 researchers from a cross section of disciplines and institutions, including the National Center for Ecological Analysis and Synthesis (NCEAS) at the University of California, Santa Barbara, have created the Ocean Health Index to do just that. It rates the health of ocean waters bordering 171 coastal countries and territories. Each nation's overall score is the average of scores for 10 widely held public goals for healthy oceans, including sustainable food provision, recreation, fishing opportunities and biodiversity.

The index, which was published in August in *Nature*, is not a measure of how pristine the ocean is. (*Scientific American* is part of Nature Publishing Group.) Instead it measures how sustainably the ocean is providing the things people care about. The goals are universal measures of ecosystem health—all 10 must be met for a country's ocean to be rated as healthy—but the relative importance of each goal can vary from place to place.

Factoring human goals into assessments of ocean health is a radical departure from traditional conservation approaches. Yet public policy and conservation organizations worldwide are rapidly converging on the view that people are now a fundamental part of every ecosystem on the earth, and any effective management strategy must embrace this reality. If we focus only on excluding people from nature, conservation plans are doomed to fail.

The index is an important first step. Countries cannot make progress on ocean health without first knowing where they stand. In that sense, the index is a key benchmark. Later this year the NCEAS and various partners will test its application in the U.S., Fiji and Brazil. Policy makers and managers could use the index to guide decision making—for example, about whether offshore wind energy should be expanded in the U.S., whether land or ocean conservation measures will benefit coral reefs in Fiji and how marine-zoning plans in Brazil might affect overall ocean health.

Of course, various people or adjacent countries might put different priorities on different goals. As a tool that lays them all out, the index can aid any negotiations by identifying trade-offs and synergies.

—*Benjamin S. Halpern*

Halpern is director of the Center for Marine Assessment and Planning at the University of California, Santa Barbara.

For a longer version of this story that addresses controversy over the index and for additional interactive graphics, go to ScientificAmerican.com/sep2012/ocean-health

SOURCE: NATIONAL CENTER FOR ECOLOGICAL ANALYSIS AND SYNTHESIS

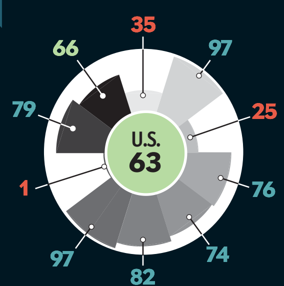
Map by XNR Productions, Graphics by Jen Christiansen

The world as a whole is preserving clean water and biodiversity but is poorly managing fisheries and tourism.

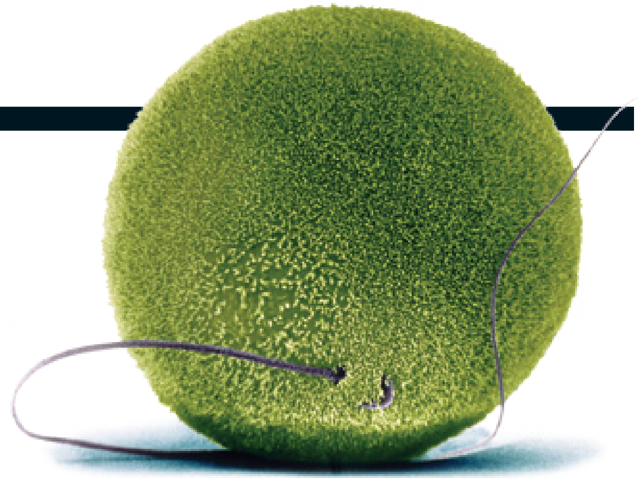
*Index score

Remote islands top the rankings, yet Germany is No. 5, having made substantial progress in meeting eight of its goals.

The U.S., at No. 27, is meeting most of its goals but lags in sustainably harvesting seafood and natural products.



The bottom five countries are in West Africa, gripped by poverty, political instability and an unsustainable use of resources.



NOW WHAT? A single sperm fertilizing an egg.

BIOLOGY

Ready, Set, Implant

Scientists are beginning to crack the other half of the fertilization equation

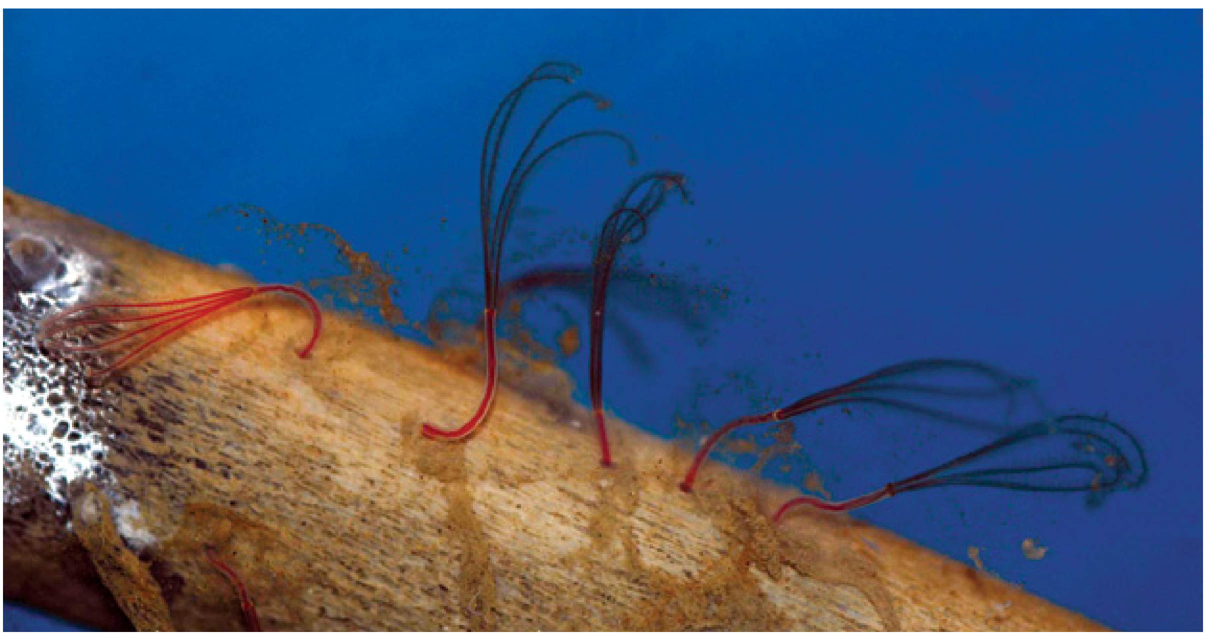
The increasing success of in vitro fertilization (IVF) has come mainly from advances in the way doctors grow and select embryos. When transferred into a woman's womb, however, only a minority of these embryos implant in the lining of the uterus, also known as the endometrium. "The reason," says Steven L. Young, professor of obstetrics and gynecology at the University of North Carolina at Chapel Hill, "lies primarily with an inability to evaluate if the endometrium is ready for the embryo." If it is not, embryos will not implant, much like good seed will not grow in bad soil.

Scientists know that the endometrium undergoes dramatic changes during the menstrual cycle and becomes receptive to embryo implantation during only a short period a few days after ovulation. They have yet to find a reliable way to figure out when and if a patient's uterus is ready to accept a hard-won embryo.

Ongoing studies are just starting to provide some answers. Linda Giudice and her colleagues at the University of California, San Francisco, have used genomic analysis to identify a group of genes that turn on and off at different phases of the menstrual cycle. Nicholas S. Macklon, professor of obstetrics and gynecology at the University of Southampton in England, has found that the protein content of endometrial fluid changes depending on whether it is in a receptive or nonreceptive stage. If validated in clinical trials, the finding might lead to the development of a laboratory test that could determine on the spot if a patient is ready for embryo transfer.

Such tests and treatments are still several years away. But just as the challenges ahead are great, so are the potential rewards. If researchers can determine the molecular processes that predict when an embryo can implant, Macklon notes, they may transform the diagnosis and treatment of infertility.

—*Oscar Berlanga*



WHAT IS IT?

Bone-eating worms: Scientists recently discovered how worms with no mouth wiggle their way through whale skeletons. The genus *Osedax*, seen here on a whale's rib at the bottom of Monterey Canyon off the California coast, releases acid through its roots, according to findings presented at the Society for Experimental Biology's annual meeting earlier this summer. "Understanding how *Osedax* uses acid to dissolve the bone matrix is the first step in understanding the nutrition of these animals," says Greg Rouse of the Scripps Institution of Oceanography, who is one of the researchers. Investigators first found the worms, living in and thriving off of whale carcasses, 10 years ago.

—*Ann Chin*

DAVID M. PHILLIPS *Photo Researchers, Inc.* (*top*); COURTESY OF GREG ROUSE *Scripps Institution of Oceanography* (*bottom*)

COMMENT AT ScientificAmerican.com/sep2012

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ADVANCES

PHYSICS

The Import of the Higgs Boson

Finding a new particle completes one puzzle and begins another

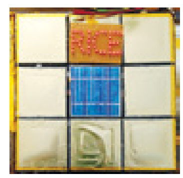
When physicists at CERN's Large Hadron Collider announced the discovery of a new particle on July 4, they did not call it "the Higgs boson." This was not just the typical caution of scientists. It also signified that the announcement comes at a profound moment. We are at the end of a decades-long theoretical, experimental and technological odyssey, as well as at the beginning of a new era in physics.

The search for this particle grew out of a single phrase in the 1964 paper by physicist Peter Higgs of the University of Edinburgh in Scotland. At the time, what we now call the Standard Model of particle physics, which describes all known elementary particles, was only just starting to coalesce. The Standard Model makes hundreds of testable predictions and, in the decades since its inception, has been proved right every time. The Higgs boson was the last remaining piece of the puzzle, tying together all the known particles of matter (fermions) and the carriers of the forces acting on them (bosons). It paints a compelling picture of how the subatomic world works, but we do not yet know if this picture is just part of a larger canvas.

ENGINEERING

Cover Charge

A new spray-on battery could convert any object into an electricity-storage device



COURTESY OF JEFF FITLOW *Rice University*

Perhaps someday you'll need to go to the store because you ran out of cathode paint. In June a team of researchers at Rice University and the Catholic University of Louvain in Belgium announced a new paint-on battery design. The advance, described in the online journal *Scientific Reports,* could change the way batteries are produced and eliminate restrictions on the surfaces used for energy storage.

The paint-on battery consists of five layers: a positive current collector, a cathode that attracts positively charged ions, an ion-conducting separator, an anode to attract negative ions and a negative current collector. For each layer, the challenge was to find a way to mix the electrically conductive material with various polymers to create a paint that could be sprayed onto surfaces one coat at a time.

To test their design, the researchers applied the battery paints on ceramic bathroom tiles, glass, a flexible transparency film, stainless steel and the side of a beer stein. They attached small circuits to the batteries to harness the electricity. In one experiment, they hooked a solar cell to one of the batteries and used solar power to light an LED display.

Paint-on batteries are not quite ready to hit the shelves at the local hardware store. For one, the electrolyte separator layer is not yet oxygen-stable. It would explode if it came into contact with air, so special conditions are necessary when creating the battery.

Neelam Singh, a member of the team at Rice, says the researchers are currently trying to make all the materials less reactive to air and moisture and more environmentally friendly. She adds that other groups are working on developing paint-on solar cells. These, Singh envisions, will be followed by "paintable solar cells on top of paintable solar batteries." Houses could become capture-and-storage devices for solar energy.

—Evelyn Lamb

Illustrations by Thomas Fuchs

The Standard Model is based in part on electroweak symmetry, which unites electromagnetism and the weak force. But the particles that carry those forces have very different masses, showing that the symmetry is broken. Theorists were left to explain the divergence of forces. In 1964 three separate papers—by Higgs, by François Englert and Robert Brout, and by Gerald Guralnik, Carl Hagen and Tom Kibble—in our journal, *Physical Review Letters,* showed that a ubiquitous quantum ocean called a spin-0 field could accomplish the symmetry breaking. Higgs mentioned that this ocean had waves that correspond to a new particle—the boson that came to bear his name.

This particle, key to the Standard Model, has been arguably the hardest to find—it required generations of ever bigger colliders to produce a sufficient number of sufficiently energetic collisions. Yet completing the Standard Model hardly closes the book on particle physics. The discovery of the Higgs may in fact point the way to what lies beyond the realm of this venerated theory.

Experimenters still need to verify that the new particle is a spin-0 Higgs boson. Next, they must test how the Higgs interacts with other particles to high precision. At this writing, its couplings do not quite match predictions, which could be just a statistical fluctuation or a sign of some deeper effect. Meanwhile experimenters have to keep taking data to see whether more than one Higgs boson exists.

These are important tests because theorists have constructed many hypothetical models that put the Standard Model in a broader framework, and many of these predict multiple bosons or deviations from the usual couplings. The models include extra fermions, extra bosons and even extra dimensions of space. The most studied broader framework is supersymmetry, which hypothesizes that each known fermion has an undiscovered partner boson and that each known boson has an undiscovered partner fermion. If supersymmetry is correct, there is not one Higgs boson but at least five. So we are just beginning to explore a new realm.

—*Robert Garisto and Abhishek Agarwal*

Garisto and Agarwal are editors for the physics journal Physical Review Letters.

STATISTICS

Not Worth the Risk?

For bank robbers, crime rarely pays

STICK 'EM UP: Notorious robbers Bonnie Parker and Clyde Barrow (Bonnie and Clyde) in 1932.

Aspiring bank robbers, take heed. Recent statistical analyses of confidential bank data suggest that mountains of riches aren't in your future but that a jail cell is.

"The return on an average bank robbery is, frankly, rubbish," wrote the authors of a June article about the economics of British bank robberies in *Significance,* a bimonthly statistics magazine published by the American Statistical Association and the Royal Statistical Society. To complete their research, economists Neil Rickman and Robert Witt of the University of Surrey and Barry Reilly of the University of Sussex spent months negotiating with the British Bankers' Association to obtain confidential records detailing 364 bank heists that occurred in the U.K. between 2005 and 2008. Such detailed data are not available in the U.S., where, in contrast, if banks even record them, they are lost in the anonymity of the FBI's quarterly reports on bank robberies.

The statistics reveal that the average British bank robbery is committed by 1.6 thieves and nets $31,900 per heist, with a standard deviation of $84,000. Assuming an equal share, the average take was $19,900 per robber per heist—roughly equivalent to a coffee shop barista's annual salary.

Wielding a gun increased the average haul by $16,100, as did adding more accomplices to a raid. Going alone, however, netted the average robber more money because the amount gained by increasing a heist party did not outpace the hit taken by splitting an individual robber's spoils.

The sums are not chump change, Rickman notes, but bank robbing is risky business. Roughly 33 percent of British bank heists end with no robber earning anything, and about 20 percent of raids end in capture. The odds of arrest get worse as a robber attempts more heists. On a robber's fourth heist, for example, the odds of capture compound to 59 percent. "Somehow I expected most bank robbers to be doing much better than what the data actually show," Rickman says.

Some would-be criminals do better than others. Economist Giovanni Mastrobuoni of the University of Turin's Carlo Alberto College in Italy takes issue with the article's lack of attention to the professionals, who presumably raked in most of the $11.6 million stolen from British banks between 2005 and 2008. The article suggests, for example, that fast-rising bulletproof screens in some banks reduce a robbery's success by one third. "But I'd argue that the dumb robbers target banks with fast screens, while professional ones scope out the place thoroughly before robbing," Mastrobuoni says. Rickman counters that information on professionals is even harder to come by because it requires access to confidential police and bank records. The new report, economists say, underscores the need for more and better data on bank heists. —*Dave Mosher*

REDUX PICTURES

FIELD NOTES

Meteor Hunt

An astronomer describes his search for meteor showers and hopes others will join in the fun

THEY CAME FROM SPACE: Jenniskens found these meteorites near Sutter's Mill, Calif., in April.

PROFILE

NAME
Peter Jenniskens

TITLE
Meteor astronomer, SETI Institute and NASA Ames Research Center

LOCATION
Mountain View, Calif.

Meteors are windows to our past and our future. When a stream of rocky material hits Earth's atmosphere and we observe what looks like shooting stars, that is called a meteor shower. The sand grains and pebbles of a meteor shower form a trail of crumbs to their body of origin: usually a comet, which is an icy leftover from the formation of our solar system. Meteor showers betray the presence of yet undiscovered comets that may one day strike us.

Only now are some of those comets being discovered in near-Earth object surveys. They periodically break, creating many of the meteor showers we see on Earth.

To map out those meteor showers, we are doing surveillance of the night sky. We use 60 video security cameras distributed over three locations. Those are at Lick Observatory, Fremont Peak Observatory and Sunnyvale, all near the San Francisco Bay Area. Instead of watching out for burglars, we look for meteors. Each meteor seen from two or three perspectives can be triangulated to measure its trajectory and speed in the atmosphere. Last year we measured 47,000. Showers are meteors arriving from the same direction. We have seen showers come into focus that I've never heard of before.

Just one was a bright fireball that penetrated deep enough in the atmosphere for something to have survived. These surviving space rocks that hit Earth are called meteorites.

My most exciting adventure hunting meteorites was in 2008. For the first time, a small asteroid was spotted in space heading right toward us. (An asteroid is like a comet but has lost its ice and some or all of its carbon compounds. It holds together better.) This object was about four meters in size. It entered over Sudan and broke into pieces. Most of them went to dust, but a few scraps survived. With students at the University of Khartoum, we searched the desert and ultimately found about 600 meteorites. To our surprise, it was a mixed bag of at least 10 different meteor types. This asteroid was a little world unto itself.

If you would like to participate in our meteor-shower surveillance, you can use a camera hooked up to your PC. You just have to find a friend who lives between 30 and 90 miles from your location so that you can triangulate the tracks. That project is online at http://cams.seti.org. There are meteors every night, and every night can bring you surprises, so keep your eyes open. *—As told to Marissa Fessenden*

COURTESY OF ERIC JAMES NASA *(left)*; COURTESY OF SETI INSTITUTE *(right)*

Best of the Blogs

BIOLOGY

Fish Swap Dinner for Sex

Unendowed males lure females with treats

The promise of a nice dinner might not always win over a woman, but for some male fish a tasty-looking lure seems to get the girl pretty reliably. The trick is to make sure the offering resembles the local cuisine, and then they can reel in the ladies, hook, line and sinker.

Swordtail characins (*Corynopoma riisei*) that live in the rivers of Trinidad feast mostly on hapless bugs that plop into the water from surrounding vegetation. In areas where streams flow mostly through forests, the characins' main fare is arboreal ants.

Characins are unusual in the fish world in that they rely on internal fertilization. For male characins, however, size is beside the point: they do not even have a penetrating organ. Still, they need to do their thing by somehow getting their genetic goods inside the female. How do they do it? The evolutionary answer turns out to be a fishing line and lure. Over the eons the male characins have developed a thin cord that extends from their gill area, on the end of which is an ornament of sorts. When a female bites onto this piece of flesh, she is in close enough range and a good position for the male to do the deed.

Yet how important is the appearance of a male's lure? A team of researchers, led by Niclas Kolm of Uppsala University in Sweden, found that ant-fed females were much more likely to get lured in by the male with the antlike ornament.

Does the female understand the game, or does she think she is just catching a meal and then is surprised to wind up with a mate? The researchers, who published their study online in July in *Current Biology*, admit that their findings "blur the distinction between female food preferences and female mate preferences." But characin dinner-dating strategies seem to work for both him and her.

These male fish are not the only ones that seem to use the promise of food to find a female, Kolm and his colleagues point out. Male orchid bees bathe themselves in the scent of flowers that females frequent for nectar. And male water mites have been documented vibrating their legs at a frequency similar to the vibrations made by the small copepods that the females eat. Food as a way to, um, you know, is perhaps even more entwined evolutionarily than we realize. *—Katherine Harmon*

Adapted from Observations at blogs.ScientificAmerican.com/observations

MATTHIAS BREITER *Minden Pictures*

CONSERVATION

Howdy, Neighbor

Cougars are returning to the U.S. Midwest

Cougars (*Puma concolor*) have not lived in Oklahoma, Missouri and other states around the Midwest since the beginning of the 20th century. Now the cats are returning to and repopulating some of their former Midwestern habitats, according to research published in June by the *Journal of Wildlife Management.*

Cougars once lived throughout most of the U.S. and Canada, but state-sponsored bounties put in place to protect livestock and humans from what were often deemed "undesirable predators" led to the cats' extermination in eastern North America and the Midwest. By the second half of the 20th century they were mostly restricted to states and provinces west of the Rocky Mountains.

Things started to turn around for the cougar in the 1960s and 1970s, when, one by one, states rescinded the bounties and made the animals a managed-game species. They have now been seen in Oklahoma, Missouri, Arkansas, Illinois and several other U.S. states and Canadian provinces in and around the Midwest, and the sightings are growing more frequent, according to the new paper.

The expansion has been driven by the cougars' solitary, territorial nature, explains the paper's lead author, Michelle LaRue, research fellow for the Polar Geospatial Center at the University of Minnesota. "When a female cougar has males, they have to disperse away from where they were born," she says, which prevents the males from inbreeding with their female relatives and helps them to avoid conflicts with older, more powerful males. LaRue and her fellow researchers examined 178 confirmed Midwestern cougar sightings from 1990 to 2008. These included carcasses, as well as scat and tracks, along with camera and video evidence. The number of confirmed sightings during this period increased steadily each year, from two animals in 1990 to 34 in 2008. By comparison, the total population of cougars in North America is estimated at around 30,000 animals. Of the 56 carcasses, 76 percent were male, typical of the gender's role as the primary dispersers of the species.

LaRue says this trend is probably just the beginning of cougars recolonizing the Midwest. "Now we can start asking more questions: Where are they going to end up, how many are they going to be and how are they going to interact with their ecosystems?" LaRue and her co-authors suggest that wildlife professionals begin to think "about public awareness campaigns in areas likely to encounter dispersing cougars" because people in these Midwestern states are not used to living with large predators. *—John R. Platt*

Adapted from the Extinction Countdown blog at blogs.ScientificAmerican.com/extinction-countdown

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AGRICULTURE

Chickpea Revolution

A better bean is boosting Ethiopia's economy

Ethiopia is an island of relative calm in a volatile region. Last year the U.S. Agency for International Development called for expanding Ethiopia's economy and increasing its crop yields as a way of bringing more stability to East Africa.

The agency focused on a key crop: the chickpea (*Cicer arietinum*), which is in high demand as an ingredient in hummus and in nutritional supplements for famine-stricken regions. It is also relatively sustainable to grow: it acts as a natural fertilizer by fixing nitrogen in the soil and demands less water than some other popular crops such as the cereal grass teff.

Ethiopia was already Africa's largest producer of chickpeas, but researchers wanted to develop seeds that could grow more efficiently. In August 2006 in the *Journal of Semi-Arid Tropical Agricultural Research,* scientists at the International Crop Research Institute for Semi-Arid Tropics (ICRISAT) identified favorable traits among more than 20,000 variations in the chickpea genetic code, allowing them to breed plants that mature more quickly and resist drought and disease. Rather than using biotechnological tools, scientists instead applied traditional crossbreeding techniques, which are effective yet more affordable. ICRISAT researchers are using the same techniques on other crops across the developing world. Tanzania, Sudan, Kenya, Myanmar (Burma) and India are all benefiting from better chickpeas, pigeon peas, groundnuts, pearl millet and sorghum.

The improved chickpea seeds have already made a difference: Ethiopia's chickpea harvest increased 15 percent between March 2010 and March 2012. Farmers sell whole, dried chickpeas to local markets, which sell them as snacks or grind them into flour, and an expanding export market buys the crop to supply a growing global demand for hummus. Last year PepsiCo, which co-owns hummus maker Sabra, partnered with USAID and the United Nations World Food Program to expand Ethiopian farmers' access to more productive seeds and to such sustainable agricultural practices as drip irrigation. Says Timothy Durgan of the development nonprofit ACDI/VOCA, which has been implementing USAID's agricultural efforts in Ethiopia: "Improved [farming] practices should enable Ethiopia to increase exports while adequately supplying local demand."

—*Aishwarya Nukala*

COMMENT AT ScientificAmerican.com/sep2012

FACT FINDER Information bits from the news

WOBBLE, WOBBLE

As Earth orbits the sun, it exerts a gravitational pull that makes the sun "wobble" to and fro at a rate of up to nine centimeters per second. This so-called radial velocity variation is what astronomers often measure to find exoplanets. Yet their instruments are only sensitive enough to turn up large exoplanets—some of them many times more massive than Jupiter—that can exert a tug of more than one meter per second. A group of researchers at Germany's Max Planck Institute for Quantum Optics has developed a calibration technique using a device called a laser-frequency comb to make radial velocity searches more sensitive. It will make it easier to find smaller, potentially Earth-like planets that may be hospitable to life. *—John Matson*

MEDICINE

Cholesterol Confusion

A protein may turn good cholesterol bad and bad cholesterol lethal

We have been hearing for years that high-density lipoprotein (HDL)—the "good cholesterol"—may not be all it's cracked up to be. Now a new study shows that a certain subclass of HDL may actually be "bad," increasing the risk of coronary heart disease.

A small protein may be to blame. HDL with a small proinflammatory protein called apolipoprotein C-III (apoC-III) on its surface may nearly double the risk of heart disease in healthy men and women, according to Frank Sacks, professor of cardiovascular disease prevention at the Harvard School of Public Health and senior author on a paper in the April *Journal of the American Heart Association.* Conversely, Sacks's study found, HDL without apoC-III may be especially heart-protective. A number of studies have shown that LDL (low-density lipoprotein)—the "bad cholesterol"—with apoC-III on its surface is particularly harmful, leading to higher incidence of plaque buildup in artery walls. Yet, Sacks says, this is the first large-scale prospective study with healthy subjects to show that apoC-III on HDL may have similar effects.

The scientists examined blood samples taken from 572 women in the Nurses' Health Study and from 699 men in the Health Professionals Follow-Up Study, two of the largest long-term investigations of factors that affect women's and men's health. Over 10 to 14 years of follow-up, they documented 634 cases of coronary heart disease, which they matched with control subjects for age, smoking status and the date blood was drawn. After adjusting for those and other lifestyle-based cardiovascular risk factors, they found a nearly twofold increase in risk for HDL with apoC-III. The men and women whose levels of HDL with apoC-III were in the top 20 percent had a 60 percent higher risk of developing heart disease than those in the bottom 20 percent.

Sacks says the techniques his team used to measure the levels of the two HDL subclasses, which Harvard is patenting, could lead to more precise tests to evaluate heart disease risk and treatment response. Moreover, the findings, if replicated in his and others' ongoing studies, could spur development of drugs that target HDL subclasses, working to raise HDL without apoC-III and lower HDL with it. "The bottom line is, there's a lot more to be learned about HDL and how it acts," says Nilesh Samani of the University of Leicester in England and co-author of a paper that found raising HDL levels might not change heart disease risk. *—Thea Singer*

PALEONTOLOGY

Tooth Sleuths

Ancient tartar shows our ancestors ate bark and some other surprising foods

PAY DIRT: Tartar on the teeth of *A. sediba*

A recent scientific discovery had researchers buzzing about, of all things, tartar. That's right, the crusty deposits that the dentist scrapes off your teeth when you go for a cleaning. Except in this case, it was the tartar on the teeth of the nearly two-million-year-old *Australopithecus sediba*, which has been held up as a candidate ancestor for our genus, *Homo*. No one had ever before found tartar in an early hominin (a creature on the line leading to humans, after the split from the line leading to chimpanzees). And in analyzing the ancient tartar, the researchers had recovered evidence of what *A. sediba* ate. It wasn't at all what they expected.

In a paper published in July in *Nature*, Amanda Henry of the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany, Lee Berger of the University of the Witwatersrand in Johannesburg and their colleagues report on tartar, tooth chemistry and wear-mark analyses conducted on an adult female and a subadult male found at a site just outside Johannesburg. Their tooth chemistry indicated that over their lifetime they dined mostly on trees and shrubs (or, possibly, animals that ate those foods). This is surprising because other hominins of similar antiquity relied more heavily on tropical grasses and sedges.

The tartar analysis yielded traces of plant foods no one thought our ancient kin ate, such as bark. Berger notes that many primates use bark as a fallback food during times when fruit is hard to come by. He has speculated that the hominins, whose remains were recovered from what was once a deep underground cave, may have ended up there because drought conditions drove them to try to access a pool of water inside. The bark finding could bolster that scenario.

Conventional wisdom holds that *Homo* adapted to changing environmental conditions that favored the spread of grasslands by incorporating meat into its diet. *A. sediba* has small teeth, which are associated with an increase in higher-quality foods such as meat, and dexterous hands that may have been capable of making tools. So did *A. sediba* eat meat? With the "type of data we are getting, I think we will reach answers to these questions," Berger says. —*Kate Wong*

COURTESY OF AMANDA HENRY *Max Planck Institute for Evolutionary Anthropology*

NEUROSCIENCE

I Think, Therefore I Spell

Brain-machine devices help the paralyzed communicate

Researchers are developing new ways to help the paralyzed communicate with their thoughts alone. Many of the new techniques rely on computers that analyze patients' brain activity and translate it into letters or other symbols. In a study published online in June in *Current Biology*, Bettina Sorger of Maastricht University in the Netherlands and her colleagues taught six healthy adults to answer questions by selecting letters on a computer screen with their thoughts.

While lying inside a functional magnetic resonance imaging scanner, which measures changes in blood flow in the brain, volunteers stared at a screen displaying a table containing the 26 letters of the alphabet and a space bar. Each of three rows of letters was paired with one of three mental tasks: a motor imagery task, such as tracing flowers in one's mind; a mental calculation task; and an inner speech task, during which patients silently recited a poem or prayer. Different blocks of letters were highlighted on the screen at different times. To choose a particular letter, participants waited for the screen to highlight that letter and performed the mental task associated with that letter's row for as long as the letter was selected. The computer program, which could not read the volunteers' thoughts but could distinguish among the different kinds of brain activity, achieved an 82 percent accuracy rate.

Although Sorger's study is only a proof of concept, the new program is a promising complement to a growing collection of similar technologies. Niels Birbaumer of the University of Tübingen in Germany has created a "thought translation device" that allows paralyzed patients to spell words and choose pictograms using electroencephalography—a net of electrodes placed on the scalp. John Donoghue of Brown University and his colleagues taught one paralyzed man to open e-mail and play Pong by moving a cursor with his mind.

Researchers have also created brain-computer interfaces that allow paralyzed patients to type one or two words a minute on a screen with their thoughts as well as devices that convert thoughts into vowel sounds spoken by a voice synthesizer. One advantage of Sorger's device is that it would work for patients whose skulls are severely damaged. "Even if one person benefits, I would be very happy," she says. —*Ferris Jabr*

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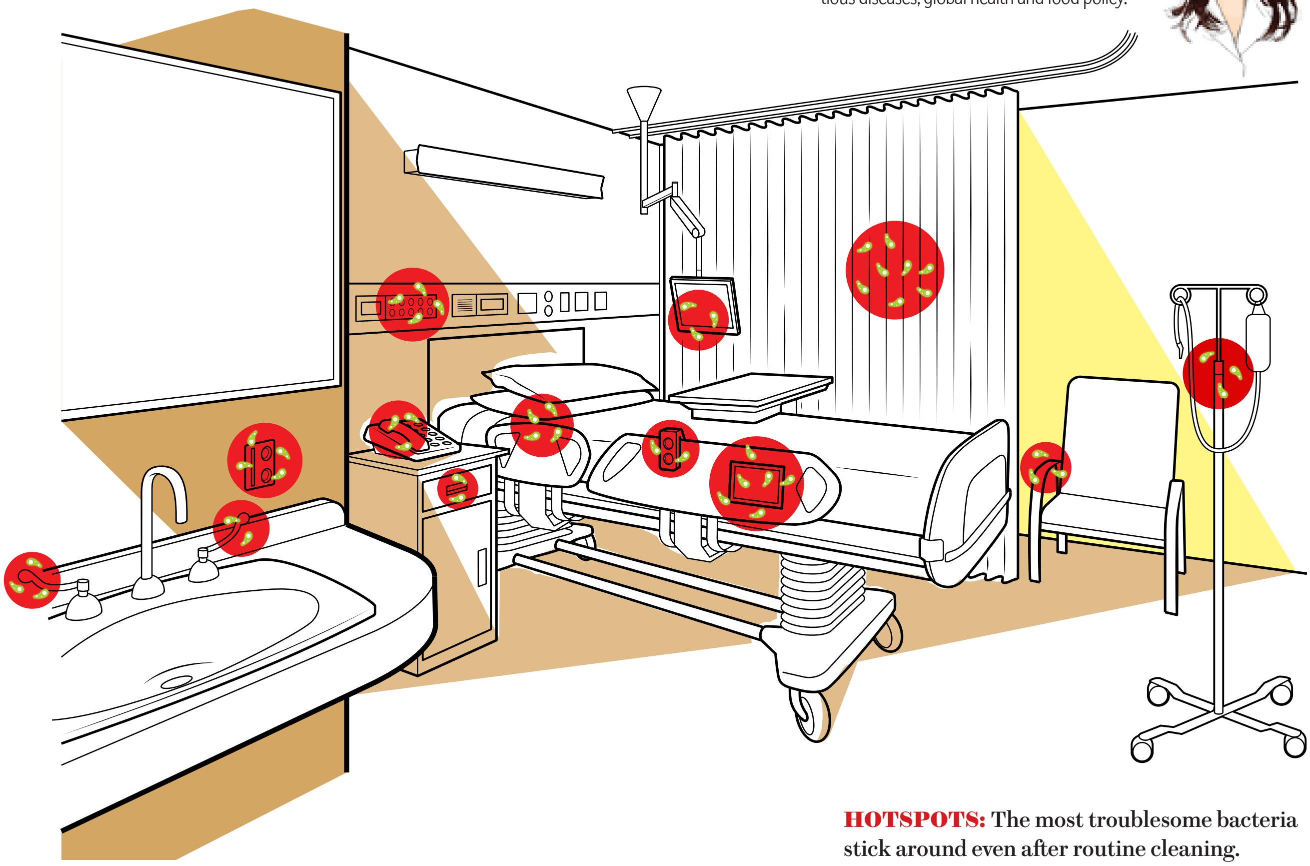
Maryn McKenna is the author of two books on public health and a senior fellow at the Schuster Institute for Investigative Journalism at Brandeis University. She writes about infectious diseases, global health and food policy.



HOTSPOTS: The most troublesome bacteria stick around even after routine cleaning.

Clean Sweep

Hospitals bring janitors to the front lines of infection control

When hospitals want to make a name for themselves, they spend on reputations and technology—on the esteemed surgeon or the top-of-the-line gamma knife and the star radiologist to operate it. Such investments attract publicity as well as patients seeking the best available health care. Lately, though, some hospitals have been making an unexpected discovery. The kinds of expenditures that truly improve patient care are often not directed at the top of their pay scale, with the famous specialists, but rather at the bottom, with the anonymous janitors.

Hospitals have reached this realization while trying to cope with an alarming trend. Over the past decade the organisms that cause most infections in hospitalized patients have become more difficult to treat. One reason is increasing drug resistance; some infections now respond to only one or two drugs in the vast armamentarium of antibiotics. But the problem also arises because the cast of organisms has changed.

Just a few years ago the poster bug for nasty bacteria that attack patients in hospitals was MRSA, or methicillin-resistant *Staphylococcus aureus*. Because MRSA clings to the skin, the chief strategy for limiting its spread was thorough hand washing. Now, however, the most dangerous bacteria are the ones that survive on inorganic surfaces such as keyboards, bed rails and privacy curtains. To get rid of these germs, hospitals must rely on the staff members who know every nook and cranny in each room, as well as which cleaning products contain which chemical compounds.

"Hand hygiene is very, very important," says Michael Phillips, a hospital epidemiologist at New York University Langone Medical Center who has been studying this problem. "But we are coming to understand that it is one of just several important interventions necessary to break the chain of infection that threatens our patients."

PERSISTENT PESTS

THE INFECTIOUS ORGANISMS that require all this extra effort became a serious problem around 10 years ago. The first outbreaks were caused by vancomycin-resistant *Enterococcus,* or VRE, and *Clostridium difficile,* known as *C. diff,* followed by a group of bacteria collectively referred to as highly resistant gram-negative organisms: *Escherichia coli, Klebsiella, Pseudomonas* and *Acinetobacter.*

This varied lot enters hospital rooms via multiple avenues. *Acinetobacter* and *Pseudomonas* prefer to live in the soil and

Illustration by MCKIBILLO

water, but they are carried into hospitals from the outside world on people's shoes and clothes. In contrast, VRE, *E. coli, Klebsiella* and *C. diff* thrive inside human beings. These bacteria enter hospitals in patients' intestines and escape when bedbound patients suffer from diarrhea, contaminating the air and equipment around them.

The new scourges are particularly tough to clear away for several reasons. The gram negatives, for instance, have a double wall that gives them extra defenses against antibiotics and shields them from damage by other compounds, including cleaning chemicals. Many of the bugs can survive in low-nutrient environments, such as glass, plastic, metal and other materials that make up a hospital room. Consider VRE. One strain that caused an outbreak at the University Medical Center Utrecht in the Netherlands grew in a lab dish for 1,400 days after being dried in a test that mimicked what might happen in a patient's room. (MRSA also survives on surfaces, but for much shorter duration.)

Because of such abilities, the latest bacterial threats create an infection risk at least as great as health care workers' contaminated hands. "It forces us to raise the cleanliness of the hospital as a clinical issue, just as washing our hands is a clinical issue," says Cliff McDonald, a medical epidemiologist at the U.S. Centers for Disease Control and Prevention.

Within hospitals, these resistant, hardy organisms are ubiquitous. A review article last year found that 10 percent of hard and soft surfaces in hospital rooms may be contaminated with gram-negative bacteria and that 15 percent of them may be contaminated with *C. diff.* A study at the University of Iowa Carver College of Medicine, published online in April, demonstrated the potential infection risk posed by the privacy curtains around hospital beds. In an initial survey, 95 percent of curtains in 30 rooms harbored VRE or MRSA. When the curtains were replaced, 92 percent became recontaminated within a week.

OPERATION CLEAN TEAM

RECENTLY HOSPITAL CLEANLINESS has become a matter of reputation, especially since the federal government's Hospital Compare Web site started posting institutions' rates of health care–associated infections. Cleanliness is also becoming a bottom-line issue: in 2008 the federal Centers for Medicare and Medicaid Services ceased reimbursing hospitals for the treatment of any infections that those hospitals caused—a controversial carrot-and-stick venture that, according to new research, has successfully begun to lower infection rates.

Institutions also employ infection-control specialists, who track infections and investigate their causes. Yet when the problem is bacteria on surfaces, eliminating them depends on the building-services crews. "This is the level in the hospital hierarchy where you have the least investment, the least status and the least respect," says Jan Patterson, president of the Society for Healthcare Epidemiology of America. Traditionally, medical centers regard janitors as disposable workers—hard to train because their first language may not be English and not worth training because they may not stay long in their jobs.

At N.Y.U. Langone in 2010, Phillips and his co-workers launched a pilot project that redefined those formerly disposable workers as critical partners in patient protection. Janitors, they realized, know better than anyone else which rails are touched most frequently and which handles are hardest to clean. The Langone "clean team" paired janitors with infection-control specialists and nurses in five acute care units to ensure that all high-touch surfaces were thoroughly sanitized. In its first six months the project scored so high on key measures—reducing the occurrence of *C. diff* infections and the consumption of last-resort antibiotics—that the hospital's administration agreed to make the experiment routine procedure throughout the facility. It now employs enough clean teams to assign them to every acute care bed in the hospital.

SHIELDED SURFACES

EVEN THE MOST AGGRESSIVE disinfecting regimen might miss something, though. Thus, some researchers are tackling a once unheard of goal: rooms that clean themselves. Most of their early work focuses on engineered coatings and textiles that rebuff infectious organisms or kill them.

A company called Sharklet Technologies imprints the surface of catheters with a pattern that mimics the scaly texture of sharkskin, an innovation inspired by the realization that sharks, unlike whales, do not develop encrustations of algae. In the company's peer-reviewed research, the engineered surface makes it difficult for bacteria to cling and multiply.

Other projects capitalize on the long-recognized antiseptic properties of precious metals, chiefly silver and copper. Metal ions seem to interfere with crucial proteins within bacterial cells. Those results are similar to the effect of some antibiotics, but the metals, unlike drugs, do not provoke resistance.

Research by the company EOS Surfaces shows that bacteria in patients' rooms cannot survive on wall panels sheathed in copper, and a study funded by the Department of Defense at three hospitals, including Memorial Sloan-Kettering Cancer Center in New York City, demonstrated an association between copper-coated "high touch" surfaces in rooms—the call button, intravenous pole and bed rails, among others—and lower infection rates. PurThread Technologies is developing a proprietary alloy of copper and silver, which it melts into polyester and spins into yarn that is eventually woven into textiles ranging from sheets to scrubs.

Infection-prevention specialists think these efforts are promising but still preliminary. Most have not been tested in randomized clinical trials that could record whether the engineered surfaces were solely responsible for reducing patient infections.

"They need a lot more work, but I do think they will be a part of the solution," says Eli Perencevich, an infection-control specialist at the University of Iowa and interim director of the Center for Comprehensive Access and Delivery Research and Evaluation at the Department of Veterans Affairs, who consults for PurThread. Yet, he adds, they will be one additional weapon against infections, not a replacement for other strategies: "We can never let go of making sure that surfaces are cleaned and that health care workers wear gloves and wash their hands." SA

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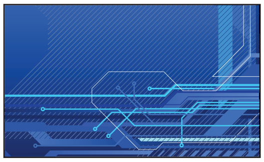


NANOSCIENCE

Chris Sorensen, Ph.D.

Fire, Fractals and the Divine Proportion

Physicist Chris Sorenson discusses the mysteries, beauties, and curiosities of soot. Take an unlikely journey of discovery of soot to find fractal structures with non-Euclidian dimensionality, networks that tenuously span space and commonalities among spirals, sunflowers and soot. Gain an appreciation for the unity of Nature, and the profound lessons in the commonplace as well as the sublime through soot!

Light Scattering

Take a *particle* physics perspective and ask: how do particles scatter light and why does light scatter in the first place? What are the effects of scattering on the polarization? How do rainbows, glories and sundogs work? How do light scattering and absorption effect the environment? Get the latest on scattering and see your universe in a new light.

Nanoparticles: The Technology.

Nanoscience has spawned a significant nanotechnology. Explore new nanomaterials such as self cleaning surfaces and fibers stronger yet lighter than steel. Then we'll do some informed daydreaming about far reaching possibilities like nanobots that could take a "fantastic voyage" inside your body or stealth materials for the invisible man. Enjoy reality science fiction at its best!

Nanoparticles: The Science.

What makes "nano" so special? Why does nano hold such great promise? Take a look at the clever chemistry that creates the nanoparticle building blocks of the new nanomaterials. Find out why physical properties of nanoparticles differ from larger particles. When this session is over, you'll understand why small can be better.

ASTROBIOLOGY

Speaker: Seth Shostak, Ph.D.

Hunting for Life Beyond Earth

Is Earth the only planet to sport life? Researchers are hot on the trail of biology beyond Earth, and there's good reason to think that we might find it within a decade or two. How will we find alien biology, and what would it mean to learn that life is not a miracle, but as common as cheap motels?

Finding E.T.

Life might be commonplace, but what about intelligent life? What's being done to find our cosmic confreres, and what are the chances we'll discover them soon? While most people expect that the cosmos is populated with anthropomorphic aliens aka "little gray guys with large eyes and no hair" you'll hear that the truth could be enormously different.

What Happens If We Find the Aliens?

One-third of the public believes that aliens are visiting Earth, pirouetting across the skies in their saucers. Few scientists agree, but researchers may soon discover intelligent beings sharing our part of the galaxy. Could we handle the news? What facts could be gleaned

immediately, and what would be the long-term effects such a discovery would have on us and our institutions, such as religion?

The Entire History of the Universe

Where and when did the cosmos begin, and what's our deep, deep future? The book of Genesis gives only a short description of the birth of the cosmos, but modern science can tell a more complex tale. How did the universe get started, and could there be other universes? And how does it all end, or does it end at all?

SKEPTICISM

Speaker: Michael Shermer, Ph.D.

The Believing Brain: From Ghosts and Gods to Politics and Conspiracies — How We Construct Beliefs and Reinforce Them as Truths

The brain as a "belief engine"? Learn how our brains' pattern-recognition and confirmation bias help form and reinforce beliefs. Dr. Shermer provides real-world examples of the process from politics, economics, and religion to conspiracy theories, the supernatural, and the paranormal. This discussion will leave you confident that science is the best tool to determine whether beliefs match reality.

Skepticism 101: How to Think Like a Scientist

Harvest decades of insights for skeptical thinking and brush up on critical analysis skills in a lively session that addresses the most mysterious, controversial, and contentious issues in science and skepticism. Learn how to think scientifically and skeptically. You'll see how to be open-minded enough to accept new ideas without being *too* open-minded.

The Science of Good and Evil: The Origins of Morality and How to be Good Without God

Tackle two challenging questions of our age with Michael Shermer: (1) The origins of morality and (2) the foundations of ethics. Dr. Shermer peels back the inner layers covering our core being to reveal complex human motives — good and evil. Gain an understanding of the evolutionary and cultural underpinnings of morality and ethics and how these motives came into being.

The Mind of the Market: Compassionate Apes, Competitive Humans, and Other Lessons from Evolutionary Economics

How did we evolve from ancient hunter-gatherers to modern consumer-traders? Why are people so irrational when it comes to money and business? Michael Shermer argues that evolution provides an answer to both of these questions through the new science of evolutionary economics. Learn how evolution and economics are both examples of complex adaptive systems. Get your evolutionary economics tools together.

SCIENTIFIC AMERICAN Travel HIGHLIGHTS

IGUAZU FALLS

March 5–7, 2013 — Surround yourself with 260 degrees of 240 foot-high walls of water at Iguazu Falls. Straddling the Argentinian-Brazilian border, Iguazu Falls is split into about 270 discrete falls and at peak flow has a surface area of 1.3 million square feet. (By comparison, Niagara Falls has a surface area of under 600,000 square feet.) Iguazu is famous for its panoramic views and breath-taking vistas of huge sprays of water, lush rainforest, and diverse wildlife.

You'll walk Iguazu National Park's extensive and well-engineered circuit paths over the Falls, go on a boat ride under the Falls, be bowled over by the massiveness and eco-beauty, and take a bazillion pictures.

MACHU PICCHU

February 15–20, 2013 — Scale the Andes and absorb Machu Picchu's aura. Visit this legendary site of the Inca World, draped over the Eastern slopes of the Peruvian, wrapped in mystery. Whether it was an estate for the Inca emperor Pachacuti or a site for astronomical calculations, it captures the imagination. Visit Machu Picchu, and see for yourself the massive polished dry-stone structures, the Intihuatana ("Hitching Post of the Sun"), the Temple of the Sun, and the Room of the Three Windows. Iconic ruins, rich flora and fauna, and incomparable views await your eye (and your lens).

EASTER ISLAND

Febrruary 16–20, 2013 — The moai of Easter Island linger in many a mind's eye, monumental statues gazing inland, away from the South Pacific. Join Bright Horizons on a four-day pre-cruise excursion to explore the mysteries of Rapa Nui. Visit archaeological sites, learn about the complex cultural and natural history of the island, and absorb the ambiance of one of the most remote communities on Earth. Come along on an adventure where archaeology and environment create memories and food for thought.

GALAPAGOS

February 12–20, 2013 — Enter an unearthly natural world in an eight-day pre-cruise excursion to the Galapagos Islands. "See the world in a grain of sand" and hone your knowledge of evolution with your observations in the Galapagos, a self-contained natural history laboratory. We'll tour Santiago, Chile, and straddle the Equator at the "Middle of the World" complex in Quito, Ecuador. Then off to the Galapagos for a four-day expedition on the mv Galapagos Legend. Accompanied by certified naturalists see the incredibly diverse flora and fauna up close. You'll have the opportunity to swim and snorkel, and photograph legendary wildlife and wild landscapes. Join Bright Horizons in the Galapagos for all the intangibles that communing with nature provides.

Are you restless? Seeking new science horizons? Slake your thirst for knowledge, Viking style, on Bright Horizons 17 cruise conference aboard Celebrity Cruises' Infinity, sailing roundtrip from Harwich, England to the Norwegian fjords, July 5–15, 2013. Pack your curiosity and join a floating community of keen minds and quick wits voyaging into a landscape of epic beauty.

Top off your reservoir of knowledge about chemical bonds. Venture into the weird, weird world of quantum mechanics. Go deep into the neurobiology of stress and aggression. Marvel at the Vikings' ingenuity and adaptation. As we travel, you can visit the UNESCO World Heritage sites of Geiranger Fjord and Bryggen, enjoy scenic and noteworthy rail trips and view glaciers and waterfalls.

Powered by the midnight sun, immerse yourself in essential Norway. Bring a friend and relax amidst scenic beauty from sky to fjord. Refresh the spirit, share downtime with near and dear, savor Nordic cuisine. Absorb new views and innovative thinking from the experts while enjoying the delights of Scandinavia. Join the fun on Bright Horizons 17. Visit www.InsightCruises.com/SciAm-17, contact concierge@insightcruises.com, or call (650) 787-5665.

Cruise prices vary from $1,569 for an Interior Stateroom to $7,499 for a Royal Suite, per person. For those attending our Program, there is a $1,475 fee. Port charges are $235. Government taxes and an Insight Cruises service fee are $215 per person. Gratuities are $150 per person. Program subject to change.

Neurobiology

Speaker: Robert Sapolsky, Ph.D.

The Biology of Memory

Consider the biology of memory. We'll start with the neurobiology of different types of memory, from the pertinent regions of the brain down to the pertinent molecules and genes. Learn about memory's impressive features, wild inaccuracies, and failings in neurological diseases. Examine individual differences in memory skills and find out how to improve your own memory capacity.

Sushi and Middle Age

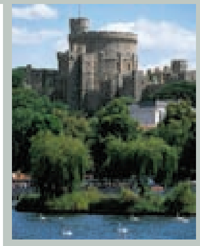
When was the last time you tried a really different, strange type of food, explored the work of a new composer, or made a substantial change in appearance? As we age, we get less interested in novelty and increasingly crave the familiar. Examine the neurobiology and psychology underlying this age-related effect.

Humans: Are We Just Another Primate? Are We Just a Bunch of Neurons?

Dr. Sapolsky does neurobiology research both in the lab and in East Africa on wild baboons. In this talk, he'll consider human nature from these two perspectives. Are we just another primate on a continuum with all the others, or are we intrinsically special? Find out a biologist's answer.

The Biology of Aggression and Violence

The biology of violence is one of the most complicated subjects in behavioral biology for the single fact that humans don't hate violence, just violence in the wrong context. Looking at neurobiology, us/them dichotomies, hormones, evolutionary biology, and game theory, put the phenomenon of violence in a scientific context.



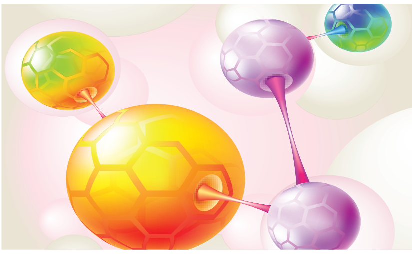
Hampton Court and Windsor Castle (July 2)

Join us visiting two timeless treasures in a day designed to bring British history to life. Enhance your knowledge of Britain's history with an idyllic day trip to Windsor Castle (left) and Hampton Court Palace. They are related yet differing demonstrations of British monarchy, nationhood and domesticity.

It's good to be Queen, and the evidence is all about you at 1,000-year-old Windsor Castle. Rubens, Rembrandt, and a remarkable collection of fine art envelope you in history. Go behind the scenes at the legendary seat of the House of Windsor.

Hampton Court (also known as King Henry VIII's summer palace) is a place of royal passions and competing interests. Pomp and consequence, subterfuge and service inform the history of the palace. Our visit will put the juxtaposed Tudor and Baroque architecture, larger than life personalities, exquisite Chapel Royal, and magnificent gardens in historical context for you.

For more info please call 650-787-5665 or log on to ScientificAmerican.com/Travel



Chemistry

Speaker: Robert Hazen, Ph.D.

Genesis: The Scientific Quest for Life's Origins — Is life's origin an inevitable process throughout the cosmos, or is it an improbable accident, restricted to a few planets (or only one)? How does a lifeless geochemical world of oceans, atmosphere and rocks transform into a living planet? Find out how scientists use experimental and theoretical frameworks to deduce the origin of life.

The Diamond Makers
Diamond forms deep in Earth when carbon experiences searing heat and crushing pressure. Decades ago General Electric scientists learned how to mimic those extreme conditions of Earth's interior in the laboratory to make synthetic diamonds. Learn the human drama and technological advances involved in producing this coveted gem and industrial tool from carbon-rich substances.

The Story of Earth: How the Geosphere and Biosphere Co-evolved
Earth is a planet of frequent, extravagant change. Its near-surface environment has transformed over and over again across 4.5 billion years of history. Learn about the work of Dr. Hazen and colleagues that suggests that Earth's living and nonliving spheres have co-evolved over the past four billion years.

Chemical Bonding — The solid, liquid, and gaseous materials around us depend on the specific elements involved and the chemical bonds that hold those atoms together. By looking at the nature and significance of ionic, metallic and covalent bonds you'll gain a new understanding of the workings of the world around you.

Quantum Physics

Speaker: Benjamin Schumacher, Ph.D.

Private Lives of Quantum Particles
Quantum systems can exhibit all sorts of bizarre behavior. But many of these phenomena can only be observed under conditions of the strictest privacy, where systems are "informationally isolated" from the world. These are not accidental features of quantum theory. They are inescapable facts about the microscopic world: Quantum physics is what happens when nobody is looking.

2π Is Not Zero (But 4π Is) — If you rotate any geometrical shape by 360 degrees (2π radians) about any axis, you will end up with exactly the same shape. But this fact, seemingly obvious, is not true for quantum particles with spin. Learn how a rotation by 2π makes a big difference, and how it all comes down to a simple minus sign — probably the most important minus sign in all of physics. Enjoy quantum fun, demystified by Dr. Schumacher.

The Physics of Impossible Things
Physicists find it surprising useful to ponder the impossible. Using the laws of nature, assess the possibility of science fiction's favorite phenomena and explore seemingly impossible things, which while odd, are possible. Venture into the study of impossible things and come away with an affirmation of the consistent logic of nature, and renewed wonder at real phenomena.

The Force That Isn't a Force — What makes a rubber band elastic? Its entropy, the microscopic disorder of its molecules. Now, entropy may provide a clue to the most familiar and mysterious of the basic forces of nature: gravity. Explore the link between entropy and gravity, and gain fascinating and unexpected insights of contemporary theoretical physics.

Archaeology

Speaker: Kenneth Harl, Ph.D.

From Old Europe to Roman Provinces
Explore the prehistoric foundations of Scandinavia and the Viking Age from ca. 3000 B.C. to 400 A.D. From Megalithic cultures to the arrival of Indo-Europeans, to Northern Bronze Age innovations and Celtic and Roman contributions, learn the unique environmental, cultural, and social factors that create a context for the Vikings.

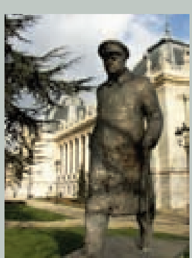
Great Halls and Market Towns in Viking Age Scandinavia — Using archaeological and literary sources (especially saga and Eddas), learn how the "great halls" emerged as the main focus of Scandinavia civilization. Find out how the development of towns facilitated trade and were vital for the transformation and technological advance of Scandinavian society.

Ships and Ship Building in the Viking Age — European history records the effectiveness of the fearsome Viking longship; find out the features and technologies that made it so. Based on archaeological finds, learn about the multi-millennial evolution of the longship, from linden to oak, dugout to mast and sail. Gain an appreciation for the form and function, as well as the wider implications of Norse naval mastery for three hundred years.

Warfare in the Viking Age — The Viking's applied technologies led to three centuries of robust military and economic power for Scandinavia. Discover what factors made the Vikings accomplished warriors and learn what archaeological finds tell us about Viking exploration, settlement, and development of kingdoms.

SCIENTIFIC AMERICAN Travel HIGHLIGHTS

NORWEGIAN FJORDS
JULY 5–15, 2013

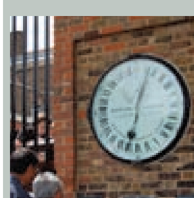


The Royal Observatory and the Churchill War Room/Museum (July 4)

Take the road less traveled in London, visiting two less well known gems of the City, both uniquely fascinating and inspiring.

Courage, duty, shared sacrifice, and conviction are the foundation of the Churchill Cabinet War Rooms. Hidden in plain sight in the heart of London, a scant 600 miles from Berlin. Step back in time and discover how Churchill and Britain's government functioned in secrecy in these quarters, from the Blitz to VE Day. The furnishings, maps, and ephemera are as they were on VE day, May 8, 1945. Hear the stories and imagine life under bombardment in the simple and inspiring environment of the Cabinet War Rooms.

Are you the precise type? Are you a fan of Google maps or GPS? Or Cutty Sark? Join us on a tour of maritime Greenwich, where our prime objective is visiting the Royal Observatory, Greenwich, home of the Prime Meridian of the World and Greenwich Mean Time. Stroll a deeply historic corner of London significant in local, national, and international culture. See the Royal Observatory, the National Maritime Museum, the tea clipper Cutty Sark, and the Royal Naval College. Master the lingo of time — UT0, UT1, UTC, and GMT. Stand astride two hemispheres on the Prime Meridian, a moment sure to be recorded on your timeline.



Stonehenge and Bath (July 3)

Pass a day on the Salisbury Plains and Somerset Hills, absorbing the history of two spots with ancient cultural roots.

Mute, mysterious, and megalithic, Stonehenge calls to us across the millennia. We'll respond, and walk the site in its details. Learn the significant geography, the archaeological and astronomical background, and the key stone names. But those are just the facts — the memories and true meaning of Stonehenge will be up to you.

Bath beckons the seasoned traveler. People are drawn to Bath to see its honey-colored Bath limestone buildings, and to explore its 2,000 year history as a place of relaxation and restoration. Plumb the details and nuances of Bath's fusion of architecture, culture, and history in a city with many echoes of and homages to the ancient world, while embodying the Georgian worldview.

For more info please call 650-787-5665 or log on to ScientificAmerican.com/Travel

David Pogue is the personal-technology columnist for the *New York Times* and host of *NOVA scienceNOW,* whose new season premieres in October on PBS.

Hollywood Killed the Video Star

The death of the DVD is pushing users to piracy

Face it, movie fans: the DVD is destined to be dead as a doornail.

Only a few Blockbuster stores are still open. Netflix's CEO says, "We expect DVD subscribers to decline steadily every quarter, forever." The latest laptops don't even come with DVD slots. So where are film enthusiasts suppose to rent their flicks? Online, of course.

There are still some downsides to streaming movies—you need a fast Internet connection, for example, and beware the limited-data plan—but overall, this should be a delightful development.

Streaming movies offers instant gratification: no waiting, no driving—plus great portability: you can watch on gadgets too small for a DVD drive, like phones, tablets and superthin laptops.

Hollywood movie studios should benefit, too. The easier it is to rent a movie, the more people will do it. And the more folks rent, the more money the studios make.

Well, apparently, none of that has occurred to the movie industry. It seems intent on leaving money on the table.

For all of the apparent convenience of renting a movie via the Web, there are a surprising number of drawbacks. For example, when you rent the digital version, you often have only 24 hours to finish watching it, which makes no sense. Do these companies really expect us to rent the same movie again tomorrow night if we can't finish it tonight? In the DVD days, a Blockbuster rental was three days. Why should online rentals be any different?

When you rent online, you don't get any of the DVD extras—deleted scenes, alternative endings, subtitles—even though you're paying as much as you would have paid to rent a DVD.

Yet perhaps most important, there's the availability problem. New movies aren't available online until months after they are finished in the theaters, thanks to the "windowing" system—a long-established obligation that makes each movie available, say, first to hotels, then to pay-per-view systems, then to HBO and, only after that, to you for online rental.

Worse, some movies never become available. *Star Wars, Raiders of the Lost Ark, Jurassic Park, A Beautiful Mind, Bridget Jones's Diary, Saving Private Ryan, Meet the Fockers,* and so on, are not available to rent from the major online distributors.

None of the movie studios would talk to me on the record about this subject, so I can't tell you why so many major movies are missing. Obviously somebody, somewhere, objects to releasing the rights—a lawyer, a director, a studio executive. (Disney's Web site answers the question this way: "Unfortunately, it is not possible to release or have all our titles in the market at once." Oh, okay. So they're not available because they're not available.)

The people want movies. None of Hollywood's baffling legal constructs will stop the demand. The studios are trying to prevent a dam from bursting by putting up a picket fence.

And if you don't make your product available legally, guess what? The people will get it illegally. Traffic to illegal download sites has more than sextupled since 2009, and file downloading is expected to grow about 23 percent annually until 2015. Why? Of the 10 most pirated movies of 2011, guess how many of them are available to rent online, as I write this in midsummer 2012? Zero. That's right: Hollywood is actually encouraging the very practice they claim to be fighting (with new laws, for example).

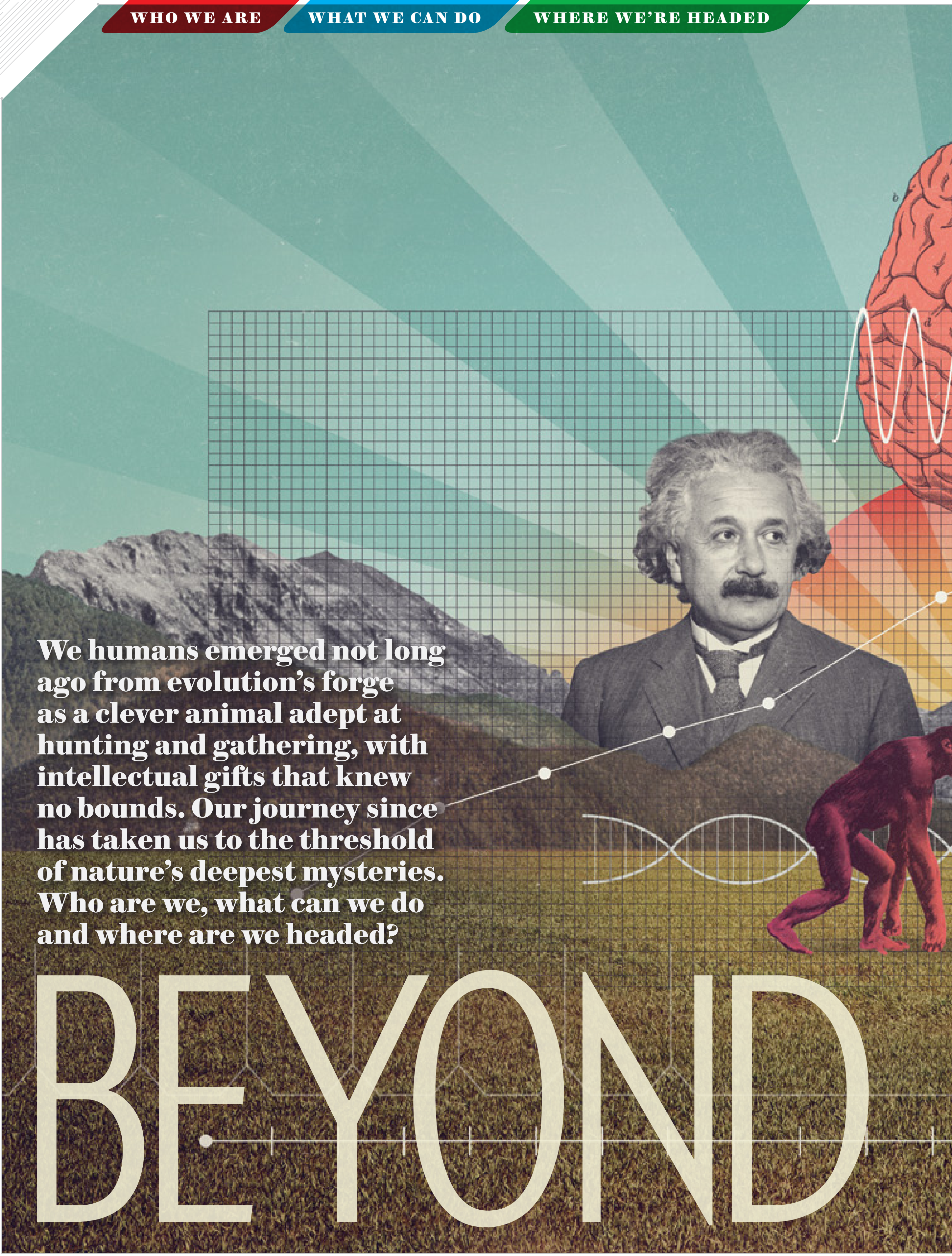
Yes, times are changing. Yes, uncertainty is scary. But Hollywood has case studies to learn from. The music industry and the television industry used to fight the Internet the same way—with brute force: copy protection, complexity, legal challenges.

Eventually all of them found roads to recoup some of their lost profit not by fighting the Internet but by working with it. The music industry dropped copy protection and made almost every song available for about $1 each. The TV industry made its shows available for free at sites such as Hulu, paid for by ads.

The moral? Make your wares available legally, cleanly and at a fair price—and only the outliers will resort to piracy. And you can keep making money. SA

SCIENTIFIC AMERICAN ONLINE
Five ways Hollywood is hobbling itself: ScientificAmerican.com/sep2012/pogue

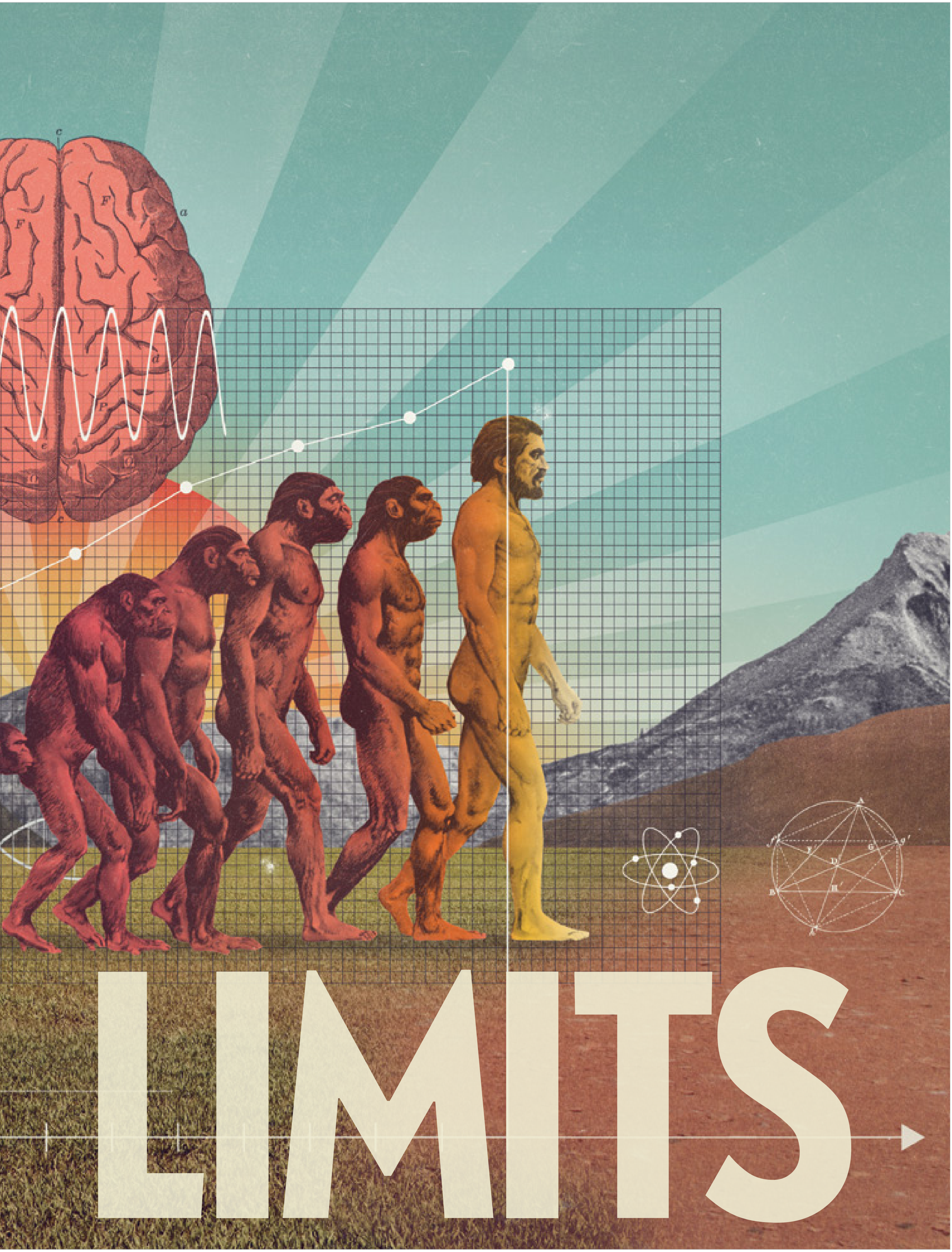
Illustration by Jude Buffum



We humans emerged not long ago from evolution's forge as a clever animal adept at hunting and gathering, with intellectual gifts that knew no bounds. Our journey since has taken us to the threshold of nature's deepest mysteries. Who are we, what can we do and where are we headed?

BEYOND

Illustration by Mark Weaver


LIMITS

EVOLUTION

Super Humanity

Our drive to exceed our evolutionary limits sets us apart from other beasts

By Robert M. Sapolsky

SIT DOWN WITH AN ANTHROPOLOGIST TO TALK about the nature of humans, and you are likely to hear this chestnut: "Well, you have to remember that 99 percent of human history was spent on the open savanna in small hunter-gatherer bands." It's a classic cliché of science, and it's true. Indeed, those millions of ancestral years produced many of our hallmark traits—upright walking and big brains, for instance. Of course, those wildly useful evolutionary innovations came at a price: achy backs from our bipedal stance; existential despair from our large, self-contemplative cerebral cortex. As is so often the case with evolution, there is no free lunch.

Compounding the challenges of those trade-offs, the world we have invented—and quite recently in the grand scheme of things—is dramatically different from the one to which our bodies and minds are adapted. Have your dinner come to you (thanks to the pizza delivery guy) instead of chasing it down on foot; log in to Facebook to interact with your nearest and dearest instead of spending the better part of every day with them for your whole life. But this is where the utility of the anthropologist's cliché for explaining the human condition ends.

The reason for this mismatch between the setting we evolved to live in and the situations we encounter in our modern era derives from another defining characteristic of our kind, arguably the most important one: our impulse to push beyond the limitations evolution imposed on us by developing tools to make us faster, smarter, longer-lived. Science is one such tool—an invention that requires us to break out of our Stone Age seeing-is-believing mindset so that we can clear the next hurdle we encounter, be it a pandemic flu or climate change. You could call it the ultimate expression of humanity's singular drive to aspire to be better than we are.

HUMAN ODDITIES

TO UNDERSTAND how natural selection molded us into the unique primates we have become, let us return to the ancestral savanna. That open terrain differed considerably from the woodlands our ape forebearers called home. For one thing, the savanna sun blazed hotter; for another, nutritious plant foods were scarcer. In response, our predecessors lost their thick body hair to keep cool. And their molars dwindled as they abandoned a tough vegetarian diet for one focused in part on meat from grassland grazers—so much so that they are now nearly useless, with barely any grinding surface.

Meanwhile the selective demands of food scarcities sculpted our distant forebearers into having a body that was extremely thrifty and good at storing calories. Now, having inherited that same metabolism, we hunt and gather Big Macs as diabetes becomes a worldwide scourge. Or consider how our immune systems evolved in a world where one hardly ever encountered someone carrying a novel pathogen. Today if you sneeze near someone in an airport, your rhinovirus could be set free 12 time zones away by the next day.

Our human oddities abound where behavior is concerned. By primate stan-

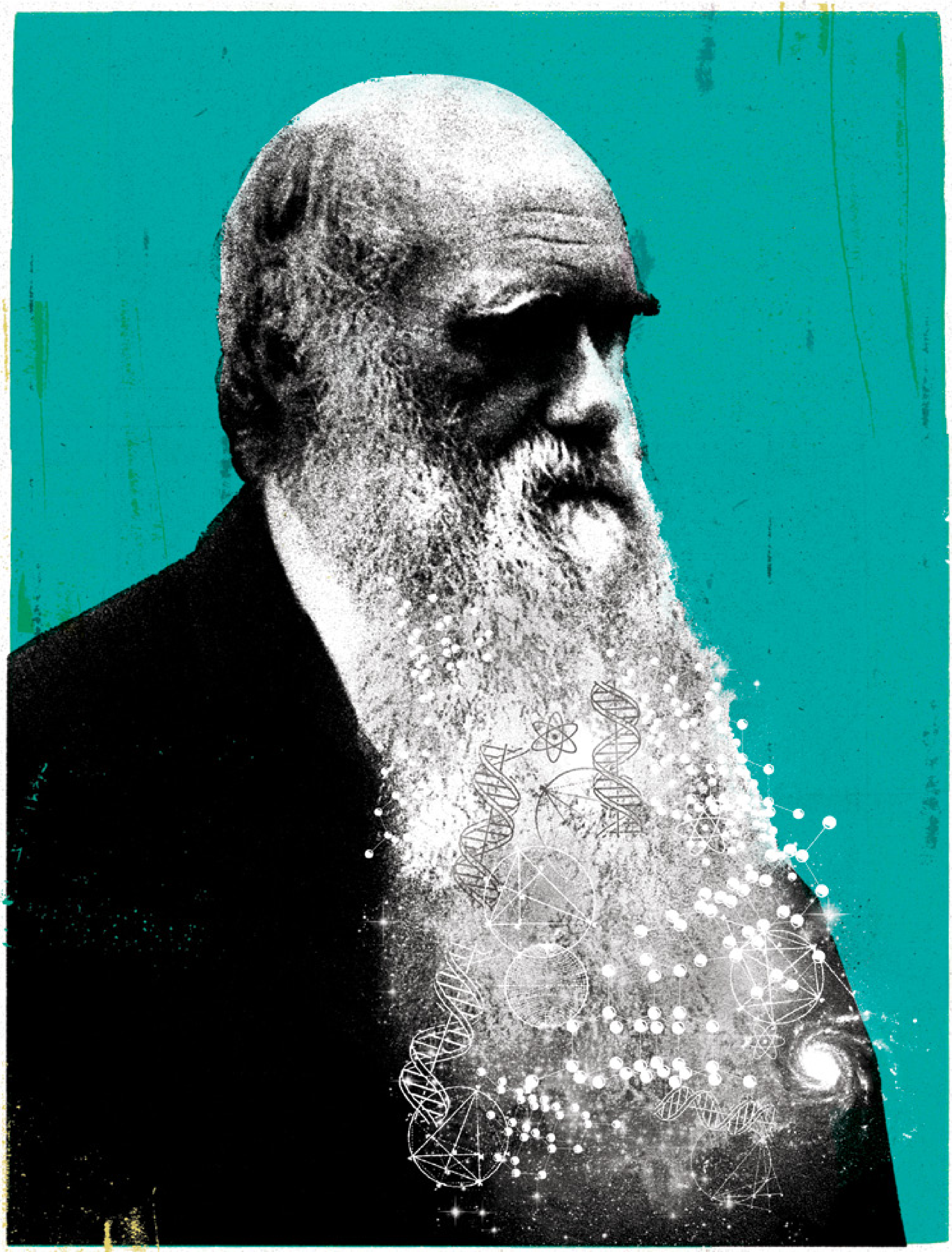


Illustration by Heads of State

Robert M. Sapolsky is a professor of biology and neurology at Stanford University. His research centers on stress in wild baboons. Sapolsky has written numerous popular essays and books on the human condition.

IN BRIEF

Many of the challenges we humans face today are the result of a mismatch between the environment our ancestors adapted to over millions of years and the world we now live in.

But this incongruity is itself the result of a uniquely human characteristic: our impulse to extend ourselves beyond the limits evolution set for us.

Science is one of the tools humans use to achieve this goal of stretching our physical and mental capabilities.

dards, we are neither fish nor fowl in lots of ways. One example is particularly interesting. Primate species generally fall into two distinct types: on one hand, there are pair-bonding species, in which females and males form stable, long-lasting pairs that practice social and sexual monogamy. Monogamous males do some or even most of the caring for the young, and females and males in these species are roughly the same size and look very similar. Gibbons and numerous South American monkeys show this pattern. "Tournament" species take the opposite tack: females do all the child care, whereas males are far larger and come with all kinds of flashy displays of peacockery—namely, gaudy, conspicuous facial coloration and silver backs. These tournament males spend a ridiculous percentage of their time enmeshed in aggressive posturing. And then there are humans, who, by every anatomical, physiological and even genetic measure, are neither classic pair-bonding nor tournament creatures and instead lie stuck and confused somewhere in the middle.

Yet in another behavioral regard, humans are textbook primates: we are intensely social, and our fanciest types of intelligence are the social kinds. We primates may have circumstances where a complex mathematical instance of transitivity bewilders us, but it is simple for us to figure out that if person A dominates B, and B dominates C, then C had better grovel and submissively stick his butt up in the air when A shows up. We can follow extraordinarily complex scenarios of social interaction and figure out if a social contract has been violated (and are better at detecting someone cheating than someone being overly generous). And we are peerless when it comes to facial recognition: we even have an area of the cortex in the fusiform gyrus that specializes in this activity.

The selective advantages of evolving a highly social brain are obvious. It paved the way for us to fine-tune our capacities for reading one another's mental states, to excel at social manipulation, and to adeptly deceive and attract potential mates and supporters. Among Americans, the extent of social intelligence in youth is a better predictor of our adult success in the occupational world than are SAT scores.

Indeed, when it comes to social intelligence in primates, humans reign supreme. The social brain hypothesis of primate evolution is built on the fact that across primate species, the percentage of the brain devoted to the neocortex correlates with the average size of the social group of that species. This correlation is more dramatic in humans (using the group sizes found in traditional societies) than in any other primate species. In other words, the most distinctively primate part of the human brain co-evolved with the demands of keeping track of who is not getting along with whom, who is tanking in the dominance hierarchy and what couple is furtively messing around when they should not be.

Like our bodies, our brains and behaviors, sculpted in our distant hunter-gatherer past, must also accommodate a very different present. We can live thousands of miles away from where we were born. We can kill someone without ever seeing his face. We encounter more people standing on line for Space Mountain at Disneyland than our ancestors encountered in a lifetime. My God, we can even look at a picture of someone and feel lust despite not knowing what that person smells like—how weird is that for a mammal?

BEYOND LIMITS

THE FACT that we have created and are thriving in this unrecognizable world proves a point—namely, that it is in our nature to be unconstrained by our nature. We are no strangers to going out of bounds. Science is one of the strangest, newest domains where we challenge our hominid limits. Some of the most dramatic ways in which our world has been transformed are the direct products of science, and the challenges there are obvious. Just consider those proto-geneticists who managed to domesticate some plants and animals—an invention that brought revolutionary gains in food but that now threatens to strip the planet of its natural resources.

On a more abstract plane, science tests our sense of what is the norm, what counts as better than well. It challenges our sense of who we are. Thanks to science, human life expectancy keeps extending, our average height increases, our scores on standardized tests of intelligence improve. Thanks to science, every world record for a sporting event is eventually surpassed.

As science pushes the boundaries in these domains, what is surprising is how little these changes have changed us. No matter how long we can expect to live, we still must die, there will still be a leading cause of death, and we will still feel like

The very scientific process defies our basic hominid limits.

our loved ones were taken from us too soon. And when it comes to humans becoming, on average, smarter, taller and better at athletics, there is a problem: Who cares about the average? As individuals, we want to, individually, be better than other individuals. Our brain is invidious, comparative, more interested in contrasts than absolutes. That state begins with sensory systems that often do not tell us about the quality of a stimulus but instead about the quality relative to the stimuli that surround it. For example, the retina contains cells that do not so much respond to a color as to a color in the context of its proximity to its "opposite" color (red versus green, for instance). Although we may all want to be smart, we mostly want to be smarter than our neighbor. The same is true for athletes, which raises a question that has long been pertinent to hominids: How fast do you have to run to evade a lion? And the answer always is: faster than the person next to you.

Still, science most asks us to push our limits when it comes to the kinds of questions we ask. I see four particular types. The first has to do with the frequent asocial nature of science. By this, I am not referring to the solitary task of some types of scientific inquiry, the scientist slaving away alone at three in the morning. I mean that science often asks us to be really interested in inanimate things. There are obviously plenty of exceptions to this rule—primatologists sit around and gossip at night about the foibles and peccadilloes of their monkeys; paleontologist Louis Leakey used to refer to his favorite fossil skull as "Dear Boy." Yet some realms of science consider extremely inanimate issues—astrophysicists trying to discover planets in other solar systems, for instance. Science often requires our social, hominid brain to be passionate about some pretty unlikely subjects.

Science pushes our envelope in a second way when we contemplate the likes of quantum mechanics, nanotechnology and particle physics, which ask us to believe in things that we cannot see. I spent my graduate school years pipetting fluids from one test tube to another, measuring levels of things like hormones and neurotransmitters. If I had stopped and thought about it, it would have seemed completely implausible that there actually are such things as hormones and neurotransmitters. That implausibility is the reason why so many of us lab scientists who measure or clone or inject invisible things get the most excited when we get to play with dry ice.

Science, by the nature of the questions it can generate, can push the bounds of our hominid credulity in a third way. We are unmatched in the animal kingdom when it comes to remembering the distant past, when it comes to having a sense of the future. These skills have limits, however. Traditionally our hunter-gatherer forbearers may have remembered something their grandmother was told by her grandmother, or they may have imagined the course of a generation or two that would outlive them. But science sometimes asks us to ponder processes that emerge with time spans without precedent. When will the next ice age come? Will Gondwana ever reunite? Will cockroaches rule us in a million years?

Everything about our hominid minds argues against the idea that there are processes that take that long or that such processes could be interesting. We and other primates are creatures of steep temporal discounting—getting $10 or 10 pellets of monkey chow right now is more appealing than waiting until tomorrow for 11, and the dopamine reward pathways in our brain light up on brain-imaging tests when we go for the impulsive immediate reward. It seems most of us would rather have half a piece of stale popcorn next week than wait a 1,000 years to win a bet about a key hypothesis in plate tectonics.

Then there are scientific questions that stretch our limits in the most profound ways. These are quandaries of dazzling abstractness: Does free will exist? How does consciousness work? Are there things that are impossible to know?

It is tempting to fall for an easy insight here, which is that our Paleolithic minds give up on challenges like these and just turf them to the gods to contemplate. The problem is the human propensity toward creating gods in our own image (one fascinating example being that autistic individuals who are religious often have an image of an asocial god, one who is primarily concerned with the likes of keeping atoms from flying apart). Throughout the history of humans inventing deities, few of these gods had a gargantuan capacity for the abstract. Instead they had familiar appetites. No traditional deities would be particularly interested in chewing the fat with Gödel about knowingness or rolling dice with Einstein (or not rolling the dice, as it were). They would be much more into having the biggest ox sacrificed to them and scoring with the most forest nymphs.

The very scientific process defies our basic hominid limits. It asks us to care intensely about tiny, even invisible, things, things that do not breathe or move, things vast distances away from us in space and time. It encourages us to care about subjects that would bore the crap out of Thor or Baal. It is one of the most challenging things that we have come up with. No wonder all those nerd-detector alarms would go off back in middle school when we were spotted reading a magazine like *Scientific American*. This venture of doing, thinking, caring about science is not for the fainthearted—we are far better adapted to face saber-toothed cats—and yet here we are, reinventing the world and striving to improve our lot in life one scientific question at a time. It's our human nature. SA

MORE TO EXPLORE

Monkeyluv: And Other Essays on Our Lives as Animals. Robert M. Sapolsky. Scribner, 2006.

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SCIENTIFIC AMERICAN ONLINE
Watch the author talk about human uniqueness at **ScientificAmerican.com/sep2012/sapolsky**

INTELLIGENCE

Can We Keep Getting Smarter?

Ever rising IQ scores suggest that future generations will make us seem like dimwits in comparison

By Tim Folger

TWENTY-EIGHT YEARS AGO JAMES R. FLYNN, A researcher at the University of Otago in New Zealand, discovered a phenomenon that social scientists still struggle to explain: IQ scores have been increasing steadily since the beginning of the 20th century. Flynn went on to examine intelligence-test data from more than two dozen countries and found that scores were rising by 0.3 point a year—three full points per decade. Nearly 30 years of follow-up studies have confirmed the statistical reality of the global uptick, now known as the Flynn effect. And scores are still climbing.

"To my amazement, in the 21st century the increases are continuing," says Flynn, whose most recent book on the subject—*Are We Getting Smarter?*—is being published this month. "The latest data show the gains in America humming right along at the old rate of three tenths of a point a year."

One of the strangest aspects of the Flynn effect is its relentless monotony—it does not slow or stop and restart. It just moves steadily upward, "as if guided by an invisible hand," Flynn says. Joseph Rodgers, a psychologist at the University of Oklahoma, examined the test results of nearly 13,000 American students to see if he could detect the Flynn effect on more granular timescales. "We wondered if the students' scores would get better over a five- or 10-year period. Well, they get better over a one-year period," Rodgers says. "The increase is there, systematically, year by year by year. Kids born in 1989 do a little better than kids born in 1988."

The Flynn effect means that children will, on average, score about 10 points higher on IQ tests than their parents did. By the end of this century our descendants will have nearly a 30-point advantage over us—the difference between average intelligence and the top 2 percent of the population—*if* the Flynn effect continues. But can it continue? Will the trend go on indefinitely, leading to a future filled with people who would be considered geniuses by today's standards? Or is there some natural limit to the Flynn effect and to human intelligence?

THE MODERN MIND

ALMOST AS SOON AS researchers recognized the Flynn effect, they saw that the ascending IQ scores were the result almost entirely of improved performances on specific parts of the most widely used intelligence tests. One such test, the Wechsler Intelligence Scale for Children, or WISC, has multiple sections, each of which assesses different skills. It would seem more natural to expect improvements in crystallized intelligence—the kind of knowledge picked up in school. That is not happening, however. The scores in the sections that measure skills in arithmetic and vocabulary levels have remained largely constant over time.

Most of the IQ gains come from just

Tim Folger is an award-winning science writer and editor of *The Best American Science and Nature Writing* series of books.

IN BRIEF

IQ scores have been steadily rising for a century, a phenomenon now known as the Flynn effect.

The surge in scores comes from supposedly "culture-free" tests of intelligence such as pattern matching.

Researchers believe the effect has its root in the increasingly abstracted nature of modern life.

More advanced minds create technologies that, in turn, enhance intelligence still further, forging a feedback loop that shows no signs of abating.

two subtests devoted to abstract reasoning [*see box on opposite page*]. One deals with "similarities" and poses questions such as "How are an apple and an orange alike?" A low-scoring answer would be "They're both edible." A higher-scoring response would be "They're both fruit," an answer that transcends simple physical qualities. The other subtest consists of a series of geometric patterns that are related in some abstract way, and the test taker must correctly identify the relation among the patterns.

A paradox of the Flynn effect is that tests such as these were designed to be completely nonverbal and culture-free measurements of what psychologists call fluid intelligence—an innate capacity to solve unfamiliar problems. Yet the Flynn effect clearly shows that something in the environment is having a marked influence on the supposedly culture-free components of intelligence in populations the world over. Ainsley Mitchum and Mark Fox, psychologists at Florida State University who have made detailed studies of generational differences in performance on intelligence tests, suspect that our enhanced ability to think abstractly may be linked to a new flexibility in the way we perceive objects in the world.

"Everybody is familiar with the start 'button' on a computer screen, but it's not really a button," Mitchum says. "I was trying to explain to my grandmother how to turn her computer off, and I said, 'Well, you hit the start button and select shutdown.' She was banging the mouse on the screen."

Mitchum adds that his grandmother is not unintelligent. She did, however, grow up in a world where buttons were buttons, and phones certainly were not cameras. Many researchers, Flynn among them, argue that rising IQ scores do not reflect an increase in our raw brainpower. Rather the Flynn effect shows how *modern* our minds have become. Such tests require a facility with recognizing abstract categories and making connections among them. And that facility, Flynn says, has become more useful over the past century than at any previous time in human history.

"If you don't classify abstractions, if you're not used to using logic, you can't really master the modern world," Flynn says. "Alexander Luria, a Soviet psychologist, did some wonderful interviews with peasants in rural Russia in the 1920s. He would say to them, 'Where there is always snow, bears are always white. There is always snow at the North Pole. What color are the bears there?' They would say they had never seen anything but brown bears. They didn't think of a hypothetical question as meaningful."

The peasants were not stupid. Their world just required different skills. "I think the most fascinating aspect of this isn't that we do so much better on IQ tests," Flynn says. "It's the new light it sheds on what I call the history of the mind in the 20th century."

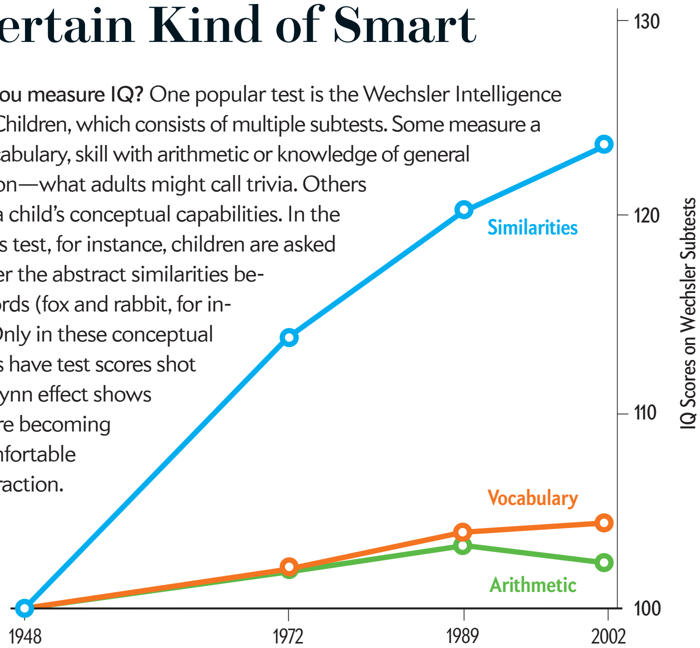
A naive interpretation of the Flynn effect quickly leads to some strange conclusions. Simply extrapolating the effect back in time, for example, would suggest that the average person in Great Britain in 1900 would have had an IQ of around 70 by 1990 standards. "That would mean that the average Brit was borderline mentally retarded and wouldn't have been able to follow the rules of cricket," says David Hambrick, a cognitive psychologist at Michigan State University. "And of course, that's absurd."

We may not be more intelligent than our forebearers, but there is no doubt our minds have changed. Flynn believes the change began with the industrial revolution, which engendered mass education, smaller families, and a society in which technical and managerial jobs replaced agricultural ones. New professional classes emerged—engineers, electricians, industrial architects—and their positions demanded a mastery of abstract principles. Education, in turn, became the driver for still more innovation and social change, setting up an ongoing positive feedback loop between our minds and a technology-based culture that does not seem likely to end any time soon.

Most researchers agree with Flynn's broad assessment that the industrial revolution and technological advances are responsible for his eponymous effect. Yet pinning down precise causes—which might allow for the design of educational or social policies to augment the effect—has been difficult. Improvements in education certainly account for part of the advances. As recently as the beginning of the 20th century, most Americans spent no more than seven years in school. Today about half of all adults have had at least some tertiary education.

A Certain Kind of Smart

How do you measure IQ? One popular test is the Wechsler Intelligence Scale for Children, which consists of multiple subtests. Some measure a child's vocabulary, skill with arithmetic or knowledge of general information—what adults might call trivia. Others examine a child's conceptual capabilities. In the similarities test, for instance, children are asked to consider the abstract similarities between words (fox and rabbit, for instance). Only in these conceptual categories have test scores shot up. The Flynn effect shows that we are becoming more comfortable with abstraction.



SOURCE: *ARE WE GETTING SMARTER? RISING IQ IN THE TWENTY-FIRST CENTURY,* BY JAMES R. FLYNN. CAMBRIDGE UNIVERSITY PRESS, 2012

Formal education, though, cannot entirely explain what is going on. Some researchers had assumed that most of the IQ increases seen over the 20th century might have been driven by gains at the left end of the intelligence bell curve among those with the lowest scores, an outcome that would likely be a consequence of better educational opportunities. A recent study by Jonathan Wai and Martha Putallaz of Duke University, however, looked at 20 years of data that comprise 1.7 million test results of fifth, sixth and seventh graders and found that the scores of the top 5 percent of the students were going up in perfect lockstep with the Flynn effect. "For the first time we have evidence that the whole intelligence curve is rising," Wai says. Wai and Putallaz's results suggest that because the whole curve is shifting, the cultural forces behind the increase must be influencing everyone equally. In a paper now in press, the researchers speculate that the ubiquity of sophisticated video games—and even some television shows—may provide a training ground that enhances the problem-solving skills needed for IQ tests.

For Rodgers, the universality of the Flynn effect confirms the pointlessness of seeking a single cause: "There must be four or five dominant causes, any one of which can stand against fluxes or wanes in the other." Improved childhood nutrition, universal education, smaller families and the influence of educated mothers on their children are some of the most likely causes. "As long as two causes were in existence, even when something like the Second World War came along and caused the other two to disappear, the Flynn effect kept cranking along," he says.

MENTAL EVOLUTION

WHAT WILL the future bring? Will IQ scores keep going up? One thing we can be sure of is that the world around us will continue to change, largely because of our own actions.

Flynn likes to use a technological analogy to describe the long-term interaction between mind and culture. "The speeds of automobiles in 1900 were absurdly slow because the roads were so lousy," he says. "You would have shaken yourself to pieces." But roads and cars co-evolved. When roads improved, cars did, too, and improved roads prompted engineers to design even faster cars.

Our minds and culture are locked in a similar feedback loop. We are creating a world where information takes forms and moves with speeds unimaginable just a few decades ago. Every gain in technology demands minds capable of accommodating the change, and the changed mind reshapes the world even more. The Flynn effect is unlikely to end during this century, presaging a future world where you and I would be considered woefully premodern and literal.

Of course, our minds are not only changing in ways that can be captured by IQ tests. "People are getting faster—I'm certain of this," Hambrick says. "A common practice in reaction-time research is to discard responses that are below about 200 milliseconds. It had been thought that 200 milliseconds is about the fastest that people can respond. But if you ask someone who has done this sort of research, they're having to discard more trials; people are getting faster. We text, we play video games, we do a lot more things that require really fast responses. I think once we have enough data, we'll be able to see a Flynn-like effect on measures of perceptual speed."

Maybe we should not be so surprised by the existence of something like the Flynn effect. Its absence would be more startling; it would mean we were no longer responding to the world we are creating. The Flynn effect itself is neither good nor bad—it is a symptom of our adaptability, and the abilities it reflects allow us to destroy as well as to create. If we are lucky, perhaps we will keep building a world that will make us smarter and smarter—one where our descendants will marvel at our simplicity. SA

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SCIENTIFIC AMERICAN ONLINE
Listen to an interview with James R. Flynn at **Scientific American.com/sep2012/flynn**

CONSCIOUSNESS

The Case of the Sleeping Slayer

In the neurological netherworld between sleep and wakefulness, the mind's delirium can turn tragically real

By James Vlahos

THERE WAS NOTHING OUTWARDLY UNUSUAL about the man who showed up at the Minnesota Regional Sleep Disorders Center on June 27, 2005. Like thousands of other clinic patients, Benjamin Adoyo (not his real name) was a sleepwalker. A 26-year-old college student, originally from Kenya, Adoyo had been wandering at night since childhood. Lately, though, the behavior had been getting worse. Adoyo had gotten married in February, and his wife would wake to him shaking her while looming over their bed and babbling unintelligibly. Scared, she would simply do her best to rouse Adoyo, who, once awakened, never remembered a thing. They lived in a one-bedroom apartment in Plymouth, a suburb of Minneapolis, and the sleepwalking was straining their young marriage. The referral form from Adoyo's primary care doctor noted that the patient's wife was "sometimes startled by his behavior, but no injury, per se."

After evaluating Adoyo, the sleep center's clinicians directed him to return on August 10 for an overnight electroencephalography (EEG) study of the electrical waves generated by his brain during sleep. In the middle of the night, Adoyo began thrashing about and yanking at the wires connected to the electrodes, pulling out tufts of hair as he ripped them off. But he did not wake up. The next morning Michel Cramer Bornemann, director of the center, told Adoyo that the study supported a diagnosis of a sleep disorder known as a non-REM parasomnia. Recounting when Adoyo ripped off the sensors, Bornemann asked, "Do you recall feeling any pain or pulling?"

"Nope," Adoyo replied without any hesitation.

Adoyo's next visit to the sleep center was on October 17. He said that the anti-anxiety medication Bornemann had prescribed to treat the sleepwalking was not helping much, so Bornemann bumped the dosage from one milligram to two. The doctor sincerely hoped that he could help his patient. "He was the nicest guy—friendly, engaging," Bornemann recalls. "I had no premonition at all that there was a malignant bone in his body."

Adoyo never came back. The sleep clinicians found out why several months later, when they received a letter from the Minnesota Public Defender's office informing them that on October 19, only two days after the last clinic visit, Adoyo had been arrested for killing his wife and was now charged with the crime. "We are looking for someone to consult with regarding any relationship this sleep disorder may have with his offence," the letter stated.

PERCHANCE TO DREAM

THE MOST BASIC and seemingly indisputable fact about sleep is that you are either asleep or awake. Sure, scientists subdivide the unconscious state into rapid eye movement (REM) and non-REM (NREM) cy-

Photograph by Gerald Slota

James Vlahos is an independent journalist who has written for *National Geographic Adventure*, the *New York Times Magazine* and *Popular Science*.

IN BRIEF

Whether or not the brain is asleep or awake is not an either-or proposition, according to some scientists.

Their research suggests that what we recognize as sleep—closed eyes, physical stillness and lack of consciousness—occurs only after a number of different parts of the brain cycle into a sleep state.

If this partial-sleep hypothesis is correct, some parts of the brain may be asleep while we actually appear to be awake, and vice versa.

This new view could explain why, in extremely rare cases, individuals may commit serious crimes, including murder, during sleep.

cles, and the latter is further divided into three substages. Overall, however, for most of the century-plus that scientists have been studying human rest, they have supported the notion that sleep and wakefulness are two distinct states with well-defined limits.

These supposedly firm boundaries are why judges and juries are skeptical when a sleep disorder is presented as an explanation for a crime such as Adoyo's. "I was asleep when I did it" sounds like a classic Twinkie defense, one in which science is twisted to abrogate personal responsibility. How, after all, could a person be anything other than totally awake if he is able to molest, injure or kill someone else? In the past two decades, though, sleep science has been revolutionized by a new theory that helps to explain everything from sleep crimes to the fundamental nature of sleep itself. As Bornemann puts it, "Sleep-or-wake is not an all-or-none, black-and-white phenomenon. It occurs on a spectrum."

The idea that a person could be physically animate but mentally off-line is well established in popular culture—recall the sleepwalking of Shakespeare's Lady Macbeth—and in courtrooms. The first time in American legal history that sleepwalking was successfully used as a defense against murder was in the 1846 trial of Albert Jackson Tirrell, who killed a prostitute by nearly beheading her with a razor. More recently, in Toronto in 1987, a 23-year-old man named Kenneth Parks drove 14 miles and murdered his mother-in-law, allegedly all while sleepwalking unaware. He was subsequently acquitted.

Sleep murders grab headlines but are thankfully rare; a 2010 review in the neuroscience journal *Brain* listed 21 sample cases, with the defendant being acquitted about a third of the time. Nonlethally violent, sexual and otherwise illegal behaviors during sleep, however, are more common than the public might suspect. Some 40 million Americans suffer from sleep disorders, and a telephone survey in the U.S. from the late 1990s estimated that two people in 100 have injured themselves or others while sleeping.

Bornemann, along with his colleagues Mark Mahowald and Carlos Schenck, is among the world's preeminent experts on parasomnias—the umbrella term for unwanted sleep behaviors—and they frequently receive lawyers' requests for help. To distinguish between their medical and legal work, the doctors launched a separate entity in 2006 with Bornemann at the helm and Mahowald and Schenck serving as consultants. They call themselves Sleep Forensics Associates.

Sleep Forensics operates as a kind of scientific detective agency. Its more than 250 cases so far have been divided equally between work for the prosecution and the defense. Regardless of who is paying the fee, the agency's approach is not simply to serve up a medical opinion that supports a desired verdict. Instead the doctors try to discover the truth. The title Bornemann gave himself is "lead investigator," and he says that "in many ways, what I am is a neuroscientific profiler."

The outcomes of investigations are unpredictable. "If I can refute a parasomnia defense, the prosecuting attorney can say, 'Now I have the potential for a conviction,'" Bornemann says. But his work also offers the possibility of absolution. "True parasomnia behaviors are done without awareness, intent or motivation," Bornemann says. "Therefore, from a defense attorney's perspective, you have the grounds for a complete acquittal." He knows, however, that judges and juries struggle to accept the idea of sleep existing on a spectrum. In the courtroom, then, it is not just the accused who is on trial but the very definition of consciousness itself.

AWAKE AND UNAWARE?

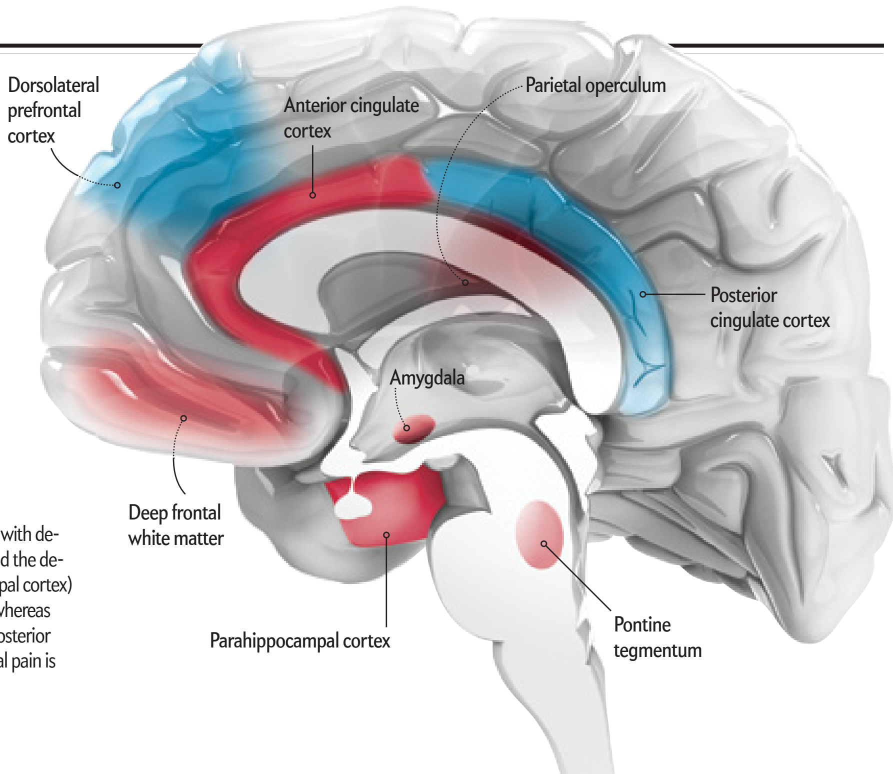
THE ESSENCE of what is known as local sleep theory is obvious from the name: parts of the brain can be asleep while others are awake. If true, the theory helps to account for people driving less safely when they are tired and for somnambulists scarfing pints of Chunky Monkey ice cream. It also explains "sexsomniacs" who fondle their partners or their children while unconscious. The concept of local sleep was first articulated neuroscientifically in a 1993 paper co-authored by James Krueger, who is currently at Washington State University, Spokane. At the time, the idea was heretical among senior sleep researchers. "It *still* is heretical," Krueger says, although the localists now form a significant and well-regarded subset of sleep scientists throughout the world.

Conventionally, sleep has been understood as a whole-brain phenomenon and, what is more, a state that is controlled top-down by regulatory circuits. But this view

NEUROSCIENCE

How Sleeping Brains Lie

Investigators have long believed that the human brain progresses through the admittedly complex stages of awareness in a well-coordinated manner (*right*). But recent studies (*below*) suggest that the patterns of neuronal activity during sleep are more haphazard than researchers once thought.



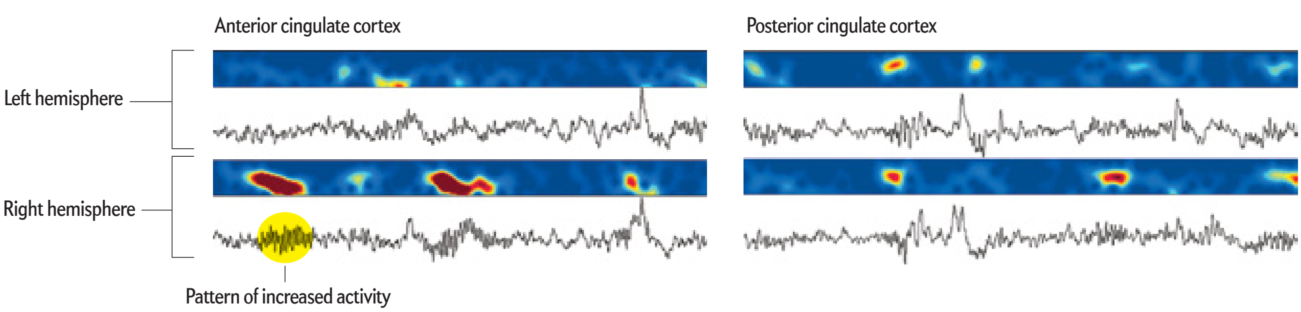
Regular Cycles

For unknown reasons, parts of the brain that help with detecting errors and conflicts (anterior cingulate) and the development of long-term memory (parahippocampal cortex) typically become more active during REM sleep, whereas the region that mediates the awareness of pain (posterior cingulate) becomes less active. As a result, physical pain is unusual in dreams experienced during REM.

More active — Less active

Irregular Activity

These EEG readings show that the left and right halves of the same parts of the cerebrum experience spurts of activity at different times during NREM sleep. Such evidence supports the hypothesis that the various regions of the brain do not fall asleep all at once or progress through the various stages of sleep in lockstep.



SOURCES: FROM "REM SLEEP AND DREAMING: TOWARDS A THEORY OF PROTOCONSCIOUSNESS," BY J. ALLAN HOBSON, IN *NATURE REVIEWS NEUROSCIENCE*, VOL. 10; NOVEMBER 2009 (*brain regions*); FROM "REGIONAL SLOW WAVES AND SPINDLES IN HUMAN SLEEP," BY YUVAL NIR ET AL., IN *NEURON*, VOL. 70, NO. 1; APRIL 14, 2011 (*EEG and spectrograms*)

has never made much sense to Krueger. He points out that scientists already have real-world evidence for partial brain sleep among other mammals. Dolphins, for instance, snooze with half of their brain at a time, swimming with one eye open. Krueger has also reviewed the scientific literature on brain lesions in humans and found that no matter what part—or how much—of the brain is damaged or missing, people are always able to sleep. This argues against the presence of a centralized sleep command center in the brain.

In a 2011 paper entitled "Local Use-Dependent Sleep," Krueger summarizes the alternative view—that of a scattered, bottom-up process. "The new paradigm views sleep as an emergent property of the collective output of smaller functional units within the brain," he wrote. Krueger and other like-minded researchers suspect that individual parts of the brain—neural networks and perhaps even individual neurons—go to sleep at different times around the clock depending on how much they have been taxed recently. (This is why the researchers describe sleep as both local—affecting only distinct parts of the brain at different times—and use-dependent—occurring only after the region has been sufficiently taxed.) Only when most of the brain's neurons are in the sleep condition does sleep's characteristic behavioral state kick in—that is, stillness, closed eyes, slackened muscles. Well before that point, though, tiny chunks of the brain are effectively taking a snooze.

Some of the most direct evidence for the theory has come out of the lab of David Rector, a colleague of Krueger's at W.S.U., Pullman. Rector works with rats, twitching their whiskers in a precise, controlled fashion. Each whisker is associated with a particular cortical column, a group of hundreds of tightly interconnected neurons that are located at the surface, or cortex, of the brain. He inserts probes through the rats' skulls into these cortical columns and

Illustration by AXS Biomedical Animation Studio can thus measure their electrical responses to the whisker twitching.

First, Rector established what the electrical response to whisker twitching looked like when the whole animal was behaviorally awake and when it was behaviorally asleep. Then he uncovered exciting exceptions to the rule. "The findings that columns can exist in a sleeplike state during whole-animal wake episodes and, conversely, that columns can exist in awakelike states during whole-animal sleep suggest that sleep is a property of individual cortical columns," he and Krueger reported in a 2008 paper.

Human lab subjects, needless to say, do not like having metal probes inserted into their brain, so researchers have devised less direct experimental gauges. In work by Hans Van Dongen, another scientist at W.S.U., Spokane, subjects look at a computer screen and must press a button as soon as a reaction-time counter pops up. The subjects are directed to perform this action repeatedly for 10 minutes, and their response times slow as the task progresses. Vigilance tests like this one repeatedly tax the same neural pathways, and the excessive use during the experiment essentially forces them into a sleep state, Van Dongen says. He sees this as evidence of local sleep rather than more globalized fatigue or boredom because the performance of his subjects improves immediately when they are allowed to switch to a different task that calls on another area of the brain.

If people can be partially asleep while otherwise outwardly awake, then you also have to consider the opposite proposition—that they can be partially awake while behaviorally asleep. This possibility would help explain something that has long puzzled sleep scientists: insomniacs who report after a night of monitoring in the lab that they "didn't sleep a wink," even though EEG measurements clearly show the brain-wave patterns that are characteristic of sleep. Looking for an explanation for this conflict, Daniel Buysse of the University of Pittsburgh's Sleep Medicine Institute performed a series of brain-imaging studies on insomniacs at night. He concluded that while the subjects were asleep as gauged by EEG and, for that matter, by behavioral observation, the parietal cortices of their brain—where the perception of alertness is formulated—remained active overnight. In that sense, the insomniacs' reports that they were awake were quite true.

"Sleep-or-wake is not an all-or-none phenomenon. It occurs on a spectrum."

FOLLOWING THE CLUES

"WHAT'S GOING ON?" the 911 operator asks.

"You just get here," the man on the other end of the line replies tersely.

"You need to tell me what's going on," the operator insists.

"Somebody is dead," the man says.

"Somebody is dead?"

"Yes."

"Where are they at?"

"In their house. Somebody is dead. Get here."

The call, which was received by the Hennepin County's emergency communication center at 3:41 A.M. on October 19, 2005, had been placed by Benjamin Adoyo. He used the cell phone of his wife, who at that moment was lying on the bathroom floor in a pool of her own blood.

When news of the killing reached Sleep Forensics Associates via Adoyo's defense attorney, Bornemann set out to understand both the alleged criminal and the crime. After being briefed by the attorney, he read the police reports and the transcripts of Adoyo's interrogation in the predawn hours after the homicide. He even visited the apartment and had a computer-animated video made to help him reconstruct the events leading up to the murder.

The peculiar syntax of the 911 call was one of the first things to catch Bornemann's attention. Adoyo did not say, "My wife is dead," Bornemann noted, but rather, "Somebody is dead." He did not say, "In our house," but rather, "In their house." In other words, Adoyo sounds like someone who does not know who he is, who the dead woman is or what has happened. He sounds like someone who is just waking up.

There are alternative interpretations, of course. Maybe Adoyo was knowingly guilty and wanted to reveal as little information as possible when he called 911. But when Bornemann read through the police reports, he did not see evidence of concealment or evasion. When officers from the Plymouth Police Department arrived on the scene, Adoyo was waiting for them on the front steps. At the police station, after he had been read his Miranda rights, Adoyo readily confessed to attacking his wife, although he seemed hazy about the details. "How is she?" he asked an officer at one point in the interrogation.

These initial findings—the detachment of the 911 call, the lack of concealment, the partial amnesia—all suggested to Bornemann that it was at least possible that Adoyo had been sleepwalking when he killed his wife. But a judge or jury would question the science behind this explanation before ever considering an acquittal. Could somebody really kill unknowingly while asleep and, if so, how?

To answer that question, first consider how sleep works for people *without* parasomnias. The shifts between wakefulness and REM and NREM sleep states are established by "literally hundreds" of hormonal, neural, sensory, muscular and other physiological variables, Bornemann's colleague Mahowald remarks. "Amazingly, these variables usually cycle together, and you've got billions of people in the world all cycling through wake, REM and NREM states multiple times every 24 hours." Sure, there will be pockets of "awake" neural networks when the rest of the brain is asleep, and vice versa—that is what local sleep theory tells us—but overall, the transitions are clear.

In people with parasomnias, though, the myriad regulatory variables become out of sync, and the switching between awake and sleep states gets mixed up. The result, Mahowald says, is what amounts to an extreme form of the local sleep phenomenon, a condition known as state dissociation, in which the physical and mental attributes of alertness, deep sleep and dreaming overlap. Afflicted people effectively suffer from having significant parts of their brain off-line even when their body is active.

Many Sleep Forensics cases illustrate how state dissociation can lead to criminal behavior. In late April of this year, for example, Bornemann was investigating a sleeping U.S. soldier who, when his wife attempted to rouse him, savagely pistol-whipped her. After the fact, he claimed that he had no intention of attacking her, nor did he have any memory of doing so. What he does remember is dreaming about using a knife to fend off an attacking Nazi spy. To Bornemann, this sounds like a possible example of REM behavior disorder, in which the afflicted person lacks the slackened muscles that normally accompany dreaming and is able to get up and physically act out the fantastical scenarios running through his head.

Another case Bornemann was investigating in late April concerned a well-off businessman in Utah. The businessman was asleep one night when his nine-year-old daughter slipped into his bed, which she apparently did when she was having trouble sleeping. The father awoke later and discovered, to his horror, that he was pelvic thrusting against his daughter and that his hand was touching her genitals.

The businessman had no past record of sex crimes. After the incident, he was evaluated by a psychologist, took a polygraph test and even had his penile tumescence measured while being shown inappropriate images of children. None of these measures indicated that he was a pedophile. Bornemann suspects that his behavior may instead be caused by an arousal disorder, the subcategory of state dissociations that includes sleepwalking, sleep eating and sexsomnia. What all of them have in common is that they arise when the neurophysiological attributes of NREM sleep overlap with the complex motor abilities of wakefulness.

Knowing just which parts of the brain are working and which are slumbering helps to explain the perversity and violence that parasomniacs sometimes exhibit. Brain-imaging studies reveal that during NREM sleep, the prefrontal cortex—a section of the brain located just behind the forehead, where reason and moral judgments are formulated—is much less active than it is when an individual is awake. The midbrain, meanwhile, is active and capable of generating simple behaviors known as fixed-action patterns. "These tend to be very primal in nature," Bornemann says. "You can have standing, walking, predatory attack, eating and drinking, grooming, and sexual and maternal behaviors." The prefrontal cortex normally checks such patterns when they are inappropriate, but during NREM sleep, this part of the brain is no longer on the job. People become more like wild animals, governed by instinctive urges and impulsive reactions.

THE VERDICT

THE CRUX of a Sleep Forensics investigation is when Bornemann interviews the accused. Face-to-face is best. The two questions he must answer is whether the person legitimately has a sleep disorder and, incorporating all of the other evidence, whether that disorder might have been active at the time of the criminal act.

With Adoyo, Bornemann was in the highly unusual position of having treated the accused as a patient, so he knew that the young man was not a faker. Family members also vouched for the fact that Adoyo had been a sleepwalker since he was a boy. The second question, though, was tougher: Was Adoyo's sleep disorder the reason he committed the crime? That query could not be answered with total certainty because Bornemann could not travel back in time and enter Adoyo's mind to see what he was or was not thinking during the criminal act. That said, it is not easy to fake a sleepwalking defense. "The general public has the impression that anything can happen during sleepwalking," Bornemann says. "But only certain behaviors can occur and, in general, for a limited amount of time."

For instance, "proximity is the key in the vast majority of sleepwalking violence," Bornemann says. The victims are often lying next to the parasomniac or are attacked when they attempt to rouse the sleeper. The latter was the case with the soldier who was dreaming about the Nazi spy as well as with the sleep-driving Parks, who attacked his family only after they tried to wake him. Sleep crimes are also usually inexplicable—motiveless and out of character, such as in the case of the Utah businessman who fondled his daughter.

During the Adoyo investigation, Bornemann learned that his former patient had not in fact been physically proximate to his wife before the attack; he had nodded off on the couch while she was asleep in the bedroom. Also, the violent outburst was not brief and random, as sleep-based ones typically are, he notes, and instead was prolonged and "procedural," meaning several complex behaviors were involved. Adoyo first entered his wife's bedroom and assaulted her with a hammer; then he chased her into the hall outside the apartment and back inside to the bathroom; and he finally stabbed and strangled her. "It is highly unusual to see three mechanisms of sleepwalking violence" at once, Bornemann says.

Any remaining doubts were erased by Adoyo's admission—and the account that Bornemann read in the dead woman's own diary—that the couple had been fighting on the last day of her life. Adoyo suspected that his wife was having an affair and confronted her with what he believed to be evidence—condoms in her laundry—before she stalked off to bed. The crime, in short, was out of character but not motiveless, and Bornemann reported this and all of his other findings to the public defender. Adoyo ultimately pled guilty to second-degree murder, and he is currently serving a 37-year prison sentence.

Bornemann, for his part, says he is not personally invested in the guilt or innocence of the people he investigates. To him, what his work offers is the opportunity to do behavioral research on extreme sleep disorders that could never be replicated in the lab. The goal is to gather enough evidence to help shift the attitudes of jurors, judges and the general public, for whom on/off notions of consciousness still hold sway. "Neuroscience has moved far ahead of the paradigms of the legal community," he says, "and the legal community needs to catch up." SA

MORE TO EXPLORE

Violence in Sleep. Francesca Siclari et al. in *Brain*, Vol. 133, No. 12, pages 3494–3509; December 2010. **http://brain.oxfordjournals.org/content/133/12/3494.long**

Sleep Forensics Associates: **http://sleepforensicsassociates.com/aboutSfa**

SCIENTIFIC AMERICAN ONLINE
To learn more about sleep crimes, visit **ScientificAmerican.com/sep2012/sleep-crime**

AGING

How We All Will Live to Be 100

Two approaches to longevity research aim to extend the average life span out to a century or more

By Katherine Harmon

IN BRIEF

Researchers are exploring two main approaches to extending healthy human life span.

One camp believes we should focus on curing disease and replacing damaged body parts via stem cell therapies.

Another camp believes we must slow the aging process on the cellular and molecular levels.

AN AMERICAN BORN A CENTURY AGO WOULD have been expected to live, on average, just 54 years. Many children died young, and giving birth was one of the most dangerous things a woman would do. But thanks to vaccinations, antibiotics, sanitation and better maternal care, we are now much more likely to die in old age than in our youth. An infant born today should live to see a 78th birthday.

The easy gains against the grim reaper have been won. Now as people live to ever older ages, they confront two broad sets of forces that conspire to impose the ultimate human limit. First, each extra year we live means another year of accumulated damage to the body's cells and organs—damage that slower cellular-repair systems cannot quite fix. In addition, age is the biggest risk factor for common deadly ailments that researchers have been relatively powerless against, such as cancer, heart disease and Alzheimer's.

Researchers looking to push the limits of human life span are thus asking: Which of these two forces should we bet our research money on? Is it a more effective strategy to attempt to slow the aging process or to fight individual diseases? In other words, do most of us die because we get old—or because we get sick?

Scientists who support the antidisease route argue that a piecemeal approach stands the best chance of pushing life span out past a century. "If we can focus on the major causes of death—cancer, cardiovascular disease—if we can really conquer those diseases and replace parts of the body if they wear out, that is the best possible outcome," says Sarah Harper, a gerontologist at the Oxford Institute of Population Aging in England. She expects that if we can continue to beat back cancer and heart disease and improve stem cell technologies, such as personalized, laboratory-grown tissues, we could reasonably expect to live relatively healthy lives to 100—perhaps even 120—in the not too distant future.

Extending the active life span by this model requires that we figure out how to fix the body's naturally aging pieces. Scientists have already used stem cells to grow whole tracheae and jawbones. If research continues apace, as Harper and others in the field expect it will, tissues, organs and bones to replace those that fail will soon no longer be science fiction. "The small advances we are making in technology—in genetics, in stem cell research—are the kind of advances that are pushing back life span," she says.

Other investigators argue that we need to fight the aging process itself. Even if we are able to cure cancer, says S. Jay Olshansky, a researcher at the University of Illinois at Chicago School of Public Health, we will still experience heart problems or Alzheimer's—or at least macular degeneration. Similarly, regenerative medicine would solve problems only one organ at a

time. "A new esophagus would be a nice thing to have," he says, "but that hasn't influenced anything else."

That state of affairs will not be so if we can retard the aging process at the molecular level, Olshansky says. His approach would not target just one organ or system but the brain and body as a whole. He and his colleagues are launching what he calls "a Manhattan-style Project to slow aging." They are aiming for an across-the-board healthy life extension of seven years, which, he says, might easily be achieved in the next decade or two. And because the risk of disease doubles every seven years or so, by slowing aging by seven years, Olshansky reasons, we can cut disease risk roughly in half.

He has long held the human body's natural, biological expiration date to be about 85. By that time, our cells have typically suffered an insurmountable amount of oxidative stress—damage stemming from the production of oxygen free radicals that harm DNA, proteins and other important cellular components. Olshansky and his colleagues are studying those rare super-long-lived individuals who make it past 100 or 110 in good physical and mental health. These people, he notes, might already be going through cellular aging at a slower pace, perhaps because their cells can better resist oxidative stress. Locating a genetic link for this slowdown might lead to the development of systemic anti-aging therapies.

A "treatment" for aging, beyond the usual healthy diet and exercise advice, might eventually come in the form of a pill. Yet developing something so complex as a compound that might help retard the body's aging process requires serious scientific effort. And that often means starting back at the molecular and mouse levels. The Mprize, which is sponsored by the Methuselah Foundation, awards teams of researchers who break the record for the longest-lived mice. One current candidate compound is rapamycin, which works along the same cellular pathway that calorie restriction does. Both rapamycin and calorie restriction have been shown to extend life span in mice. Like many other proposed panaceas, however, rapamycin is not without drawbacks. The drug suppresses the immune system, making it not terribly desirable for a large-scale rollout

LEVI BROWN *Trunk Archive*

anytime soon. And cautionary tales do abound: resveratrol, the "red wine" drug that had previously been the big antiaging hope, has faltered in recent studies. Not everyone in the longevity field is expecting rapamycin to work as well in humans as it appears to work in rodents.

Indeed, life-extension research has long been a pseudoscience backwater, swamped with snake oil and short-lived hopes. Both Olshansky and Harper are wary of claims that we will soon be able to live to 150 and beyond. Ultimately the most successful way to increase life span for the majority of people will likely be an all-of-the-above strategy. We are going to need better disease therapies, advances at the molecular level, regenerative medicine and good old-fashioned healthy living.

Even without any exceptional scientific breakthroughs in longevity and disease research, our plodding scientific progress—not to mention advances in health care and sanitation—continues to extend our life span. Average life expectancy worldwide increases by three months every year. That is not a bad return. Even developed regions such as Europe continue to gain about two years every decade. With luck—and more hard work—those living a century from now will consider our life expectancy pitifully short. SA

Katherine Harmon *is an associate editor at* Scientific American. *Her first book will be published in 2013 by Current/Penguin Group.*

MORE TO EXPLORE

Can Human Aging Be Postponed? Michael R. Rose in *Scientific American,* Vol. 281, No. 6, pages 106–111; December 1999.

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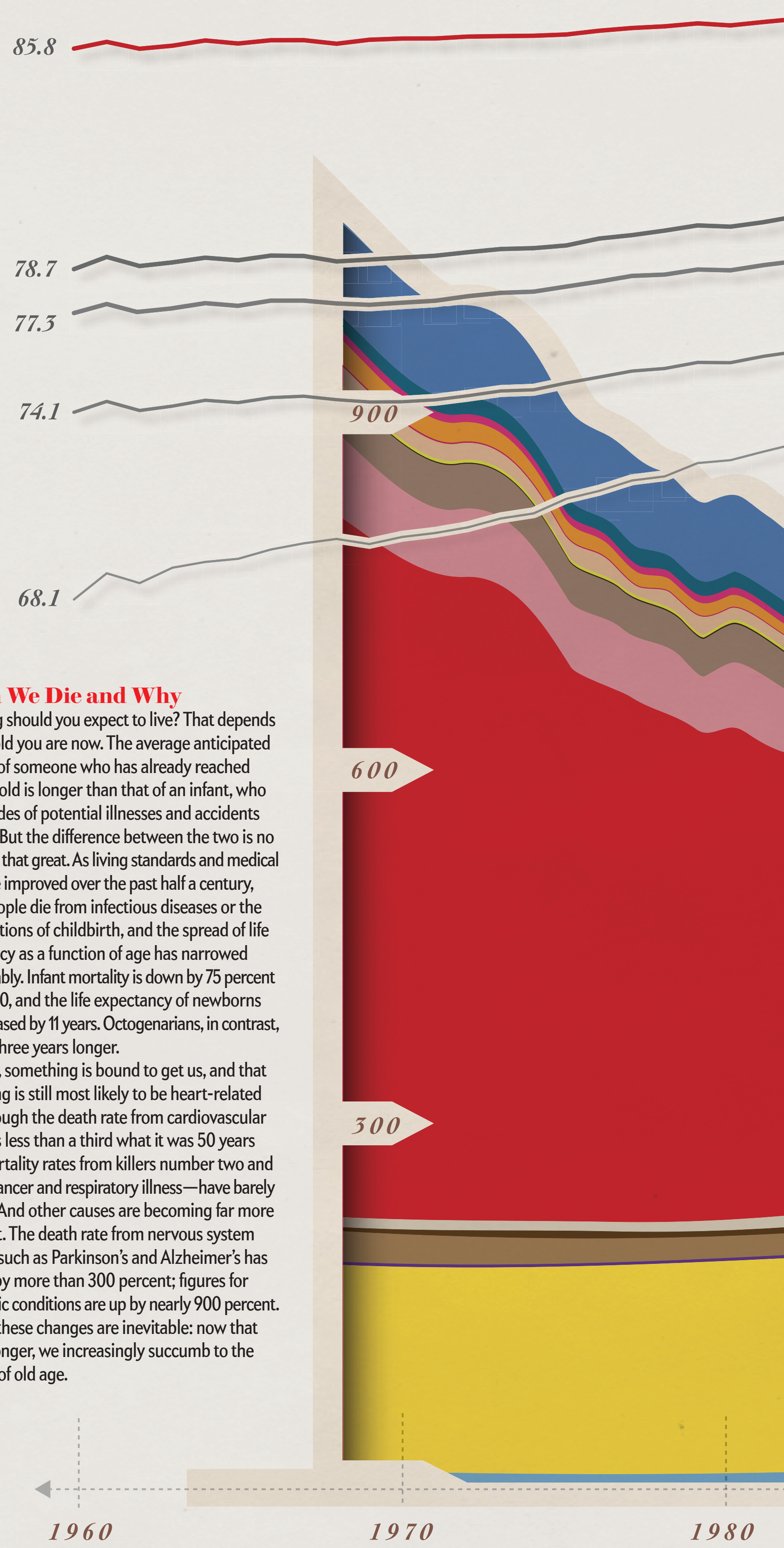
A New Path to Longevity. David Stipp in *Scientific American,* Vol. 306, No. 1, 32–39; January 2012.

SCIENTIFIC AMERICAN ONLINE
Watch a video about how to live a long time at ScientificAmerican.com/sep2012/longevity



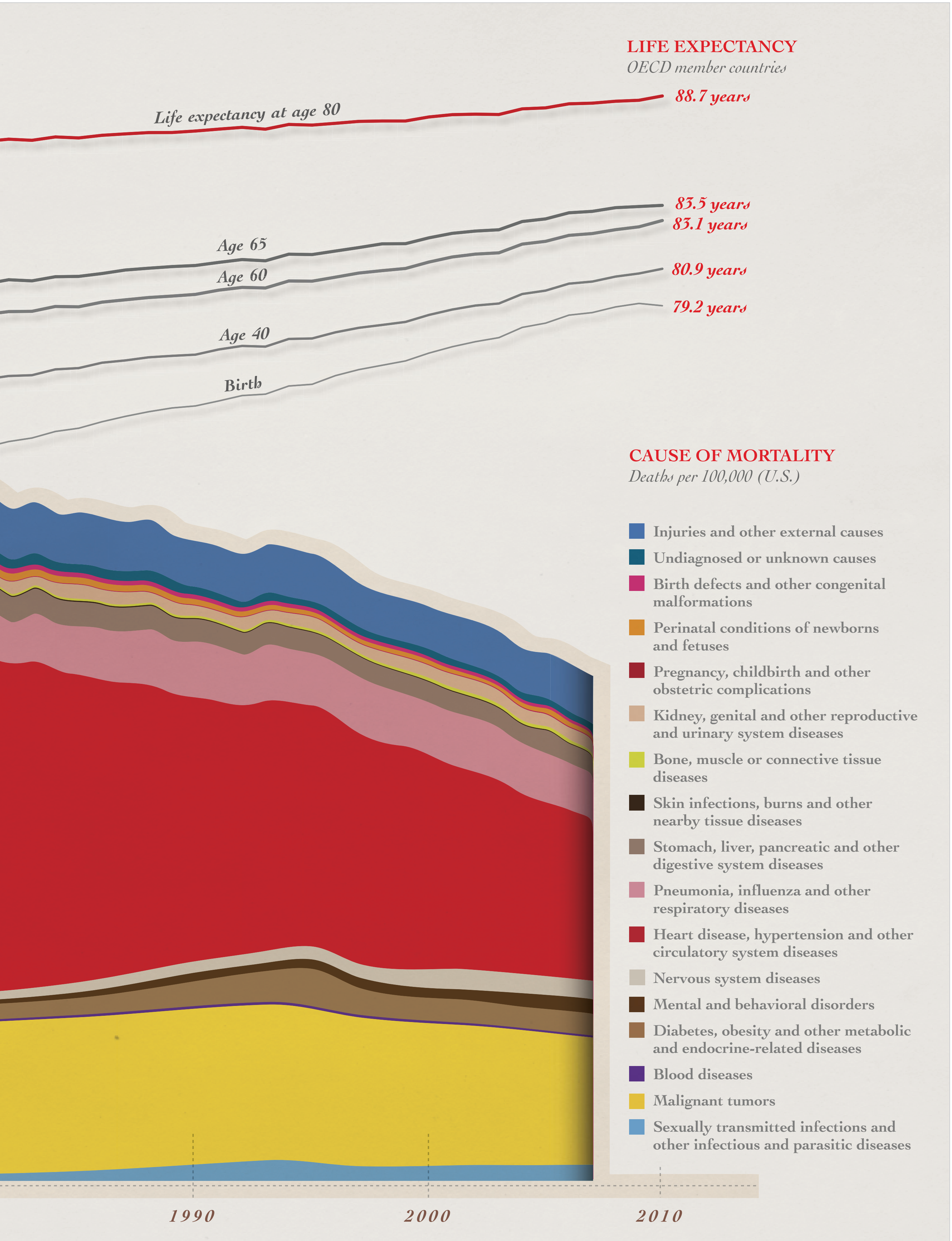
When We Die and Why

How long should you expect to live? That depends on how old you are now. The average anticipated life span of someone who has already reached 80 years old is longer than that of an infant, who has decades of potential illnesses and accidents to avoid. But the difference between the two is no longer all that great. As living standards and medical care have improved over the past half a century, fewer people die from infectious diseases or the complications of childbirth, and the spread of life expectancy as a function of age has narrowed considerably. Infant mortality is down by 75 percent since 1960, and the life expectancy of newborns has increased by 11 years. Octogenarians, in contrast, live just three years longer.

In time, something is bound to get us, and that something is still most likely to be heart-related (even though the death rate from cardiovascular disease is less than a third what it was 50 years ago). Mortality rates from killers number two and three—cancer and respiratory illness—have barely budged. And other causes are becoming far more prevalent. The death rate from nervous system diseases such as Parkinson's and Alzheimer's has jumped by more than 300 percent; figures for psychiatric conditions are up by nearly 900 percent. Perhaps these changes are inevitable: now that we live longer, we increasingly succumb to the diseases of old age.

SOURCE: ORGANIZATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT HEALTH DATA, 2011

Graphic by Chad Hagen


LIFE EXPECTANCY
OECD member countries
Life expectancy at age 80
88.7 years
Age 65
83.5 years
Age 60
83.1 years
Age 40
80.9 years
Birth
79.2 years
CAUSE OF MORTALITY
Deaths per 100,000 (U.S.)
Injuries and other external causes
Undiagnosed or unknown causes
Birth defects and other congenital malformations
Perinatal conditions of newborns and fetuses
Pregnancy, childbirth and other obstetric complications
Kidney, genital and other reproductive and urinary system diseases
Bone, muscle or connective tissue diseases
Skin infections, burns and other nearby tissue diseases
Stomach, liver, pancreatic and other digestive system diseases
Pneumonia, influenza and other respiratory diseases
Heart disease, hypertension and other circulatory system diseases
Nervous system diseases
Mental and behavioral disorders
Diabetes, obesity and other metabolic and endocrine-related diseases
Blood diseases
Malignant tumors
Sexually transmitted infections and other infectious and parasitic diseases
1990
2000
2010

NEUROENGINEERING

Mind in Motion

The idea that paralyzed people might one day control their limbs just by thinking is no longer a Hollywood-style fantasy

By Miguel A. L. Nicolelis

IN 2014 BILLIONS OF VIEWERS WORLDWIDE MAY remember the opening game of the World Cup in Brazil for more than just the goals scored by the Brazilian national team and the red cards given to its adversary. On that day my laboratory at Duke University, which specializes in developing technologies that allow electrical signals from the brain to control robotic limbs, plans to mark a milestone in overcoming paralysis.

If we succeed in meeting still formidable challenges, the first ceremonial kick of the World Cup game may be made by a paralyzed teenager, who, flanked by the two contending soccer teams, will saunter onto the pitch clad in a robotic body suit. This suit—or exoskeleton, as we call it—will envelop the teenager's legs. His or her first steps onto the field will be controlled by motor signals originating in the kicker's brain and transmitted wirelessly to a computer unit the size of a laptop in a backpack carried by our patient. This computer will be responsible for translating electrical brain signals into digital motor commands so that the exoskeleton can first stabilize the kicker's body weight and then induce the robotic legs to begin the back-and-forth coordinated movements of a walk over the manicured grass. Then, on approaching the ball, the kicker will visualize placing a foot in contact with it. Three hundred milliseconds later brain signals will instruct the exoskeleton's robotic foot to hook under the leather sphere, Brazilian style, and boot it aloft.

This scientific demonstration of a radically new technology, undertaken with collaborators in Europe and Brazil, will convey to a global audience of billions that brain control of machines has moved from lab demos and futuristic speculation to a new era in which tools capable of bringing mobility to patients incapacitated by injury or disease may become a reality. We are on our way, perhaps by the next decade, to technology that links the brain with mechanical, electronic or virtual machines. This development will restore mobility, not only to accident and war victims but also to patients with ALS (also known as Lou Gehrig's disease), Parkinson's and other disorders that disrupt motor behaviors that impede arm reaching, hand grasping, locomotion and speech production. Neuroprosthetic devices—or brain-machine interfaces—will also allow scientists to do much more than help the disabled. They will make it possible to explore the world in revolutionary ways by providing healthy human beings with the ability to augment their sensory and motor skills.

In this futuristic scenario, voluntary electrical brain waves, the biological alphabet that underlies human thinking, will maneuver large and small robots remotely, control airships from afar, and perhaps even allow the sharing of thoughts and sensations of one individu-

Illustration by Kemp Remillard

Miguel A. L. Nicolelis has pioneered the field of neuroprosthetics. He is Duke School of Medicine Professor of Neurosciences and co-director of the Duke University Center for Neuroengineering.

IN BRIEF

Brain waves can now control the functioning of computer cursors, robotic arms and, soon, an entire suit: an exoskeleton that will allow a paraplegic to walk and maybe even move gracefully.

Sending signals from the brain's outer rindlike cortex to initiate movement in the exoskeleton represents the state of the art for a number of bioelectrical technologies perfected in recent years.

The 2014 World Cup in Brazil will serve as a proving ground for a brain-controlled exoskeleton if, as expected, a handicapped teenager delivers the ceremonial opening kick.

al with another over what will become a collective brain-based network.

THOUGHT MACHINES

THE LIGHTWEIGHT body suit intended for the kicker, who has not yet been selected, is still under development. A prototype, though, is now under construction at the lab of my great friend and collaborator Gordon Cheng of the Technical University of Munich—one of the founding members of the Walk Again Project, a nonprofit, international collaboration among the Duke University Center for Neuroengineering, the Technical University of Munich, the Swiss Federal Institute of Technology in Lausanne, and the Edmond and Lily Safra International Institute of Neuroscience of Natal in Brazil. A few new members, including major research institutes and universities all over the world, will join this international team in the next few months.

The project builds on nearly two decades of pioneering work on brain-machine interfaces at Duke—research that itself grew out of studies dating back to the 1960s, when scientists first attempted to tap into animal brains to see if a neural signal could be fed into a computer and thereby prompt a command to initiate motion in a mechanical device. Back in 1990 and throughout the first decade of this century, my Duke colleagues and I pioneered a method through which the brains of both rats and monkeys could be implanted with hundreds of hair-thin and pliable sensors, known as microwires. Over the past two decades we have shown that, once implanted, the flexible electrical prongs can detect minute electrical signals, or action potentials, generated by hundreds of individual neurons distributed throughout the animals' frontal and parietal cortices—the regions that define a vast brain circuit responsible for the generation of voluntary movements.

This interface has for a full decade used brain-derived signals to generate movements of robotic arms, hands and legs in animal experiments. A critical breakthrough occurred last year when two monkeys in our lab learned to exert neural control over the movements of a computer-generated avatar arm that touched objects in a virtual world but also provided an "artificial tactile" feedback signal directly to each monkey's brain. The software allowed us to train the animals to feel what it was like to touch an object with virtual fingers controlled directly by their brain.

The Walk Again consortium—assisted by its international team of neuroscientists, roboticists, computer scientists, neurosurgeons and rehabilitation professionals—has begun to take advantage of these animal research findings to create a completely new way to train and rehabilitate severely paralyzed patients in how to use brain-machine interface technologies to regain full-body mobility. Indeed, the first baby steps for our future ceremonial kicker will happen inside an advanced virtual-reality chamber known as a Cave Automatic Virtual Environment, a room with screens projected on every wall, including the floor and ceiling. After donning 3-D goggles and a headpiece that will noninvasively detect brain waves (through techniques known as electroencephalography—EEG—and magnetoencephalography), our candidate kicker—by necessity a lightweight teenager for this first iteration of the technology—will become immersed in a virtual environment that stretches out in all directions. There the youngster will learn to control the movements of a software body avatar through thought alone. Little by little, the motions induced in the avatar will increase in complexity and will ultimately end with fine-motor movements such as walking on a changing terrain or unscrewing a virtual jelly jar top.

PLUGGING INTO NEURONS

THE MECHANICAL movements of an exoskeleton cannot be manipulated as readily as those of a software avatar, so the technology and the training will be more complicated. It will be necessary to implant electrodes directly in the brain to manipulate the robotic limbs. We will need not only to place the electrodes under the skull in the brain but also to increase the number of neurons to be "read" simultaneously throughout the cortex. Many of the sensors will be implanted in the motor cortex, the region of the frontal lobe most readily associated with the generation of the motor program that is normally downloaded to the spinal cord, from which neurons directly control and coordinate the work of our muscles. (Some neuroscientists believe that this interaction between mind and muscle may be achieved through a noninvasive method of recording brain activity, like EEG, but that goal has yet to be practically achieved.)

Gary Lehew in my group at Duke has devised a new type of sensor: a recording cube that, when implanted, can pick up signals throughout a three-dimensional volume of cortex. Unlike earlier brain sensors, which consist of flat arrays of microelectrodes whose tips record neuronal electrical signals, Lehew's cube extends sensing microwires up, down and sideways throughout the length of a central shaft.

The current version of our recording cubes contains up to 1,000 active recording microwires. Because at least four to six single neurons can be recorded from each microwire, every cube can potentially capture the electrical activity of between 4,000 to 6,000 neurons. Assuming that we could implant several of those cubes in the frontal and parietal cortices—areas responsible for high-level control of movement and decision making—we could obtain a simultaneous sample of tens of thousands of neurons. According to our theoretical software modeling, this design would suffice for controlling the flexibility of movement required to operate an exoskeleton with two legs and to restore autonomous locomotion in our patients.

To handle the avalanche of data from these sensors, we are also moving ahead on making a new generation of custom-designed neurochips. Implanted in a patient's skull along with the microelectrodes, they will extract the raw motor commands needed to manipulate a whole-body exoskeleton.

Of course, the signals detected from the brain will then need to be broadcast to the prosthetic limbs. Recently Tim Hanson, a newly graduated Ph.D. student at Duke, built a 128-channel wireless recording system equipped with sensors and chips that can be encased in the cranium and that is capable of broadcasting recorded brain waves to a remote receiver. The first version of these neurochips is currently being tested successfully in monkeys. Indeed, we have recently witnessed the first monkey to operate a brain-machine interface around the clock using wireless transmission of brain signals. We filed in July with the Brazilian government for permission to use this technology in humans.

For our future soccer ball kicker, the

SCIENCE & SOCIETY PICTURE LIBRARY (*artificial leg*); CORBIS (*Paré and Civil War officer*)

CHRONOLOGY

The Long Road to Brain-Controlled Prosthetics

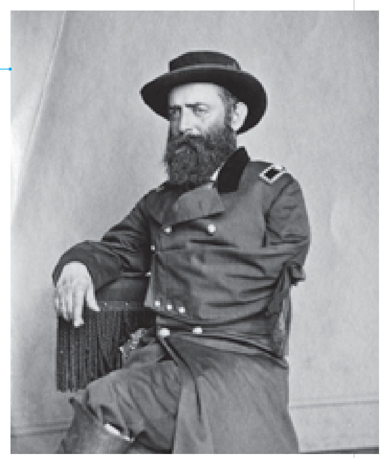
Replacement limbs have existed for millennia—a rational response to the need to address war wounds or other types of trauma and birth defects. Today the technology is so sophisticated that an artificial limb can be controlled by electrical signals channeled directly from the brain.

1500–1000 B.C.
FIRST HISTORICAL REFERENCE
A Hindu holy book written during this period mentioned Vishpala, who had a leg amputation after a wound sustained during battle. She had the limb replaced with an iron version that let her walk and return to her troops.

FOURTH CENTURY B.C.
ANCIENT ARTIFACT
One of the oldest artificial limbs discovered—a copy of which is shown here—was dug up in southern Italy in 1858. Fabricated in about 300 B.C., it was made of copper and wood and designed, it appears, for a below-knee amputee.

14TH CENTURY
GUNS AND AMPUTATIONS
The arrival of gunpowder at the European battlefront greatly amplified the number of injuries sustained by soldiers. In response, in the 16th century **AMBROISE PARÉ,** the royal surgeon for several French kings, developed techniques to attach both upper and lower limbs to patients and reintroduced the use of ligatures to tie off blood vessels.

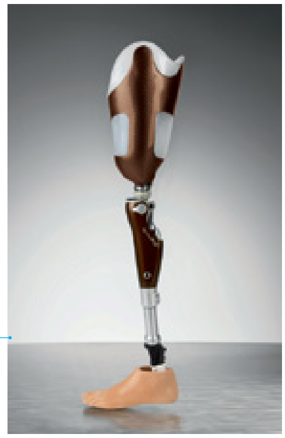
1861–1865
CIVIL WAR
The War between the States resulted in many amputations. One person affected was **BRIGADIER GENERAL STEPHEN JOSEPH MCGROARTY,** who lost an arm. An influx of government funding and the availability of anesthetics that allowed for longer operations improved prosthetic technology during this era.



1963 PRIMITIVE BRAIN INTERFACE
José Manuel Rodriguez Delgado implanted a radio-controlled electrode in the caudate nucleus deep in a bull's brain and stopped the animal dead in its tracks by pressing a button on a remote transmitter; his device was a predecessor to contemporary brain-machine interfaces.

1969 PIONEERING EXPERIMENTS
Eberhard Fetz of the University of Washington performed a study in which monkeys were trained to activate electrical signals in their brain to control the firing of a single neuron, duly recorded by a metal microelectrode.

CHRONOLOGY

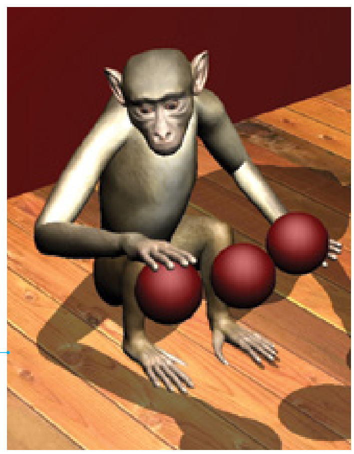


1980s
LISTENING TO BRAIN WAVES
Apostolos Georgopoulos of Johns Hopkins University discovered an electrical firing pattern in the motor neurons of rhesus macaques that occurred when they rotated their arm in a particular direction.

EARLY 1990s PLUGGING IN
John Chapin, now at S.U.N.Y. Downstate University, and Miguel A. L. Nicolelis introduced a technique that allowed for simultaneous recording of dozens of widely dispersed neurons using permanently implanted electrodes, thus paving the way for research on brain-machine interfaces.

1997 BETTER MOVES
The microprocessor-controlled **C-LEG KNEE PROSTHESIS,** which in its current version allows the wearer to turn on customized settings that can be used for activities such as bicycling, was introduced.

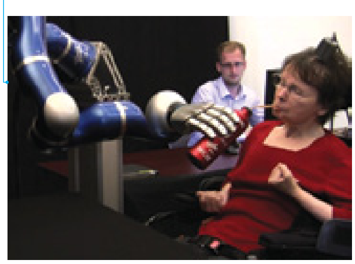
1999–2000 GOOD FEEDBACK
The Chapin and Nicolelis laboratories published the first description of a brain-machine interface operated by activity from rat brains, whereby the animals sensed the movement through a visual feedback signal. The following year the Nicolelis lab published the first study in which a monkey controlled the movements of a robotic arm using only brain activity.



2008–2011 BLADE RUNNER
After failing to qualify for the 2008 Summer Olympics Games, **OSCAR PISTORIUS** swept the 2008 Summer Paralympic Games and then got to the 400-meter semifinals at the 2011 International Association of Athletics Federations World Championships in Daegu, South Korea.

2011 MONKEY THINK, AVATAR DO
Nicolelis's team at the Duke University Center for Neuroengineering demonstrated that a monkey was able to use thoughts to manipulate the movements of a software avatar.

2012 FROM MY BRAIN TO MY ROBOT ARM
John Donoghue of Brown University and his colleagues showed with their **BRAINGATE NEURAL INTERFACE SYSTEM** that a subject with a brain implant could manipulate a robotic arm to pick up a drink.



2014 CYBORG OPENING KICK
The Nicolelis lab intends to provide an exoskeleton for a handicapped teenager to make the first kick of the opening event of the World Cup in Brazil.

data from the recording systems will be relayed wirelessly to a small computer processing unit contained in a backpack. Multiple digital processors will run various software algorithms that translate motor signals into digital commands that are able to control moving parts, or actuators, distributed across the joints of the robotic suit, hardware elements that adjust the positioning of the exoskeleton's artificial limbs.

FORCE OF BRAINPOWER

THE COMMANDS will permit the exoskeleton wearer to take one step and then another, slow down or speed up, bend over or climb a set of stairs. Some low-level adjustments to the positioning of the prosthetic hardware will be handled directly by the exoskeleton's electromechanical circuits without any neural input. The space suit–like garment will remain flexible but still furnish structural support to its wearer, a surrogate for the human spinal cord. By taking full advantage of this interplay between brain-derived control signals and the electronic reflexes supplied by the actuators, we hope that our brain-machine interface will literally carry the World Cup kicker along by force of willpower.

The kicker will not only move but also feel the ground underneath. The exoskeleton will replicate a sense of touch and balance by incorporating microscopic sensors that both detect the amount of force from a particular movement and convey the information from the suit back to the brain. The kicker should be able to feel that a toe has come in contact with the ball.

Our decade-long experience with brain-machine interfaces suggests that as soon as the kicker starts interacting with this exoskeleton, the brain will start incorporating this robotic body as a true extension of his or her own body image. From training, the accumulated experience obtained from this continuous feeling of contact with the ground and the position of the robotic legs should enable movement with fluid steps over a soccer pitch or down any sidewalk. All phases of this project require continuous and rigorous testing in animal experiments before we begin in humans. In addition, all procedures must pass muster with regulatory agencies in Brazil, the U.S. and Europe to ensure proper scientific and ethical re-

COURTESY OF OTTO BOCK HEALTHCARE (*artificial leg*); ANDREW MEDICHINI *AP Photo* (*Pistorius*); COURTESY OF MIGUEL A. L. NICOLELIS (*monkey avatar*); COURTESY OF BRAINGATE2.ORG (*BrainGate*) view. Even with all the uncertainties involved and the short time required for the completion of its first public demonstration, the simple idea of reaching for such a major milestone has galvanized Brazilian society's interest in science in ways rarely seen before.

REMOTE CONTROL

THE OPENING KICKOFF of the World Cup—or a similar event, say, the 2016 Olympic and Paralympic Games in Rio de Janeiro, if we miss the first deadline for any reason—will be more than just a one-time stunt. A hint of what may be possible with this technology can be gleaned from a two-part experiment already completed with monkeys. As a prelude, back in 2007, our research team at Duke trained rhesus monkeys to walk upright on a treadmill as the electrical activity of more than 200 cortical neurons was recorded simultaneously. Meanwhile Gordon Cheng, then at ATR Intelligent Robotics and Communication Laboratories in Kyoto, built an extremely fast Internet protocol that allowed us to send this stream of neuronal data directly to Kyoto, where it fed the electronic controllers of CB1, a humanoid robot. In the first half of this across-the-globe experiment, Cheng and my group at Duke showed that the same software algorithms developed previously for translating thoughts into control of robotic arms could also convert patterns of neural activity involved in bipedal locomotion to make two mechanical legs walk.

The second part of the experiment yielded a much bigger surprise. As one of our monkeys, Idoya, walked on the treadmill in Durham, N.C., our brain-machine interface broadcast a constant stream of her brain's electrical activity through Cheng's Internet connection to Kyoto. There CB1 detected these motor commands and began to walk as well, almost immediately. CB1 first needed some support at the waist, but in later experiments it began to move autonomously in response to the brain-derived commands generated by the monkey on the other side of the globe.

What is more, even when the treadmill at Duke stopped and Idoya ceased walking, she could still control CB1's leg movements in Kyoto by merely observing the robot's legs moving on a live video feed and imagining each step CB1 should take. Idoya continued to produce the brain patterns required to make CB1 walk even though her own body was no longer engaged in this motor task. This transcontinental brain-machine interface demonstration revealed that it is possible for a human or a simian to readily transcend space, force and time by liberating brain-derived commands from the physical limits of the biological body that houses the brain and broadcasting them to a man-made device located far from the original thought that generated the action.

These experiments imply that brain-machine interfaces could make it possible to manipulate robots sent into environments that a human will never be able to penetrate directly: our thoughts might operate a microsurgical tool inside the body, say, or direct the activities of a humanoid worker trying to repair a leak at a nuclear plant.

The interface could also control tools that exert much stronger or lighter forces than our bodies can, thereby breaking free of ordinary constraints on the amount of force an individual can exert. Linking a monkey's brain to a humanoid robot has already done away with constraints imposed by the clock: Idoya's mental trip around the globe took 20 milliseconds—less time than was required to move her own limb.

Along with inspiring visions of the far future, the work we have done with monkeys gives us confidence that our plan may be achievable. At the time of this writing, we are waiting to see whether the International Football Association (FIFA), which is in charge of organizing the ceremony, will grant our proposal to have a paraplegic young adult participate in the opening ceremony of the inaugural game of the 2014 World Cup. The Brazilian government—which is still awaiting FIFA's endorsement—has tentatively supported our application.

Bureaucratic difficulties and scientific uncertainties abound before our vision is realized. Yet I cannot stop imagining what it will be like during the brief but historic stroll onto a tropical green soccer pitch for three billion people to witness a paralyzed Brazilian youth stand up, walk again by his or her own volition, and ultimately kick a ball to score an unforgettable goal for science, in the very land that mastered the beautiful game. SA

MORE TO EXPLORE

Controlling Robots with the Mind. Miguel A. L. Nicolelis and John K. Chapin in *Scientific American,* Vol. 287, No. 4, pages 46–53; October 2002.

Cortical Control of a Prosthetic Arm for Self Feeding. Meel Velliste et al. in *Nature,* Vol. 453, pages 1098–1101; June 19, 2008.

Beyond Boundaries: The New Neuroscience of Connecting Brains with Machines—and How It Will Change Our Lives. Miguel Nicolelis. St. Martin's Griffin, 2012.

SCIENTIFIC AMERICAN ONLINE
Inspect an exoskeleton prototype at **ScientificAmerican.com/sep2012/exoskeleton**

TECHNOLOGY

The Edge of Ambition

10 projects that push the boundaries of the engineered world

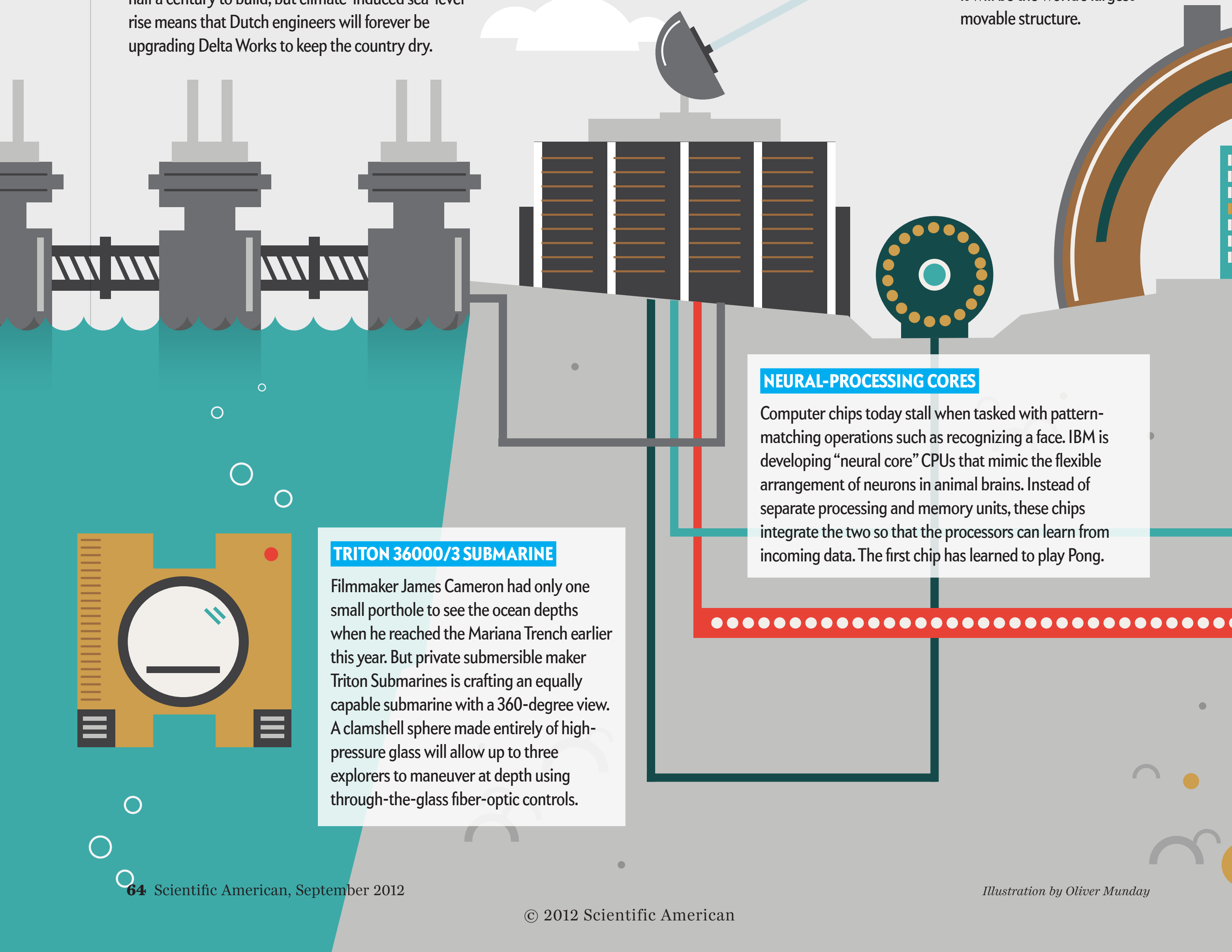
Research by Dave Mosher

DELTA WORKS

The world's largest water-battling structure isn't a dam—it's a network. More than 10,000 miles of levees, dikes and dams combine to protect the Netherlands from the North Sea. The project took half a century to build, but climate-induced sea-level rise means that Dutch engineers will forever be upgrading Delta Works to keep the country dry.

NEW SAFE CONFINEMENT

The world's largest sarcophagus since the Great Pyramid of Giza in 2560 B.C. will soon entomb the remains of the Chernobyl nuclear power plant. To minimize workers' radiation exposure, the 360-foot-high, 32,000-ton steel archway will be assembled 900 feet away from the reactor and slid into place on Teflon bearings. When completed in 2015, it will be the world's largest movable structure.



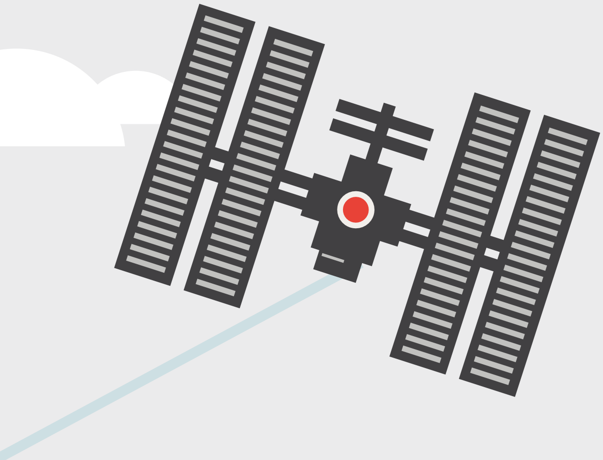
NEURAL-PROCESSING CORES

Computer chips today stall when tasked with pattern-matching operations such as recognizing a face. IBM is developing "neural core" CPUs that mimic the flexible arrangement of neurons in animal brains. Instead of separate processing and memory units, these chips integrate the two so that the processors can learn from incoming data. The first chip has learned to play Pong.

TRITON 36000/3 SUBMARINE

Filmmaker James Cameron had only one small porthole to see the ocean depths when he reached the Mariana Trench earlier this year. But private submersible maker Triton Submarines is crafting an equally capable submarine with a 360-degree view. A clamshell sphere made entirely of high-pressure glass will allow up to three explorers to maneuver at depth using through-the-glass fiber-optic controls.

Illustration by Oliver Munday

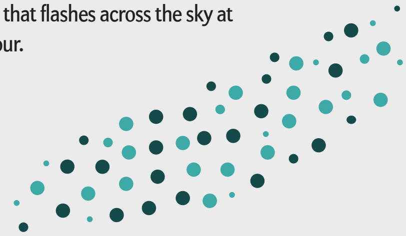


INTERNATIONAL SPACE STATION

Critics point out that this $100-billion laboratory in the sky hasn't delivered anything close to $100 billion worth of science. Yet as an engineering marvel, it is unsurpassed. Spacewalking astronauts assembled 40 major structural components, Tinkertoy-style, into a 15-room post-Earth palace that flashes across the sky at 17,000 miles an hour.

MICROROBOTIC SPIES

It took the U.S. Department of Defense five years to build a hummingbirdlike robot that flaps its wings to fly. The bird bot, unveiled in 2011, can shoot video and uplink it via satellite to its spymasters a continent away. Other researchers have created penny-size wireless robots that mimic a swarm of bees.



PROGRAMMABLE STEM CELLS

First humankind shaped tools out of stone, then steel and silicon. Next up: cells. Thousands of research trials have explored the potential of engineered stem cells, human cells programmed to carry out a specific function of our choosing. To take just one example from earlier this year: bioengineers programmed blood stem cells to morph into immune cells that seek out and kill cells infected with HIV.

INTERNET

Invisible and essential as air, the global Internet is the most important engineering feat in modern history.

MPONENG GOLD MINE

The gold in them thar hills is gone, but there's plenty left deep underground. To get to it, the South African mining company AngloGold Ashanti drilled more than two miles down, making Mponeng the deepest mine in the world. At such depths, temperatures reach 140 degrees Fahrenheit. The company keeps ambient temperatures below 85 degrees F—and workers conscious—by pumping slurry ice through metal pipes.

ENDURANCE ROBOT

NASA helped to design this autonomous swimmer to explore vast lakes buried below Antarctic ice sheets. The machine is a first draft of the robots that will one day probe the distant and perilous oceans thought to lie underneath the icy shell of Jupiter's moon Europa.

COMPLEXITY

Machines of the Infinite

Whether or not machines can quickly answer yes-or-no questions could affect everything from national security to the limits of human knowledge

By John Pavlus

ON A SNOWY DAY IN PRINCETON, N.J., IN MARCH 1956, a short, owlish-looking man named Kurt Gödel wrote his last letter to a dying friend. Gödel addressed John von Neumann formally even though the two had known each other for decades as colleagues at the Institute for Advanced Study in Princeton. Both men were mathematical geniuses, instrumental in establishing the U.S.'s scientific and military supremacy in the years after World War II. Now, however, von Neumann had cancer, and there was little that even a genius like Gödel could do except express a few overoptimistic pleasantries and then change the subject:

> *Dear Mr. von Neumann:*
>
> *With the greatest sorrow I have learned of your illness.... As I hear, in the last months you have undergone a radical treatment and I am happy that this treatment was successful as desired, and that you are now doing better....*
>
> *Since you now, as I hear, are feeling stronger, I would like to allow myself to write you about a mathematical problem, of which your opinion would very much interest me....*

Gödel's description of this problem is utterly unintelligible to nonmathematicians. (Indeed, he may simply have been trying to take von Neumann's mind off of his illness by engaging in an acutely specialized version of small talk.) He wondered how long it would take for a hypothetical machine to spit out answers to a problem. What he concluded sounds like something out of science fiction:

> *If there really were [such] a machine ... this would have consequences of the greatest importance. Namely, it would obviously mean that ... the mental work of a mathematician concerning Yes-or-No questions could be completely replaced by a machine.*

By "mental work," Gödel didn't mean trivial calculations like adding 2 and 2. He was talking about the intuitive leaps that mathematicians take to illuminate entirely new areas of knowledge. Twenty-five years earlier Gödel's now famous incompleteness theorems had forever transformed mathematics. Could a machine be made to churn out similar world-changing insights on demand?

A few weeks after Gödel sent his letter, von Neumann checked into Walter Reed Army Medical Center in Washington, D.C., where he died less than a year later, never having answered his friend. But the problem would outlive both of them. Now

SET DESIGN: KYLE BEAN; PHOTOGRAPHY: RYAN HOPKINSON

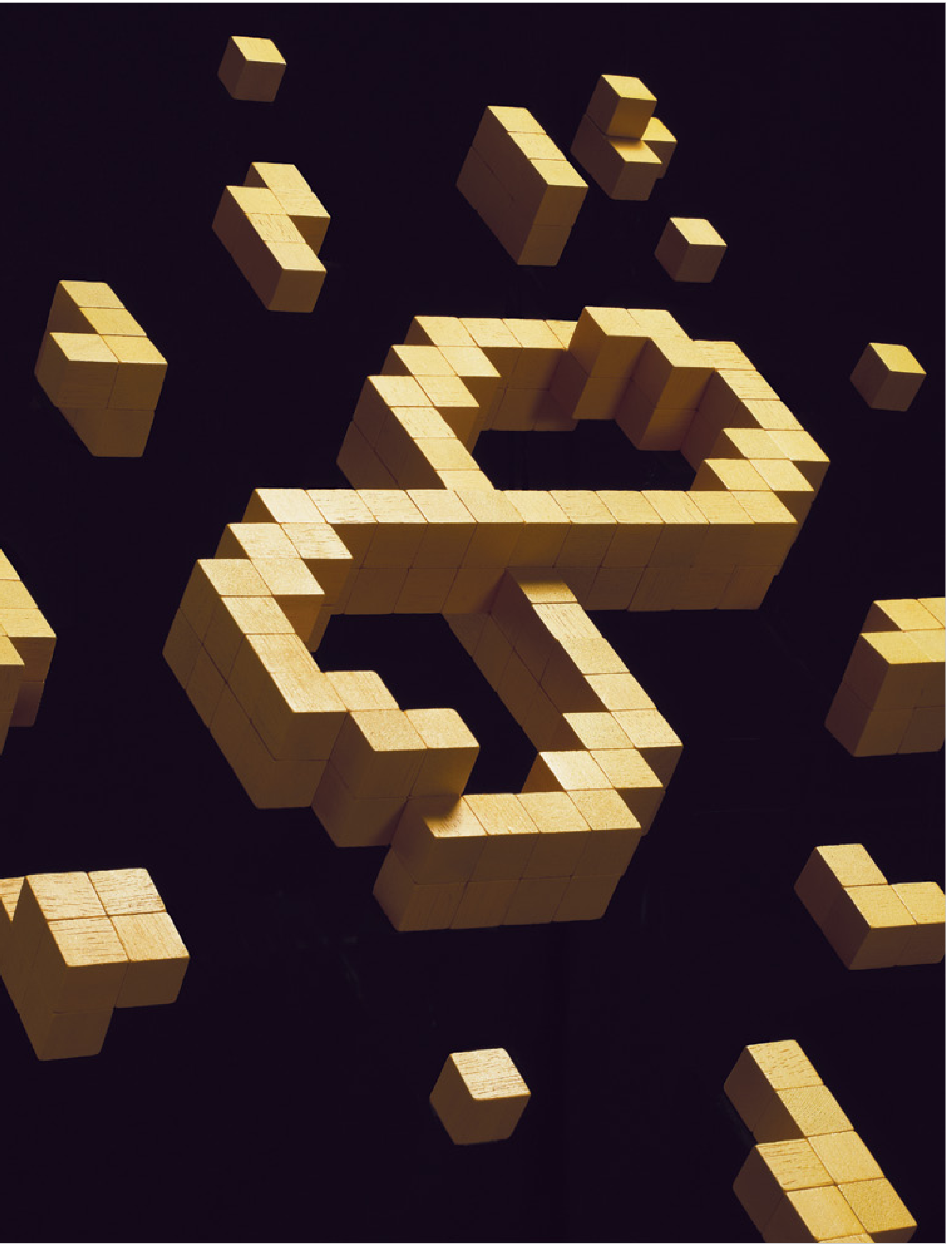


Illustration by Kyle Bean

John Pavlus is a writer and filmmaker focusing on science, technology and design topics. His work has appeared in *Wired, Nature, Technology Review* and other outlets.

IN BRIEF

The "P versus NP" question asks whether tough problems whose solutions can be quickly checked (like a jigsaw puzzle) are, at heart, easily solvable as well.

Despite decades of investigation, no one has been able to prove that the two categories are different. If they were not, machines would acquire enormous power.

The problem does not just affect code breakers and Web searches. It suggests a fundamental limitation for biological evolution, physical laws and the nature of knowledge.

known as P versus NP, Gödel's question went on to become an organizing principle of modern computer science. It has spawned an entirely new area of research called computational complexity theory—a fusion of mathematics, science and engineering that seeks to prove, with total certainty, what computers can and cannot do under realistic conditions.

But P versus NP is about much more than just the plastic-and-silicon contraptions we call computers. The problem has practical implications for physics and molecular biology, cryptography, national security, evolution, the limits of mathematics and perhaps even the nature of reality. This one question sets the boundaries for what, in theory, we will ever be able to compute. And in the 21st century the limits of computation look more and more like the limits of human knowledge itself.

THE BET

MICHAEL SIPSER was only a graduate student, but he knew someone would solve the P versus NP problem soon. He even thought he might be the one to do it. It was the fall of 1975, and he was discussing the problem with Leonard Adleman, a fellow graduate student in the computer science department at the University of California, Berkeley. "I had a fascination with P versus NP, had this feeling that I was somehow able to understand it in a way that went beyond the way everyone else seemed to be approaching it," says Sipser, who is now head of the mathematics department at the Massachusetts Institute of Technology. He was so sure of himself that he made a wager that day with Adleman: P versus NP would be solved by the end of the 20th century, if not sooner. The terms: one ounce of pure gold.

Sipser's bet made a kind of poetic sense because P versus NP is itself a problem about how quickly other problems can be solved. Sometimes simply following a checklist of steps will get you to the end result in relatively short order. Think of grocery shopping: you tick off the items one by one until you reach the end of the list. Complexity theorists label these problems P, for "polynomial time," which is a mathematically precise way of saying that no matter how long the grocery list becomes, the amount of time that it will take to tick off all the items will never grow at an unmanageable rate.

In contrast, many more problems may or may not be practical to solve by simply ticking off items on a list, but checking the solution is easy. A jigsaw puzzle is a good example: even though it may take effort to put together, you can recognize the right solution just by looking at it. Complexity theorists call these quickly checkable, "jigsaw puzzle–like" problems NP.

Four years before Sipser made his bet, a mathematician named Stephen Cook had proved that these two kinds of problems are related: every quickly solvable P problem is also a quickly checkable NP problem. The P versus NP question that emerged from Cook's insight—and that has hung over the field ever since—asks if the reverse is also true: Are all quickly checkable problems quickly solvable as well? Intuitively speaking, the answer seems to be no. Recognizing a solved jigsaw puzzle ("Hey, you got it!") is hardly the same thing as doing all the work to find the solution. In other words, P does not seem to equal NP.

What fascinated Sipser was that nobody had been able to mathematically *prove* this seemingly obvious observation. And without a proof, a chance remained, however unlikely or strange, that all NP problems might actually be P problems in disguise. P and NP might be equal—and because computers can make short work of any problem in P, P equals NP would imply that computers' problem-solving powers are vastly greater than we ever imagined. They would be exactly what Gödel described in his letter to von Neumann: mechanical oracles that could efficiently answer just about any question put to them, so long as they could be programmed to verify the solution.

Sipser knew this outcome was vanishingly improbable. Yet proving the opposite, much likelier, case—that P is not equal to NP—would be just as groundbreaking.

Like Gödel's incompleteness theorems, which revealed that mathematics must contain true but unprovable propositions, a proof showing that P does not equal NP would expose an objective truth concerning the limitations of knowledge. Solving a jigsaw puzzle and recognizing that one is solved are two fundamentally different things, and there are no shortcuts to knowledge, no matter how powerful our computers get.

Proving a negative is always difficult, but Gödel had done it. So to Sipser, making his bet with Adleman, 25 years seemed like more than enough time to get the job done. If he couldn't prove that P did not equal NP himself, someone else would. And he would still be one ounce of gold richer.

COMPLICATED FAST

ADLEMAN SHARED Sipser's fascination, if not his confidence, because of one cryptic mathematical clue. Cook's paper establishing that P problems are all NP had also proved the existence of a special kind of quickly checkable type of problem called NP-complete. These problems act like a set of magic keys: if you find a fast algorithm for solving one of them, that algorithm will also unlock the solution to every other NP problem and prove that P equals NP.

There was just one catch: NP-complete problems are among the hardest anyone in computer science had ever seen. And once discovered, they began turning up everywhere. Soon after Cook's paper appeared, one of Adleman's mentors at Berkeley, Richard M. Karp, published a landmark study showing that 21 classic computational problems were all NP-complete. Dozens, then hundreds, soon followed. "It was like pulling a finger out of a dike," Adleman says. Scheduling air travel, packing moving boxes into a truck, solving a Sudoku puzzle, designing a computer chip, seating guests at a wedding reception, playing Tetris and thousands of other practical, real-world problems have been proved to be NP-complete.

How could this tantalizing key to solving P versus NP seem so commonplace and so uncrackable at the same time? "That's why I was interested in studying the P versus NP problem," says Adleman, who is now a professor at the University of Southern California. "The power and breadth of these computational questions just seemed deeply awesome. But we certainly didn't understand them. And it didn't seem like we would be understanding them anytime soon." (Adleman's pessimism about P versus NP led to a world-changing invention: a few years after making his bet, Adleman and his colleagues Ronald Rivest and Adi Shamir exploited the seeming incommensurability of P and NP to create their eponymous RSA encryption algorithm, which remains in wide use for online banking, communications and national security applications.)

NP-complete problems are hard because they get complicated fast. Imagine you are a backpacker planning a trip through a number of cities in Europe, and you want a route that takes you through each city while minimizing the total distance you will need to travel. How do you find the best route? The simplest method is just to try out each possibility. With five cities to visit, you need to check only 12 possible routes. With 10 cities, the number of possible routes mushrooms to more than 180,000. At 60 cities, the number of paths exceeds the number of atoms in the known universe. This computational nightmare is known as the traveling salesman problem, and in over 80 years of intense study, no one has ever found a general way to solve it that works better than trying every possibility one at a time.

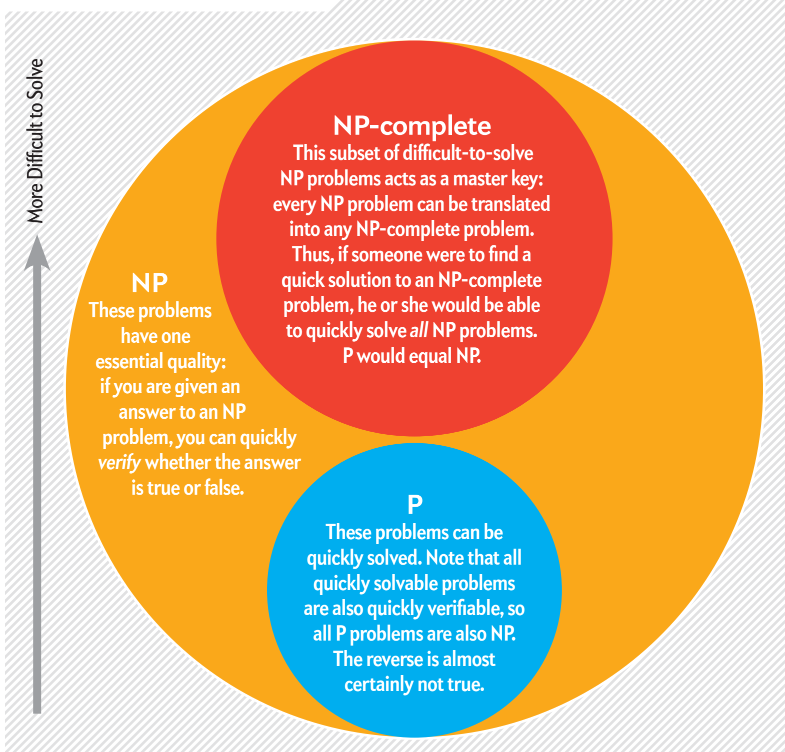
That is the perverse essence of NP-completeness—and of P versus NP: not only are all NP-complete problems equally impossible to solve except in the simplest cases—even if your computer has more memory than God and the entire lifetime of the universe to work with—they seem to pop up everywhere. In fact, these NP-com-

COMPUTATIONAL UNIVERSE

The Basics of Complexity

How long will it take to solve that problem? That's the question that researchers ask as they classify problems into computational classes. As an example, consider a simple sorting task: put a list of random numbers in order from smallest to largest. As the list gets bigger, the time it takes to sort the list increases at a manageable rate—as the square of the size of the list, perhaps. This puts it in class "P" because it can be solved in polynomial time. Harder questions, such as the "traveling salesman" problem [*see box on next page*], require exponentially more time to solve as they grow more complex. These "NP-complete" problems will quickly get so unwieldy that not even billions of processors working for billions of years can crack them.

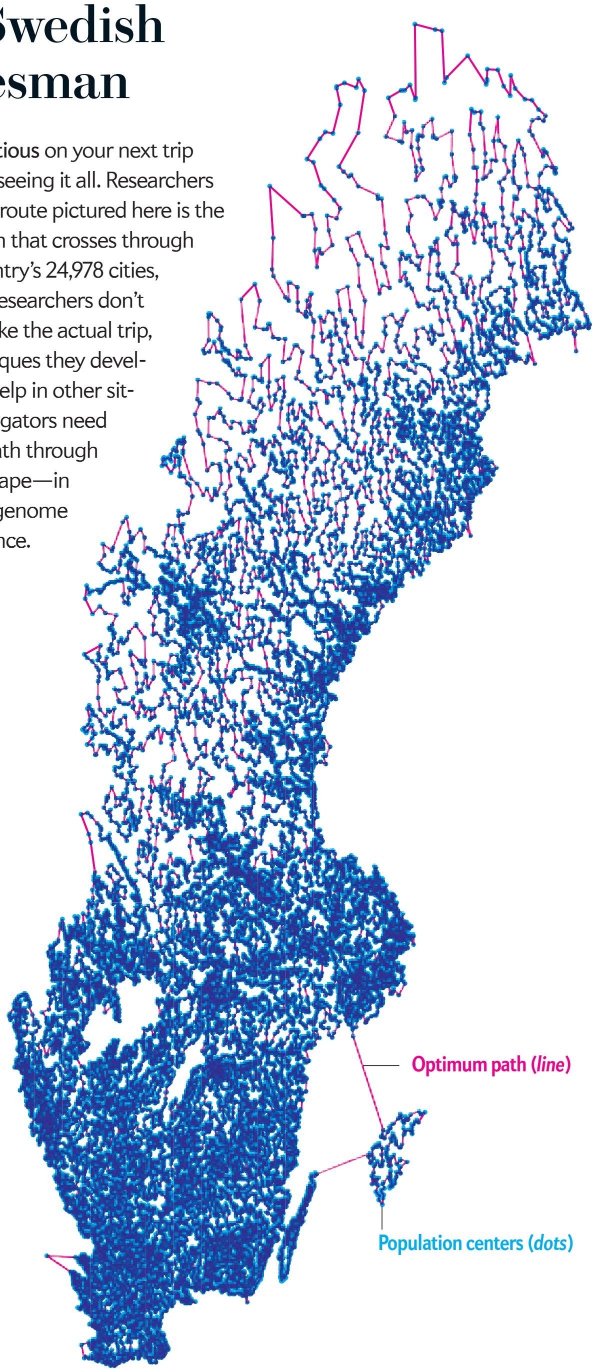
What Kind of Problem Is It?



APPLICATIONS

The Swedish Salesman

If you're feeling ambitious on your next trip to Sweden, consider seeing it all. Researchers have proved that the route pictured here is the shortest possible path that crosses through every one of the country's 24,978 cities, towns and villages. Researchers don't expect anyone to make the actual trip, but the search techniques they developed to solve it will help in other situations where investigators need to find the optimal path through a complicated landscape—in microchip design or genome sequencing, for instance.



DAVID APPLEGATE *AT&T Labs*, ROBERT BIXBY *Rice University*, VASEK CHVATAL *Concordia University* AND WILLIAM J. COOK *Georgia Institute of Technology*

plete problems don't just frustrate computer scientists. They seem to put limits on the capabilities of nature itself.

NATURE'S CODE

THE PIONEERING Dutch programmer Edsger Dijkstra understood that computational questions have implications beyond mathematics. He once remarked that "computer science is no more about computers than astronomy is about telescopes." In other words, computation is a behavior exhibited by many systems besides those made by Google and Intel. Indeed, any system that transforms inputs into outputs by a set of discrete rules—including those studied by biologists and physicists—can be said to be computing.

In 1994 mathematician Peter Shor proved that cleverly arranged subatomic particles could break modern encryption schemes. In 2002 Adleman used strands of DNA to find an optimal solution to an instance of the traveling salesman problem. And in 2005 Scott Aaronson, an expert in quantum computing who is now at M.I.T.'s Computer Science and Artificial Intelligence Laboratory, used soap bubbles, of all things, to efficiently compute optimal solutions to a problem known as the Steiner tree. These are all exactly the kinds of NP problems that computers should choke their circuit boards on. Do these natural systems know something about P versus NP that computers don't?

"Of course not," Aaronson says. His soap bubble experiment was actually a reductio ad absurdum of the claim that simple physical systems can somehow transcend the differences between P and NP problems. Although the soap bubbles did "compute" perfect solutions to the minimum Steiner tree in a few instances, they quickly failed as the size of the problem increased, just like a computer would. Adleman's DNA-strand experiment hit the same wall. Shor's quantum algorithm does work in all instances, but the factoring problem that it cracks is almost certainly not NP-complete. Therefore, the algorithm doesn't provide the key that would unlock every other NP problem. Biology, classical physics and quantum systems all seem to support the idea that NP-complete problems have no shortcuts. And that would only be true if P did not equal NP.

"Of course, we still can't prove it with airtight certainty," Aaronson says. "But if we were physicists instead of complexity theorists, 'P does not equal NP' would have been declared a law of nature long ago—just like the fact that nothing can go faster than the speed of light." Indeed, some physical theories about the fundamental nature of the universe—such as the holographic principle, suggested by Stephen Hawking's work on black holes—imply that the fabric of reality itself is not continuous but made of discrete bits, just like a computer [see "Is Space Digital?" by Michael Moyer; SCIENTIFIC AMERICAN, February]. Therefore, the apparent intractability of NP problems—and the limitations on knowledge that this implies—may be baked into the universe at the most fundamental level.

BRAIN MACHINE

SO IF THE VERY UNIVERSE itself is beholden to the computational limits imposed by P versus NP, how can it be that NP-complete problems seem to get solved all the time—even in instances where finding these solutions should take trillions of years or more?

For example, as a human fetus gestates in the womb, its brain wires itself up out of billions of individual neurons. Finding the best arrangement of these cells is an NP-complete problem—one that evolution appears to have solved. "When a neuron reaches out from one point to get to a whole bunch of other synapse points, it's basically a graph-optimization problem, which is NP-hard," says evolutionary neurobiologist Mark Changizi. Yet the brain doesn't actually solve the problem—it makes a close approximation. (In practice, the neurons consistently get within 3 percent of the optimal arrangement.) The *Caenorhabditis elegans* worm, which has only 302 neurons, still doesn't have a perfectly optimal neural-wiring diagram, despite billions on billions of generations of natural selection acting on the problem. "Evolution is constrained by P versus NP," Changizi says, "but it works anyway because life doesn't always require perfection to function well."

And neither, it turns out, do computers. That modern computers can do anything useful at all—much less achieve the wondrous feats we all take for granted on our video-game consoles and smartphones—is proof that the problems in P encompass a great many of our computing needs. For the rest, often an imperfect approximating algorithm is good enough. In fact, these "good enough" algorithms can solve immensely complex search and pattern-matching problems, many of which are technically NP-complete. These solutions are not always mathematically optimal in every case, but that doesn't mean they aren't useful.

Take Google, for instance. Many complexity researchers consider NP problems to be, in essence, search problems. But according to Google's director of research Peter Norvig, the company takes pains to avoid dealing with NP problems altogether. "Our users care about speed more than perfection," he says. Instead Google researchers optimize their algorithms for an even faster computational complexity category than P (referred to as linear time) so that search results appear nearly instantaneously. And if a problem comes up that cannot be solved in this way? "We either reframe it to be easier, or we don't bother," Norvig says.

That is the legacy and the irony of P versus NP. Writing to von Neumann in 1956, Gödel thought the problem held the promise of a future filled with infallible reasoning machines capable of replacing "the mental work of a mathematician" and churning out bold new truths at the push of a button. Instead decades of studying P versus NP have helped build a world in which we extend our machines' problem-solving powers by embracing their limitations. Lifelike approximation, not mechanical perfection, is how Google's autonomous cars can drive themselves on crowded Las Vegas freeways and IBM's Watson can guess its way to victory on *Jeopardy*.

GOLD RUSH

THE YEAR 2000 came and went, and Sipser mailed Adleman his ounce of gold. "I think he wanted it to be embedded in a cube of Lucite, so he could put it on his desk or something," Sipser says. "I didn't do that." That same year the Clay Mathematics Institute in Cambridge, Mass., offered a new bounty for solving P versus NP: $1 million. The prize helped to raise the problem's profile, but it also attracted the attention of amateurs and cranks; nowadays, like many prominent complexity theorists, Sipser says, he regularly receives unsolicited e-mails asking him to review some new attempt to prove that P does not equal NP—or worse, the opposite.

Although P versus NP remains unsolved, many complexity researchers still think it will yield someday. "I never really gave up on it," Sipser says. He claims to still pull out pencil and paper from time to time and work on it—almost for recreation, like a dog chewing on a favorite bone. P versus NP is, after all, an NP problem itself: the only way to find the answer is to keep searching. And while that answer may never come, if it does, we will know it when we see it. SA

MORE TO EXPLORE

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BASIC SCIENCE

Questions for the Next Million Years

What would scientists learn if they could run studies that lasted for hundreds or thousands of years—or more?

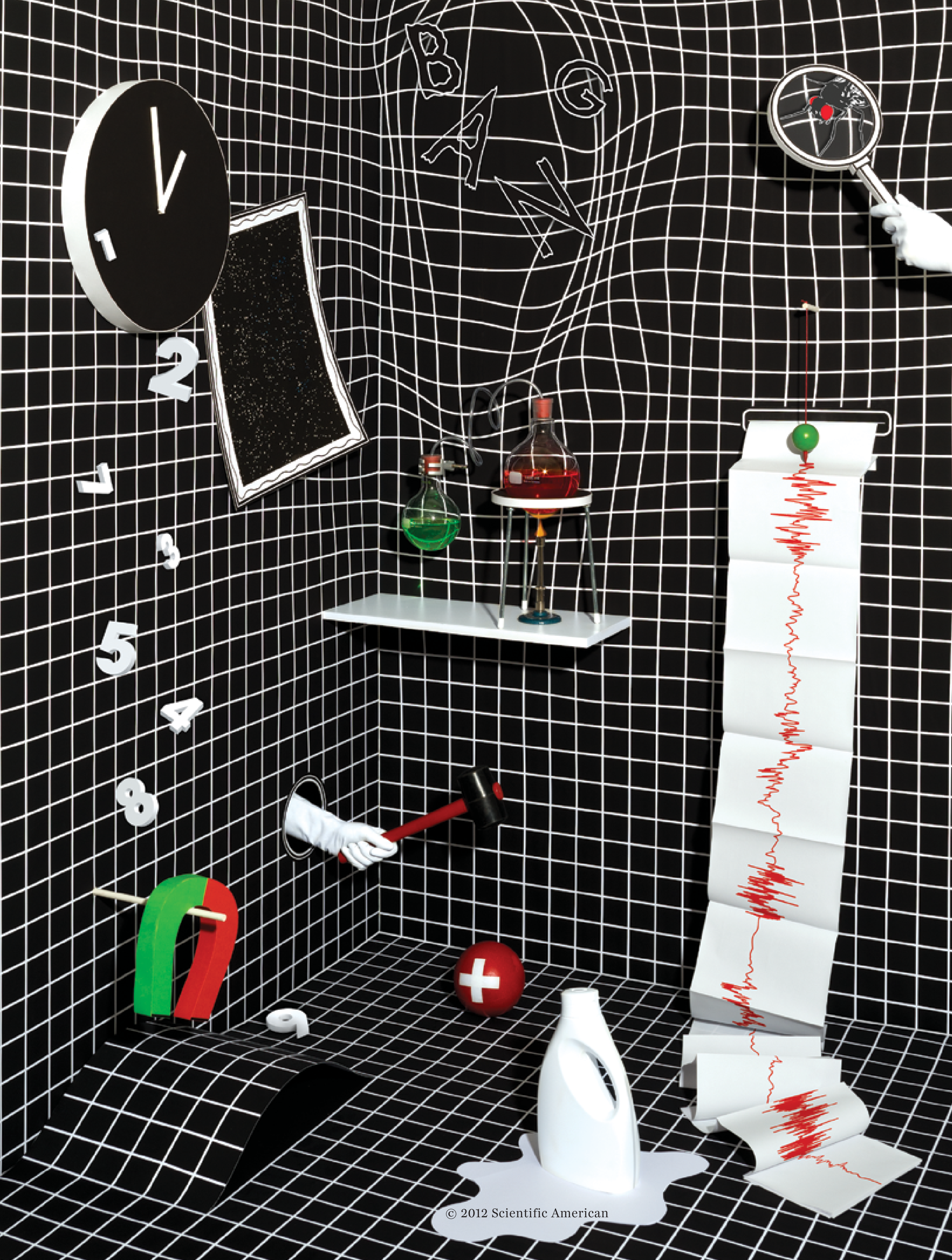
By Davide Castelvecchi

A LIFETIME IS VERY LONG RELATIVE TO THE picosecond it takes for two atoms to form a molecule, but it is the blink of an eye compared to many natural phenomena, from the rise of mountain chains to the collisions of galaxies. To answer questions that take more than a lifetime to resolve, scientists hand their efforts down from one generation to the next. In medical science, for example, longitudinal studies often follow subjects well after the original researchers have passed; some studies that are still ongoing started as far back as the 1920s. The record for the most extensive sequence of uninterrupted data gathering in history may belong to the ancient Babylonians' Astronomical Diaries, which contain at least six centuries' worth of observations from the first millennium B.C.; those records have revealed recurring patterns in such events as solar and lunar eclipses.

In most fields of scientific research, however, some of the most interesting and fundamental questions remain open because scientists simply have not had enough time to pursue them. But what if time were no object? I recently spoke with leading researchers in various fields about the problems they would attack if they had 1,000 years—or 10,000 or even a million—to make observations or perform experiments. (To keep the focus on the science rather than on futurology, I asked them to assume they could use only technology that is state of the art today.) Condensed versions of their intriguing replies follow.

Davide Castelvecchi *is a contributing editor for* Scientific American.

Photoillustration by Pixelgarten


BANG

10,000 YEARS HOW DID LIFE BEGIN?

ROBERT HAZEN, earth scientist at George Mason University

In the early 1950s Stanley Miller and Harold Urey of the University of Chicago famously showed that some basic building blocks of life, such as amino acids, form spontaneously given the right conditions. It seemed that solving the mystery of the origin of life could be just a matter of combining the right chemicals and waiting long enough. It has not turned out to be that simple, but over 10,000 years or so a modern version of the Urey-Miller experiment might yield some rudimentary self-replicating molecule able to evolve through natural selection—in short, life.

An experiment to simulate the origin of life has to take place in a geochemically plausible environment and start from scratch. The primordial soup may have contained millions of different kinds of small molecules, which could combine and react in an astronomical number of possible ways. In the ocean, though, they would have been so diluted that the chances of any two molecules running into each other, much less reacting chemically, were very low. The most plausible explanation is that self-replicating molecules first assembled on the surface of rocks. The wet surfaces of primordial Earth would have constituted a vast natural laboratory, running perhaps 10^{30} little experiments at any one time, over a period of maybe 100 million to 500 million years.

A 10,000-year laboratory effort could attempt to re-create this situation by running huge numbers of tiny experiments simultaneously. These molecular nurseries would look from the outside like rooms filled with racks of computer servers, but inside there would be chemical "labs-on-chips" containing hundreds of microscopic wells, each with different combinations of compounds reacting on a variety of mineral surfaces. The chips would constantly and autonomously monitor the reactions to check for signs that a molecule had gone into runaway self-replication.

Experimenters could cut down the time needed from millions to thousands of years by focusing on combinations of chemicals that are most likely do something interesting. With luck, eventually we will learn enough about how nature works to trim this time down to a few decades.

10,000 YEARS ARE NATURE'S CONSTANTS TRULY FIXED?

GERALD GABRIELSE, physicist at Harvard University

The basic laws of physics appear to be universal and eternal: so far as we know, all protons have the same amount of electrostatic charge, light always travels at the same speed, and so on. Yet certain proposed models of reality allow for variations, and some astronomical studies have claimed, controversially, to have seen small changes. Meanwhile all laboratory data have held steady. My lab, for instance, has measured the strength of the electron's magnetism—the most precise measurement, to my knowledge, of any property of a fundamental particle. If repeated for thousands of years, such an experiment might see a shift.

To measure the electron's magnetism or, more precisely, its "magnetic moment"—the subatomic analogue of a bar magnet's strength—we confine a single electron to a plane with an electrostatic field and use a magnetic field to force the electron to move in circles. We keep our apparatus at less than a tenth of a degree above absolute zero so that the electron's motion is in its state of lowest possible energy. With radio-frequency waves, we then force the electron's magnet to flip. The particle's response and, in particular, the rates at which we can make it flip depend on its magnetic moment, which we can then determine to three parts in 10^{13}.

If the magnetic moment had changed by one part in 1,000 over the entire history of the universe and if the change had gone on at a constant pace all along, our experiment would have already detected it. Of course, science can never prove that something is exactly constant, only that its rate of change is extremely small. Moreover the rate of change could be much slower now than it was in the early universe, making it difficult to spot in the lab. But if we repeated our experiment over 10,000 years and saw no change, that stability would place stringent constraints on any theoretical predictions of changing constants. (It would also cast doubt on assertions that experimental observations of light from distant quasars have detected slight changes in the strength of the electromagnetic interaction since the early moments of the universe.)

Naturally, our techniques and those of other labs are certain to improve. I suspect that increasingly clever methods will enable us to make more progress in far less time than 10,000 years.

IN BRIEF

Many natural phenomena are difficult to observe because they occur on timescales much longer than a human life.

The author asked leading researchers what experiments could be possible if they could live for thousands of years.

Experiments had to be based on current technology and had to address a fundamental question that cannot be answered in a shorter time.

Illustrations by Thomas Fuchs

10,000 YEARS
HOW COMMON ARE MEGAQUAKES?

THORNE LAY, seismologist
at the University of California, Santa Cruz

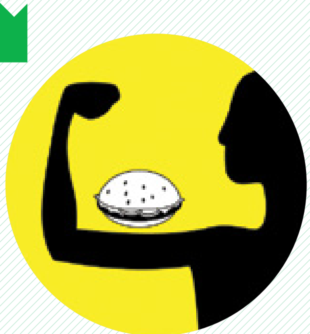
The magnitude 9.0 Tohoku-Oki earthquake and tsunami that devastated northeastern Japan in March 2011 took the seismology community by surprise: almost no one thought the responsible fault could release so much energy in one event. We can reconstruct the history of seismic activity indirectly by inspecting the local geology, but this can never fully substitute for direct detection. Modern seismographs have been around for only slightly more than a century, too short a time to give a clear idea of the largest quakes that might strike a certain area every few centuries or more. If we could let these instruments run for thousands of years, however, we could map seismic risk much more accurately—including specifying which regions are capable of magnitude 9.0 even though they have not seen more than magnitude 8.0 in recorded history.

Multimillennial records would also answer another riddle: Do megaquakes—by which I mean tremors of magnitude 8.5 or greater—come in worldwide clusters? Records of the past 100 years or so suggest that they might: six of them occurred in the past decade, for instance, and none in the three preceding decades. Measurements over a longer period would tell us if this clustering involves physical interaction or is just a statistical fluke.

How smart can they get?

"If I evolved chimps or some other nonhuman primate toward greater cognitive abilities, how far would they go?"

- **Bruce Lahn,** geneticist at the University of Chicago



Will we evolve to resist major diseases?

"Humans' diet keeps changing, causing new scourges such as the diabetes epidemic. Over tens of thousands of years, will our bodies adapt?"

- Sarah Tishkoff, human geneticist at the University of Pennsylvania

10,000 YEARS
HOW DO MASSIVE STARS BLOW UP?

COLE MILLER, astronomer
at the University of Maryland

Supernovae are rare, occurring perhaps once every several decades in a large spiral galaxy such as ours. The last time one was seen here was A.D. 1604: Johannes Kepler described it as outshining everything in the night sky but Venus. All supernovae recorded in more recent times took place in other galaxies that are millions, if not billions, of light-years away. When we finally see a supernova up close, we will be able to study it not only with ordinary telescopes but also with two new kinds of observatories—one detecting neutrinos and the other, gravitational waves—which will tell us what actually goes on inside the exploding star. If you could wait 10,000 years, you would be virtually guaranteed to get 100 or 200 of these events—enough to distinguish their subtle variations.

The explosion of a star could happen in our galaxy at any time. When it starts, the screens of computers at a handful of gravitational-wave observatories around the world will begin to flash, signaling the passage of ripples in the fabric of space. These so-called gravitational waves are a key prediction of Einstein's general theory of relativity but have so far eluded direct detection. The waves will signal that the star's core has begun to collapse under its own gravitational pull. The compressed matter turns into neutrons and releases neutrinos—particles that can zip through matter and thus escape through the star's outer layers and into space (and reach observatories on Earth). The energy released by the collapse, mostly carried by neutrinos, could blow off the outer layers of the star, making it stupendously bright. In some cases, however, the shock wave might fizzle, yielding gravitational waves but no light. We do not know for sure, because so far we have only seen the final, visible stage (with the exception of a handful of neutrinos from a supernova in 1987). Having thousands of years to observe would make all the difference. The new tools could also let us solve another open question—namely, in what conditions a dying star leaves behind a black hole or a neutron star.

100,000 YEARS HOW DO MATERIALS DECAY?

KRISTIN PERSSON, theoretical physicist and materials scientist at Lawrence Berkeley National Laboratory

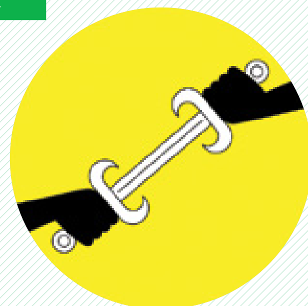
We build things all the time, but how do we know how long they will last? If we are going to build storage for nuclear waste, we need to be sure that the containers will last until the material inside is no longer dangerous. And if we are not going to fill the planet up with trash, it would help to know how much time it takes plastics and other materials to degrade.

The only way to be sure is to put these materials under stress tests for 100,000 years or so and see how they hold up. Then we could learn to build things that truly last—or that degrade in a "green" way.

We could, for example, test such materials as the copper-based alloys and glasses typically used for encasing nuclear waste. (Repositories are supposed to go deep underground in carefully chosen locations. But geologic conditions may change in unpredictable ways within a few thousand years.) Such experiments would expose the materials to accelerated wear and tear and to chemical abuse—say, varying pH. They would dial temperature up and down to simulate the cycles of day and night and of the seasons.

Even materials that seem to be impervious to the harshest conditions over scales of years may actually be degrading in subtle ways: our characterization methods are just not good enough to see whether you have lost a few atoms here and there. Yet over many thousands of years the damage could start to show, letting us know which sorts of materials are best.

Long-term testing would be tremendously helpful for other technological applications as well. Current laboratory and simulation techniques, for instance, cannot predict with confidence how the battery of a new electric car will perform over the next 15 years. Eventually computer simulations may become sophisticated enough to substitute for long-term experiments. In the meantime, though, we need to exercise extra caution when building things that need to last.



Will we eventually wage endless local wars?

"If in a few centuries we run out of cheap fossil fuels and cannot find a replacement, our societies will return from global to local. Will we relapse to tribalism and to endless small wars?"

- **Laurence Smith,** geographer at the University of California, Los Angeles

100,000 YEARS WHAT MAKES A NEW SPECIES?

JERRY COYNE, evolutionary biologist at the University of Chicago

Most new species in nature appear when a population becomes geographically isolated from other populations. It then adapts to the local environment and, sooner or later, acquires traits that prevent it from successfully mating with the original species or that would make the resulting offspring sterile, or both. The great open question of evolutionary biology is, Which of these two types of reproductive barriers tends to arise first—those that make crossbreeding difficult or those that lead to nonviable offspring?

Speciation occurs over geologic timescales. Thus, although we can see evidence of it in the fossil record or in DNA, we would have to wait a million years or more to see it reach completion. (Much faster routes to speciation have been documented that do not require geographic separation, but they are the exception rather than the norm.) But if we had, say, 100,000 years, we should be able to reproduce it in the laboratory.

The trick would be to work with an organism that produces new generations quickly, such as *Drosophila* (fruit flies). Researchers would isolate two or more populations in the lab and expose them to different diets and other conditions. You would then need to periodically test each population for genetic mutations and for changes in its anatomy, physiology, and behavior and once in a while have members of different populations meet to see what happens.

In special cases, my collaborators and I have been able to understand reproductive barriers indirectly by looking at many closely related species at different stages of evolutionary divergence. For geographically separated species of *Drosophila,* we found that the two types of barriers—mating problems and sterile offspring—evolve at about the same rate. But for species cohabiting the same area, interbreeding barriers seem to evolve quicker. It is not clear, however, whether such results apply to all groups of organisms.

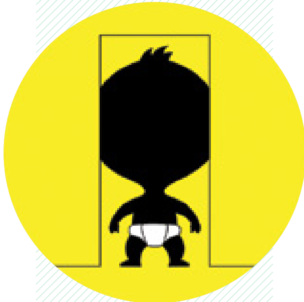
To obtain a new species much faster—perhaps in as little as 100 years—you could beef up the selection pressures to be far stronger than they would normally be in nature. In a landmark experiment in the 1980s researchers bred populations of fruit flies to adapt to different environments—as well as to prefer mating with individuals that shared their habitat preferences—in just 25 generations. Yet the conditions in that experiment were artificial, and it is doubtful whether the two populations produced could be regarded as different species. A very long experiment could be much more definitive.

1 MILLION YEARS IS THE UNIVERSE LOPSIDED?

GLENN STARKMAN, physicist at Case Western Reserve University

The heat of the big bang left behind radiation that has permeated the universe ever since. Space probes have mapped this cosmic microwave background, or CMB, over the entire sky and found it to be extraordinarily uniform save for small, random fluctuations, just as big bang theory had predicted. Such smoothness implies that the early universe was itself uniform. Yet some analyses, including those by my collaborators and me, saw an excess of symmetry between opposite sides of the sky and other anomalies, including a lack of the largest fluctuations, those that should span more than 60 degrees in the firmament.

To find out if these are real features or statistical flukes, we just need to keep observing. The CMB picture we see today is an accident of our place in space and time. The CMB has traveled to us from all directions for 13.7 billion years. Surveying it thus means mapping a spherical surface that surrounds us and has a radius of 13.7 billion light-years—the distance light has traveled in this time. If we wait long enough, the sphere will get bigger and bigger and thus cross new regions of the early universe. The anomalies are so large that it may take a billion years for the CMB sphere to get past them—when the sphere's radius would reach 14.7 billion light-years. If we could wait "just" one million years, most of the anomalies should be still there but slightly changed. By then, we would be able to see if they were on their way to disappearing—suggesting that they are flukes—or if their persistence reveals the presence of larger cosmic structures.



Will our heads get bigger?

"The narrowness of the human birth canal is a major bottleneck on the size of our heads. Will our use of C-sections, continued for hundreds of thousands of years, lead us to evolve larger brains?"

▪ **Katerina Harvati,** paleoanthropologist at the University of Tübingen in Germany

1 MILLION YEARS ARE PROTONS FOREVER?

SEAN M. CARROLL, theoretical physicist at the California Institute of Technology

The universe's ordinary matter consists, for the most part, of protons—particles that have been around since the big bang. Whereas other subatomic particles, including neutrons, can spontaneously decay, protons appear to be exceptionally stable. Yet some grand unified theories, or GUTs—attempts to reinterpret all of particle physics as different facets of a single force—predict that protons should break down, too, with average life spans of up to 10^{43} years, depending on the theory. If we wait long enough, though, could we finally see it happen?

To see the proton decay, all you have to do is fill a large underground tank with water and monitor it for little flashes of light that would go off as the protons in the water's atoms finally died. The more protons you monitor, the higher the chance that you will see one decay. Studies done with existing detectors show that protons last at least 10^{34} years, values that have already ruled out numerous GUTs. To have the final word, these detectors might need to run for 100 million years. But if we built detectors 100 times larger—making them about the size of a professional football stadium, voluminous enough to hold five million tons of water—just one million years should do. Unifying particle physics might be worth the wait.

How will giving birth at later ages change our biology?

"People are having children at an older age, when mutation rates in sperm are higher and the style of parenting is different. After tens of thousands of years, could these cultural changes affect our biology?"

▪ **Marcus Feldman,** mathematical biologist at Stanford University

MORE TO EXPLORE

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What Is a Species? Carl Zimmer in *Scientific American*, Vol. 298, No. 6, pages 72–79; June 2008.

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And the million-year experiment we're actually doing? Turn the page.

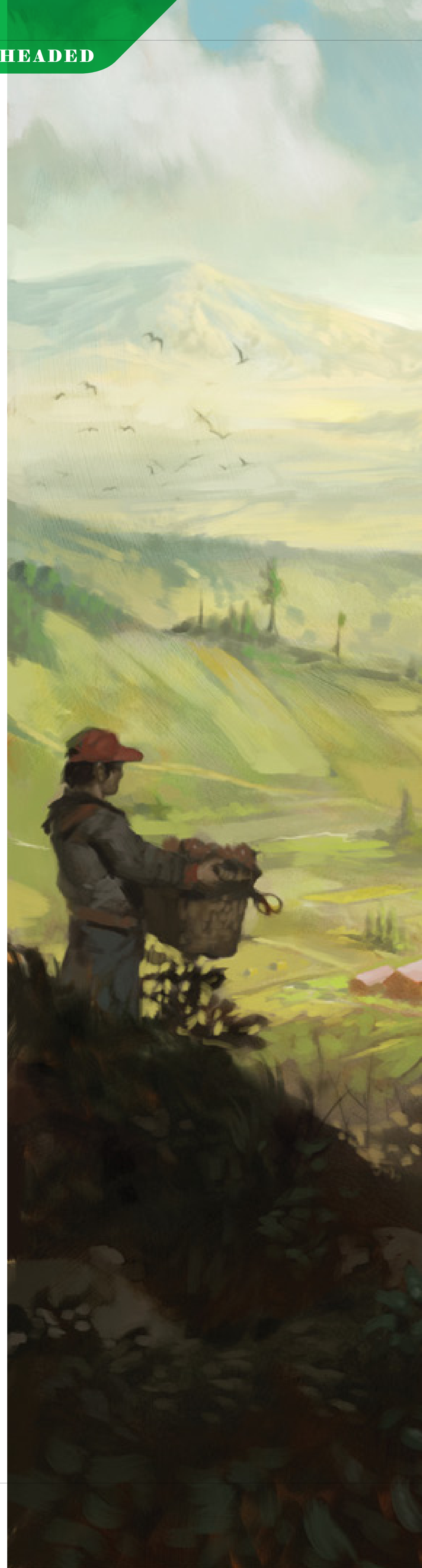
ECOLOGY

The Great Climate Experiment

How far can we push the planet?

By Ken Caldeira

Illustrations by Tyler Jacobson



BUSINESS, GOVERNMENT OR TECHNOLOGY forecasts usually look five or 10 years out, 50 years at most. Among climate scientists, there is some talk of century's end. In reality, carbon dioxide dumped into the atmosphere today will affect Earth hundreds of thousands of years hence.

How will greenhouse gases change the far future? No one can say for sure exactly how Earth will respond, but climate scientists—using mathematical models built from knowledge of past climate systems, as well as the complex web of processes that impact climate and the laws of physics and chemistry—can make predictions about what Earth will look like.

Already we are witnessing the future envisioned by many of these models take shape. As predicted, there has been more warming over land than over the oceans, more at the poles than near the equator, more in winter than in summer and more at night

NEAR FUTURE: Industrial civilization continues to pump out more and more greenhouse gases with each passing year, which will result in hotter temperatures, an acidified ocean and weirder weather by century's end.

Ken Caldeira is a climate scientist working for the Carnegie Institution for Science's Department of Global Ecology at Stanford University. He investigates issues related to climate, carbon and energy systems. Caldeira's primary tools are climate and carbon cycle models, and he also does field-work related to ocean acidification.

than in the day. Extreme downpours have become more common. In the Arctic, ice and snow cover less area, and methane-rich permafrost soils are beginning to melt. Weather is getting weirder, with storms fueled by the additional heat.

What are the ultimate limits of the change that we are causing? The best historical example comes from the 100-million-year-old climate of the Cretaceous period, when moist, hot air enveloped dinosaurs' leathery skin, crocodilelike creatures swam in the Arctic and teeming plant life flourished in the CO_2-rich air. The greenhouse that is forming now will have consequences that last for hundreds of thousands of years or more. But first, it will profoundly affect much of life on the planet—especially us.

A DESERT IN ITALY

ONE OF THE GREATEST uncertainties in climate prediction is the amount of CO_2 that will ultimately be released into the atmosphere. In this article, I will assume industrial civilization will continue to do what it has been doing for the past 200 years—namely, burn fossil fuels at an accelerating rate until we can no longer afford to pull them out of the ground.

Just how much CO_2 could we put into the atmosphere? All told, there are about one quadrillion metric tons (10^{21} grams) of organic carbon locked up in Earth's sedimentary shell in one form or another. So far we have burned only one twentieth of 1 percent of this carbon, or roughly 2,000 billion metric tons of CO_2.

With all the carbon locked in Earth's crust, we will never run out of fossil fuels. We are now extracting oil from tar sands and natural gas from water-fractured shale—both resources once thought to be technologically and economically inaccessible. No one can confidently predict just how far ingenuity can take us. Yet eventually the cost of extraction and processing will become so high that fossil fuels will become more expensive than alternative resources. In the scenario envisaged here, we ultimately burn about 1 percent of the available organic carbon over the next few centuries. That is in the range of the amount of extraction most likely to become technologically feasible in the foreseeable future. We further assume that in the future humanity will learn to extract unconventional fossil fuels but will burn them at slower rates.

Without any change in our habits, Earth may warm by about five degrees Celsius (nine degrees Fahrenheit) by 2100, although the actual warming could be half or even double this amount, depending primarily on how clouds respond. This change is about the difference between the average climate of Boston, Mass., and Huntsville, Ala.

In the northern midlatitudes between 30 degrees north and 60 degrees north—a band that includes the U.S., Europe, China, and most of Canada and Russia—the annual average temperature drops two thirds of a degree C with each degree of increasing latitude. With five degrees C of warming in a century, that translates into an average poleward movement of more than 800 kilometers in that period, for an average poleward movement of temperature bands exceeding 20 meters *each day*. Squirrels may be able to keep up with this rate, but oak trees and earthworms have difficulty moving that fast.

Then there will be the rains. Earth is a planetary-scale heat engine. The hot sun warms equatorial air, which then rises and cools. The cooling condenses water vapor in the air, which falls back to Earth as rain—hence, the belt of torrential rains that occur near the equator.

Yet this water condensation also heats the surrounding air, causing it to rise even more rapidly. This hot, dry air reaches as high as jets fly, then spreads laterally toward the poles. At altitude, the hot air radiates heat to space and thus becomes cool, which causes it to sink back toward the planet's surface. The sun's rays pass through this dry, cloudless air, beating down to heat the arid surface. Today such dry air sinks occur at about 30 degrees north and south latitude, thus creating the great belts of desert that encircle the globe.

With greenhouse warming, the rising air is hotter. Thus, it takes more time for this air to cool off and sink back to Earth. As a result, these desert bands move toward the poles.

The climate of the Sahara Desert may move northward. Already southern Europe has been experiencing more intense droughts despite overall increases in precipitation globally, and it may lose the Mediterranean climate that has long been considered one of the most desirable in the world. Future generations may say the same about the Scandinavian climate instead.

Up there in the northern midlatitudes, growing seasons are getting longer. Spring springs sooner: plants flower, lake ice melts and migratory birds return earlier than in the historical past.

That will not be the only benefit to croplands in Canada and Siberia. Plants make food by using the energy in sunlight to merge CO_2 and water. For the most part, plants absorb CO_2 via little pores in leaves known as stomata. When the stomata are open wide, the plants can get plenty of CO_2, but a lot of water evaporates through these gaping holes. Higher concentrations of atmospheric CO_2 mean a plant can get the CO_2 it needs by opening its stomata slightly or even building fewer stomata in leaves. In a high-CO_2 world, plants can grow more using the same amount of water. (This decrease in evaporation from plants also leads to a further decrease in precipitation, and because evaporation causes cooling, the decrease in evaporation causes further warming.)

Such gains will not be felt everywhere. In the tropics, high temperatures already compromise many crops; this heat stress will likely get worse with global warming. The outlook may be for increased crop productivity overall, with increases in the north exceeding the reductions near the equator. Global warming may not decrease overall food supply, but it may give more to the rich and less to the poor.

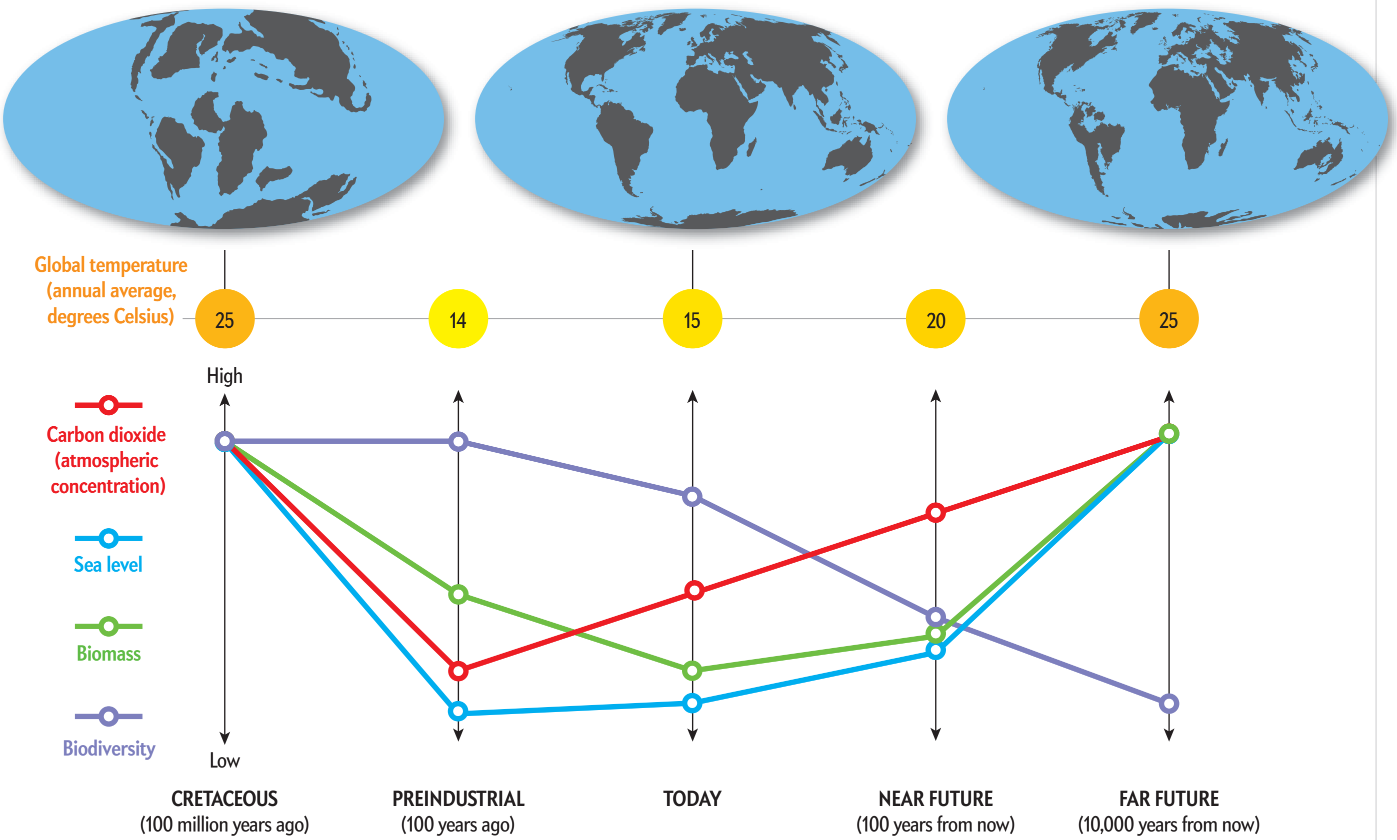
OCEANS OF CHANGE

THE VAST OCEANS resist change, but change they will. At no time in Earth's past—with the possible exception of mass-extinction events—has ocean chemistry changed as much and as rapidly as scientists expect it to over the coming decades. When CO_2

FAST-FORWARD

Climate: Past as Future

Assuming we continue to burn fossil fuels at will, releasing greenhouse gases such as carbon dioxide unabated into the atmosphere, the planet will be transformed. Already global temperatures have risen by nearly one degree Celsius—more than twice that in the Arctic. Average temperatures could eventually rise by 10 degrees C, enough to melt the vast quantities of water stored as ice in the glaciers of Greenland and Antarctica. Enough water could be released to raise sea levels by 120 meters. Atmospheric concentrations of carbon dioxide will reach levels last seen during the Cretaceous period, when dinosaurs roamed Earth, North America was cut in two by an enormous inland sea and crocodilelike creatures inhabited the poles.



FAR FUTURE: If greenhouse gas emissions from burning fossil fuels continue unabated, sea levels may rise by 120 meters and polar regions will become much warmer. Any human civilization still extant will need to adapt to these conditions.

enters the oceans, it reacts with seawater to become carbonic acid. In high enough concentrations, this carbonic acid can cause the shells and skeletons of many marine organisms to dissolve—particularly those made of a soluble form of calcium carbonate known as aragonite.

Scientists estimate that more than a quarter of all marine species spend part of their lives in coral reefs. Coral skeletons are made of aragonite. Even if chemical conditions do not deteriorate to the point where shells dissolve, acidification can make it more difficult for these organisms to build them. In just a few decades there will be no place left in the ocean with the kind of chemistry that has supported coral-reef growth in the geologic past. It is not known how many of these coral-dependent species will disappear along with the reefs.

Such chemical changes will most directly affect reef life, but the rest of us would be wise to consider the physical changes afoot. At the most basic level, water acts like mercury in a thermometer: add heat and watch it rise. The sea is also being fed by water now held in ice caps.

In high-CO_2 times in the ancient past, Earth warmed enough for crocodilelike animals to live north of the Arctic Circle. Roughly 100 million years ago annual average polar temperatures reached 14 degrees C, with summertime temperatures exceeding 25 degrees C. Over thousands of years temperatures of this magnitude would be sufficient to melt the great ice sheets of Greenland and Antarctica. With the ice sheets melted completely, sea level will be about 120 meters higher, flooding vast areas. That water's weight on low-lying continental regions will push those areas down farther into the mantle, causing the waters to lap even higher.

The poles are expected to warm about 2.5 times faster than Earth as a whole. Already the Arctic has warmed faster than anywhere else, by about two degrees C compared with 0.8 degree C globally. At the end of the last ice age, when the climate warmed by about five degrees C over thousands of years, the ice sheets melted at a rate that caused sea level to rise about one meter per century. We hope and expect that ice sheets will not melt more rapidly this time, but we cannot be certain.

CHASING VENUS

OVER THE PAST several million years Earth's climate has oscillated to cause the waxing and waning of great ice sheets. Our greenhouse gas emissions are hitting this complex system with a hammer. I have presented a scenario in which our climate evolves fairly smoothly, but jumps and starts that could shock biological, social and political systems beyond the limits of their resilience are also possible.

Consider that Arctic warming could cause hundreds of billions of metric tons of methane to rapidly bubble to the atmosphere from Arctic seabeds and soils. Molecule for molecule in the atmosphere, methane is about 37 times better at trapping heat than CO_2. Were this methane released suddenly, as may have occurred in a warming event 55 million years ago known as the Paleocene-Eocene Thermal Maximum, we could experience truly catastrophic warming. This risk is remote, however, according to most scientists.

Some have also suggested that feedback effects such as melting permafrost could cause a runaway greenhouse scenario where the oceans become so hot they evaporate. Because water vapor is itself a greenhouse gas, such a stronger water cycle could cause Earth to get so hot that atmospheric water vapor would persist and never rain out. In this case, atmospheric CO_2 from volcanoes and other sources would continue to accumulate. Cosmic rays would break apart the water vapor at high altitudes; the resulting hydrogen would eventually escape to space. Earth's climate would then settle into a state reminiscent of its planetary neighbor Venus.

Fortunately, ocean vaporization is not even a remote risk from today's greenhouse gas emissions. Simply put, there is a limit to how much CO_2 can heat the planet. Once CO_2 and water vapor concentrations rise high enough, the molecules increasingly scatter the incoming sunlight, preventing it from getting any hotter.

If we continue to burn fossil fuels, however, greenhouse gas concentrations in the atmosphere will reach levels last seen in the Cretaceous. Back then, inland seas flooded vast areas of the continents on a hot, moist Earth. Giant reptiles swam in the oceans. On land, dinosaurs grazed on luxuriant plant growth. If we burn just 1 percent of the organic carbon in Earth's crust over the next few centuries, humans will breathe the same CO_2 concentrations as the dinosaurs inhaled and experience similar temperatures.

Compared with the gradual warming of hothouse climates in the past, industrial climate change is occurring in fast-forward. In geologic history, transitions from low- to high-CO_2 atmospheres typically happened at rates of less than 0.00001 degree a year. We are re-creating the world of the dinosaurs 5,000 times faster.

What will thrive in this hothouse? Some organisms, such as rats and cockroaches, are invasive generalists, which can take advantage of disrupted environments. Other organisms, such as corals and many tropical forest species, have evolved to thrive in a narrow range of conditions. Invasive species will likely transform such ecosystems as a result of global warming. Climate change may usher in a world of weeds.

Human civilization is also at risk. Consider the Mayans. Even before Europeans arrived, the Mayan civilization had begun to collapse thanks to relatively minor climate changes. The Mayans had not developed enough resilience to weather small reductions in rainfall. The Mayans are not alone as examples of civilizations that failed to adapt to climate changes.

Crises provoked by climate change are likely to be regional. If the rich get richer and the poor get poorer, could this set in motion mass migrations that challenge political and economic stability? Some of the same countries that are most likely to suffer from the changes wrought by global warming also boast nuclear weapons. Could climate change exacerbate existing tensions and provoke nuclear or other apocalyptic conflict? The social response to climate change could produce bigger problems for humanity than the climate change itself.

STARTING OVER

THE WOODY PLANTS that flourished during the Cretaceous died, and some became coal over geologic time. The ocean's plankton ended up buried in sediments, and some became oil and gas. The climate cooled as sea life locked CO_2 in shells and skeletons.

The oceans will absorb most of our CO_2 over millennia. The resulting acidification will dissolve carbonate minerals, and the chemical effects of dissolution will allow yet more CO_2 to be absorbed. Nevertheless, atmospheric CO_2 concentrations will remain well above preindustrial levels of 280 parts per million for many tens of thousands of years. As a result, the ebb and flow of ice ages brought on by subtle variations in Earth's orbit will cease, and humanity's greenhouse gas emissions will keep the planet locked in a hothouse.

Over time increased temperatures and precipitation will accelerate the rate at which bedrock and soils dissolve. Streams and rivers will bring these dissolved rocks and minerals, containing elements such as calcium and magnesium, to the oceans. Perhaps hundreds of thousands of years from now some marine organism will take the calcium and CO_2 and form a carbonate shell. That seashell and millions of others may eventually become limestone. Just as the White Cliffs of Dover in England are a remnant of the Cretaceous atmosphere, the majority of carbon in the fossil fuels burned today will become a layer in the rocks—a record, written in stone, of a world changed by a single species. SA

MORE TO EXPLORE

Oceanography: Anthropogenic Carbon and Ocean pH. Ken Caldeira and Michael E. Wickett in *Nature*, Vol. 425, page 365; September 25, 2003.

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SCIENTIFIC AMERICAN ONLINE
For more on what to expect from climate change, watch the video at **ScientificAmerican.com/sep2012/future-climate**

PHYSICS

Beyond the Quantum Horizon

Once viewed as imposing absolute limits on knowledge and technology, quantum theory is now expanding the power of computers and the vistas of the mind

By David Deutsch and Artur Ekert

LATE IN THE 19TH CENTURY AN UNKNOWN ARTist depicted a traveler who reaches the horizon, where the sky meets the ground. Kneeling in a stylized terrestrial landscape, he pokes his head through the firmament to experience the unknown [*see illustration on page 89*]. The image, known as the Flammarion engraving, illustrates the human quest for knowledge. Two possible interpretations of the visual metaphor correspond to two sharply different conceptions of knowledge.

Either it depicts an *imaginary* barrier that, in reality, science can always pass through, or it shows a *real* barrier that we can penetrate only in our imagination. By the latter reading, the artist is saying that we are imprisoned inside a finite bubble of familiar objects and events. We may expect to understand the world of direct experience, but the infinity outside is inaccessible to exploration and to explanation. Does science continually transcend the familiar and reveal new horizons, or does it show us that our prison is inescapable—teaching us a lesson in bounded knowledge and unbounded humility?

Quantum theory is often given as the ultimate argument for the latter vision. Early on, its theorists developed a tradition of gravely teaching willful irrationality to students: "If you think you understand quantum theory, then you don't." "You're not allowed to ask that question." "The theory is inscrutable and so, therefore, is the world." "Things happen without reason or explanation." So textbooks and popular accounts have typically said.

Yet the developments of the past couple of decades contradict those characterizations. Throughout the history of the field, physicists often assumed that various kinds of constraints from quantum physics would prevent us from fully harnessing nature in the way that classical mechanics had accustomed us to. None of these impediments have ever materialized. On the contrary, quantum mechanics has been liberating. Fundamentally quantum-mechanical attributes of objects, such as superposition, entanglement, discreteness and randomness, have proved not to be limitations but resources. Using them, inventors have fashioned all kinds of miraculous devices, such as lasers and microchips.

These were just the beginning. We will increasingly use quantum phenomena for communications and computation systems that are unfathomably powerful from a classical point of view. We are discovering novel ways of harnessing nature and even of creating knowledge.

BEYOND UNCERTAINTY

IN 1965 INTEL co-founder Gordon Moore predicted that engineers would double the number of transistors on a chip every two years or so. Now known as Moore's Law, this prediction has held true for more than half a century. Yet from the outset, it

Illustration by Goñi Montes

David Deutsch, University of Oxford physicist and inventor of the concept of universal quantum computers, says he got interested in physics as a child when he rebelled at the claim that no one can understand everything that is understood.

Artur Ekert pioneered entanglement-based cryptography as a graduate student. He is now director of the Centre for Quantum Technologies in Singapore and a professor at Oxford's Mathematical Institute. He is a keen pilot and diver.

IN BRIEF

Quantum mechanics used to be described as a theory of limits, implying that our observations are unavoidably uncertain, that randomness rules the world, and that the theory itself is too weird to master and forces us to abandon the very idea that there is a world out there that science could describe.

Those misconceptions are rooted in philosophical doctrines, such as logical positivism, that were popular during the period when physicists developed and honed the theory.

In truth, quantum mechanics imposes no significant limits. The quantum world has a richness and intricacy that allows new practical technologies and kinds of knowledge.

rang warning bells. If the law continued to hold, you could predict when transistors would reach the size of individual atoms—and then what? Engineers would enter the realm of the unknowable.

In the traditional conception of quantum theory, the uncertainty principle sets a limit that no technological progress could ever overcome: the more we know about some properties, such as a particle's position, the less we can know about others, such as the particle's speed. What cannot be known cannot be controlled. Attempts to manipulate tiny objects meet with rampant randomness, classically impossible correlations, and other breakdowns of cause and effect. An inescapable conclusion followed: the end of progress in information technology was nigh.

Today, however, physicists routinely exert control over the quantum world without any such barrier. We encode information in individual atoms or elementary particles and process it with exquisite precision, despite the uncertainty principle, often creating functionality that is not achievable in any other way. But how?

Let us take a closer look at a basic chunk of information, as traditionally conceived: the bit. To a physicist, a bit is a physical system that can be prepared in one of two different states, representing two logical values: no or yes, false or true, 0 or 1. In digital computers, the presence or absence of a charge on the plates of a capacitor can represent a bit. At the atomic level, one can use two states of an electron in an atom, with 0 represented by the lowest-energy (ground) state and 1 by some higher-energy state.

To manipulate this information, physicists shine pulses of light on the atom. A pulse with the right frequency, duration and amplitude, known as a π-pulse, takes state 0 into state 1, and vice versa. Physicists can adjust the frequency to manipulate two interacting atoms, so that one atom controls what happens to the other. Thus, we have all the ingredients for one- and two-bit logic gates, the building blocks of classical computers, without any impediment from the uncertainty principle.

To understand what makes this feat of miniaturization possible, we have to be clear about what the uncertainty principle does and does not say. At any instant, some of the properties of an atom or other system, called its observables, may be "sharp"—possess only one value at that instant. The uncertainty principle does not rule out sharp observables. It merely states that not all observables in a physical system can be sharp at the same time. In the atom example, the sharp observable is energy: in both the 0 and 1 states, the electron has a perfectly well-defined energy. Other observables, such as position and velocity, are not sharp; the electron is delocalized, and its velocity likewise takes a range of different values simultaneously. If we attempted to store information using position and velocity, we would indeed encounter a quantum limit. The answer is not to throw up our hands in despair but to make a judicious choice of observables to serve as computer bits.

This situation recalls the comedy routine in which a patient tells a doctor, "It hurts when I do this," to which the doctor replies, "Don't do that." If some particle properties are hard to make sharp, there is a simple way around that: do not attempt to store information in those properties. Use some other properties instead.

BEYOND BITS

If all we want to do is build a classical computer using atoms rather than transistors as building blocks, then sharp observables are all we need. But quantum mechanics offers much more. It allows us to make powerful use of nonsharp observables, too. The fact that observables can take on multiple values at the same time greatly enriches the possibilities.

For instance, energy is usually a sharp observable, but we can turn it into a nonsharp one. In addition to being in its ground state or its excited state, an electron in an atom can also be in a superposition—both states at once. The electron is still in a perfectly definite state, but instead of being either 0 or 1, it is 0 *and* 1.

Any physical object can do this, but an object in which such states can be reliably prepared, measured and manipulated is called a quantum bit, or qubit. Pulses of light can make the energy of an electron change not only from one sharp value to another but from sharp to nonsharp, and vice versa. Whereas a π-pulse swaps states 0 and 1, a pulse of the same frequency but half the duration or amplitude, known as a $\pi/2$-pulse, sends the electron to a superposition of 0 and 1.

If we attempted to measure the energy of the electron in such a superposition, we would find it was either the energy of the ground state or the energy of the excited state with equal probability. In that case, we would encounter randomness, just as the naysayers assert. Once again, we can readily sidestep this apparent roadblock—and in doing so create radically new functionality. Instead of measuring the electron in this superposition, we leave it there. For instance, start with an electron in state 0, send in a $\pi/2$-pulse, then send in a second $\pi/2$-pulse. Now measure the electron. It will be in state 1 with a 100 percent probability [*see box on next page*]. The observable is sharp once again.

To see the significance, consider the most basic logic gate in a computer, NOT. Its output is the negation of the input: 0 goes to 1, 1 to 0. Suppose you were given the following assignment: design the square root of NOT—that is, a logic gate that, acting twice in succession on an input, negates it. Using only classical equipment, you would find the assignment impossible. Yet a $\pi/2$-pulse implements this "impossible" logic gate. Two such pulses in succession have exactly the desired effect. Experimental physicists have built this and other classically impossible gates using qubits made of such things as photons, trapped ions, atoms and nuclear spins [see "Quantum Computing with Ions," by Christopher R. Monroe and David J. Wineland; Scientific American, August 2008]. They are the building blocks of a quantum computer.

BEYOND CLASSICAL COMPUTATION

TO SOLVE a particular problem, computers (classical or quantum) follow a precise set of instructions—an algorithm. Computer scientists quantify the efficiency of an algorithm according to how rapidly its running time increases when it is given ever larger inputs to work on. For example, using the algorithm taught in elementary school, one can multiply two n-digit numbers in a time that grows like the number of digits squared, n^2. In contrast, the fastest-known method for the reverse operation—factoring an n-digit integer into prime numbers—takes a time that grows exponentially, roughly as 2^n. That is considered inefficient.

By providing qualitatively new logic gates, quantum mechanics makes new algorithms possible. One of the most impressive examples is for factoring. A quantum algorithm discovered in 1994 by Peter

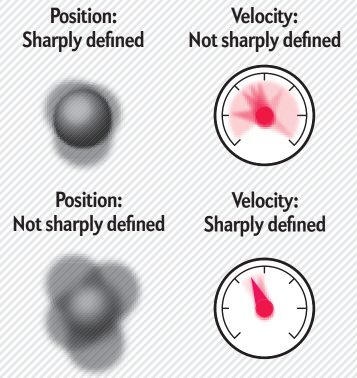
SHOWSTOPPERS NO LONGER

Supposed Limits to Quantum Computing—and How to Break Them

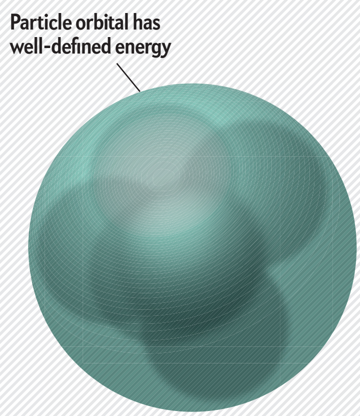
Quantum mechanics is often portrayed as the ultimate obstacle to the miniaturization of electronics. Fortunately, it is no such thing. Physicists have learned to work around the barriers they used to worry about. In fact, it is at the quantum level that computers will reach their true potential, achieving a power far beyond that of ordinary machines.

Uncertainty Principle

PROBLEM: The famous Heisenberg uncertainty principle limits the precision of certain measurements. If you pin down the position of a particle exactly, it will start moving with a range of different velocities simultaneously; if you measure its velocity exactly, you likewise force its position to spread out uncontrollably. Therefore, these properties are unreliable ways to store information.

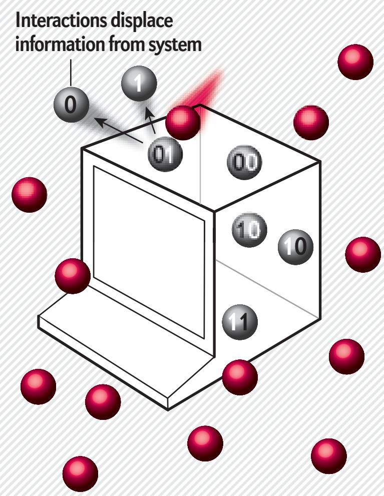


SOLUTION: Not all quantum measurements are subject to this limitation. In situations where position and velocity are uncertain, other properties such as energy may be perfectly well defined. In situations where energy is uncertain, some other variables may be suitable.

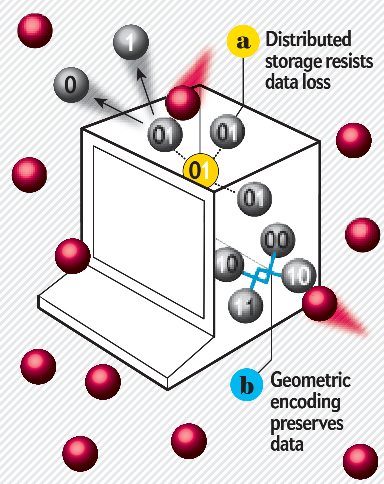


Decoherence

PROBLEM: The particles that make up a computer interact with the surroundings, so that information spreads out, spoiling quantum computations.



SOLUTION: Error-correction procedures can compensate for decoherence long enough to complete a computation. For instance, physicists can spread quantum information over multiple particles **a** or encode it in a geometric form that is naturally resistant to noise **b**.



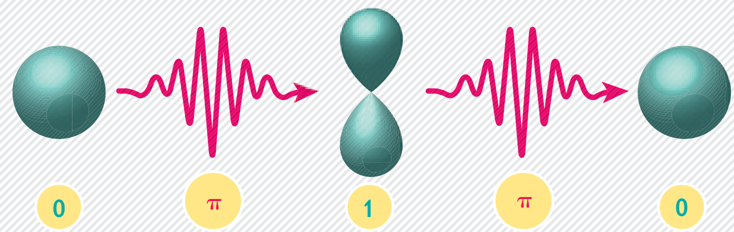
QUANTUM LOGIC

Impossible … NOT!

Quantum computers not only can do anything a classical computer can but also can perform operations outside the scope of classical logic. In this example, two energy states of an electron in an atom represent the 0 and 1 of a computer bit. In both states, the electron has no specific position and velocity: it is spread out over spherical and oval regions called orbitals, and its velocity takes a range of different values simultaneously. Nevertheless, the two states have different energies, and it is the energy that determines the bit value.

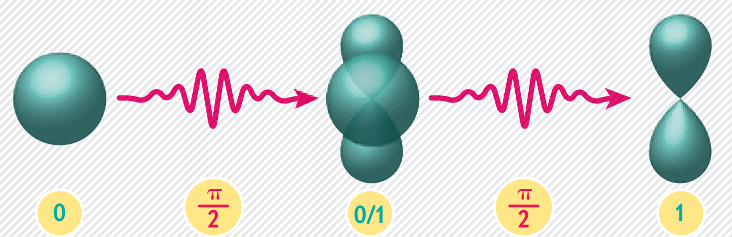
Ordinary NOT

To perform the most basic computational operation, NOT, which inverts the value of a bit, physicists shine pulses of light of appropriate frequency, duration and intensity—known as π-pulses—on the atom. If the electron begins in the 0 state, it will end up in the 1, and vice versa.



Square Root of NOT

The same procedure can be modified to perform a seemingly impossible computational operation: the square root of NOT. A so-called π/2-pulse, with a lesser amplitude or shorter duration than the π-pulse, sends the electron from the 0 or 1 state into a combination, or superposition, of both states. A second π/2-pulse then bumps the electron into either the 1 state (if it started as 0) or the 0 state (if it started as 1). This and other new operations give quantum computers their immense power.



[redacted]

Shor, then at Bell Laboratories, can factor n-digit numbers in a series of steps that grows only as n^2. For other problems, such as searching a long list, quantum computers offer less dramatic but nonetheless significant advantages. To be sure, not all quantum algorithms are so efficient; many are no faster than their classical counterparts [see "The Limits of Quantum Computers," by Scott Aaronson; SCIENTIFIC AMERICAN, March 2008].

Most likely, the first practical applications of general-purpose quantum computers will not be factorization but the simulation of other quantum systems—a task that takes an exponentially long time with classical computers. Quantum simulations may have a tremendous impact in fields such as the discovery of new drugs and the development of new materials.

Skeptics of the practicality of quantum computing cite the arduous problem of stringing together quantum logic gates. Apart from the technical difficulties of working at single-atom and single-photon scales, the main problem is that of preventing the surrounding environment from spoiling the computation. This process, called decoherence, is often presented as a fundamental limit to quantum computation. It is not. Quantum theory itself provides the means of correcting errors caused by decoherence. If the sources of error satisfy certain assumptions that can plausibly be met by ingenious designers—for instance, that the random errors occur independently on each of the qubits and that the logic gates are sufficiently accurate—then quantum computers can be made fault-tolerant. They can operate reliably for arbitrarily long durations.

BEYOND CONVENTIONAL MATHEMATICAL KNOWLEDGE

THE STORY of the "impossible" logic gates illustrates a startling fact about the physics of computation. When we improve our knowledge about physical reality, we sometimes improve our knowledge of the abstract realms of logic and mathematics, too. Quantum mechanics will transform these realms as surely as it already has transformed physics and engineering.

The reason is that although mathematical *truths* are independent of physics, we acquire *knowledge* of them through physical processes, and which ones we can know depends on what the laws of physics are. A mathematical proof is a sequence of logical operations. So what is provable and not provable depends on what logical operations (such as NOT) the laws of physics allow us to implement. These operations must be so simple, physically, that we know, without further proof, what it means to perform them, and that judgment is rooted in our knowledge of the physical world. By expanding our repertoire of such elementary computations to include ones such as the square root of NOT, quantum physics will allow mathematicians to poke their heads through a barrier previously assumed to exist in the world of pure abstractions. They will be able to see, and to prove, truths there that would otherwise remain hidden forever.

For example, suppose the answer to some unsolved mathematical puzzle depends on knowing the factors of some particular enormous integer N—so enormous that even if all the matter in the universe were made into classical computers that then ran for the age of the universe, they would still not be able to factor it. A quantum computer could do so quickly. When mathematicians publish the solution, they will have to state the factors at the outset, as if pulled out of a magician's hat: "Here are two integers whose product is N." No amount of paper could ever suffice to detail how they had obtained those factors.

In this way, a quantum computer would supply the essential key that solves the mathematical puzzle. Without that key, which no classical process could realistically provide, the result would never be known. Some mathematicians already consider their subject an empirical science, obtaining its results not only by careful reasoning but also by experiments [see "The Death of Proof," by John Horgan; Scientific American, October 1993]. Quantum physics takes that approach to a new level and makes it compulsory.

BEYOND BAD PHILOSOPHY

If quantum mechanics allows new kinds of computation, why did physicists ever worry that the theory would limit scientific progress? The answer goes back to the formative days of the theory.

Erwin Schrödinger, who discovered quantum theory's defining equation, once warned a lecture audience that what he was about to say might be considered insane. He went on to explain that when his famous equation describes different histories of a particle, those are "not alternatives but all really happen simultaneously." Eminent scientists going off the rails is not unknown, but this 1933 Nobelist was merely making what should have been a modest claim: that the equation for which he had been awarded the prize was a true description of the facts. Schrödinger felt the need to be defensive not because he had interpreted his equation irrationally but precisely because he had not.

How could such an apparently innocuous claim ever have been considered outlandish? It was because the majority of physicists had succumbed to bad philosophy: philosophical doctrines that actively hindered the acquisition of other knowledge. Philosophy and fundamental physics are so closely connected—despite numerous claims to the contrary from both fields—that when the philosophical mainstream took a steep nosedive during the first decades of the 20th century, it dragged parts of physics down with it.

The culprits were doctrines such as logical positivism ("If it's not verifiable by experiment, it's meaningless"), instrumentalism ("If the predictions work, why worry about what brings them about?") and philosophical relativism ("Statements can't be objectively true or false, only legitimized or delegitimized by a particular culture"). The damage was done by what they had in common: denial of realism, the commonsense philosophical position that the physical world exists and that the methods of science can glean knowledge about it.

It was in that philosophical atmosphere that physicist Niels Bohr developed an influential interpretation of quantum theory that denied the possibility of speaking of phenomena as existing objectively. One was not permitted to ask what values physical variables had while not being observed (such as halfway through a quantum computation). Physicists who, by the nature of their calling, could not help wanting to ask, tried not to. Most of them went on to train their students not to. The most advanced theory in the most fundamental of the sciences was deemed to be stridently contradicting the very existence of truth, explanation and physical reality.

Not every philosopher abandoned realism. Bertrand Russell and Karl Popper were notable exceptions. Not every physicist did, either. Albert Einstein and David Bohm bucked the trend, and Hugh Everett proposed that physical quantities really do take on more than one value at once (the view we ourselves endorse). On the whole, however, philosophers were uninterested in reality, and although physicists went on using quantum theory to study other areas of physics, research on the nature of quantum processes themselves lost its way.

Things have been gradually improving for a couple of decades, and it has been physics that is dragging philosophy back on track. People want to understand reality, no matter how loudly they may deny that. We are finally sailing past the supposed limits that bad philosophy once taught us to resign ourselves to.

What if the theory is eventually refuted—if some deeper limitation foils the attempt to build a scalable quantum computer? We would be thrilled to see that happen. Such an outcome is by far the most desired one. Not only would it lead to a revision of our fundamental knowledge about physics, we would expect it to provide even more fascinating types of computation. For if something stops quantum mechanics, we shall expect to have an exciting new whatever-stops-quantum-mechanics theory, followed by exciting new whatever-stops-quantum-computers computers. One way or another, there will be no limits on knowledge or progress. ■

FLAMMARION ENGRAVING: This famous 19th-century wood engraving (first printed in black and white) poses the question: Is knowledge bounded, or can we always poke our head into the beyond?

CORBIS

MORE TO EXPLORE

The Fabric of Reality: The Science of Parallel Universes—and Its Implications. David Deutsch. Penguin, 1998.

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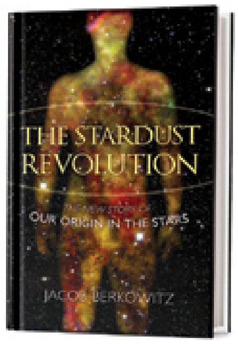
SCIENTIFIC AMERICAN ONLINE
Hear the authors dispel myths about quantum limits at **ScientificAmerican.com/sep2012/quantum-myths**

BOOKS

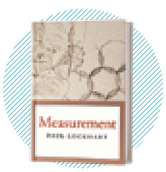


Stardust Revolution: The New Story of Our Origin in the Stars

by Jacob Berkowitz. Prometheus Books, 2012 ($27)

Our ancestors are stars in this "extreme genealogy," which follows the history of discoveries that blossomed into a new field: astrobiology. Science journalist Berkowitz gracefully chronicles the work and passion of physicists, chemists and other "stardust scientists" who probe the universe for signs of life. These researchers' eureka moments include the realization that stars forge elements, the detection of organic molecules drifting in the void of space and the discovery of the first planet beyond our solar system.

—Marissa Fessenden

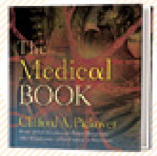


Measurement

by Paul Lockhart. Harvard University Press, 2012 ($29.95)

Lockhart is famous in the math world for a 2002 essay about the state of mathematics teaching. He described it as akin to teaching music by forcing children to transcribe notation without ever touching an instrument or singing. *Measurement* is his attempt to change the equation: a conversational book about mathematics as an art that invites the reader to join in the fun. Sounding every bit the teacher whose love for his subject is infectious, he guides us through exercises in geometry and calculus—giving information and hints along the way while always encouraging us to ask, and answer, "Why?" Lockhart does not try to make math seem easy; instead he wants his readers to understand that the difficulty brings rewards.

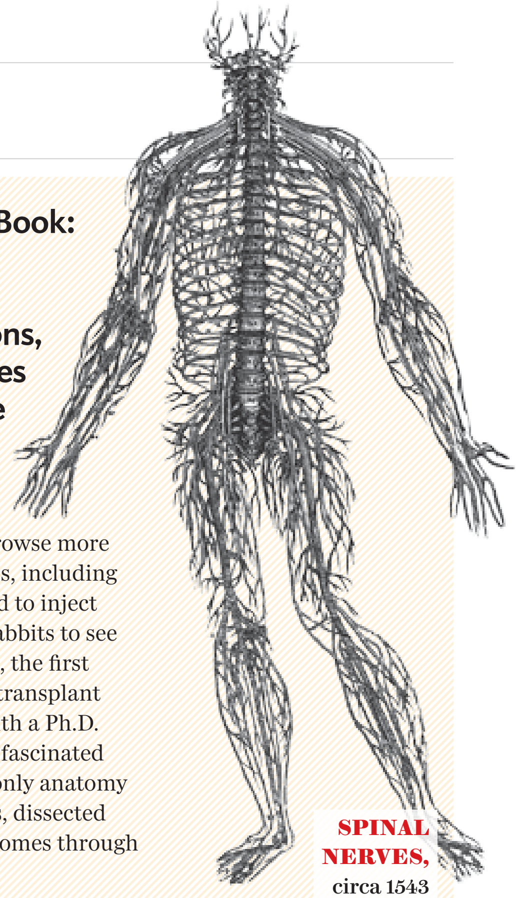
—Evelyn Lamb



The Medical Book: From Witch Doctors to Robot Surgeons, 250 Milestones in the History of Medicine

by Clifford A. Pickover. Sterling, 2012 ($29.95)

This coffee-table book lets readers browse more than 12,000 years of medical advances, including the first pregnancy tests (doctors used to inject a woman's urine into mice, frogs or rabbits to see if it would make the animals ovulate), the first sutures for surgery and the first face transplant in 2005. Pickover, a prolific author with a Ph.D. in biochemistry, notes that he was so fascinated by anatomy in college that he "wore only anatomy T-shirts featuring circulatory systems, dissected frogs, and the like." His enthusiasm comes through in this illustrated history.



SPINAL NERVES, circa 1543

Lost Antarctica: Adventures in a Disappearing Land

by James McClintock. Palgrave Macmillan, 2012 ($26)

Before scientists began exploring Antarctica in earnest at the dawn of the 20th century, many had assumed the continent was inhospitable to life. Yet as McClintock, who has made 13 trips to the region as a marine ecologist, notes, it is teeming with such colorful creatures as orange sea butterflies, red and yellow starfish, giant marine worms and 12-inch-diameter sea spiders, not to mention their better-known neighbors: penguins, seals and whales. Through firsthand observations, he makes clear what is at stake as the climate changes: Adélie penguins may vanish by the end of the century, along with krill and seafloor organisms. Some of these species harbor compounds active against cancer, flu and other diseases. If we can shrink the hole in the ozone layer, which we appear to be doing, McClintock theorizes, we should be able to reverse greenhouse gas accumulation, too.

ALSO NOTABLE

EVENTS

Shipwreck! Pirates and Treasure. Museum of Science, Boston. Opens September 23. Experience hurricane-force winds, spy gold and silver treasure, and pick up artifacts with a robotic arm. **www.mos.org**

The Great Insect Fair. Pennsylvania State University. Held on September 29. Sample wax moth larvae at the Insect Deli, visit the Insect Zoo and ask the Bug Doctor your questions.

Meteor showers. Watch the sky after midnight in September, and you are likely to see a sporadic meteor—a meteor not associated with a particular shower—according to the American Meteor Society. Find details at **www.amsmeteors.org**

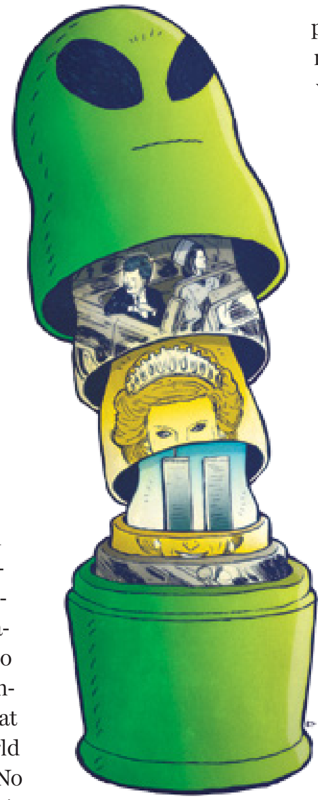
FROM ANDREAS VESALIUS'S *DE HUMANI CORPORIS FABRICA*, 1543

COMMENT AT ScientificAmerican.com/sep2012

Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com). His new book is *The Believing Brain.* Follow him on Twitter @michaelshermer

Conspiracy Contradictions

Why people who believe in one conspiracy are prone to believe others



On Wednesday, May 16, I spent several hours on a hot bus in a neon desert called Las Vegas with a merry band of British conspiracists during their journey around the Southwest in search of UFOs, aliens, Area 51 and government cover-ups, all for a BBC documentary. One woman regaled me with a tale about orange balls of energy hovering around her car on Interstate 405 in California, which were subsequently chased away by black ops helicopters. A man challenged me to explain the source of a green laser beam that followed him around the English countryside one evening.

Conspiracies are a perennial favorite for television producers because there is always a receptive audience. A recent Canadian Broadcasting Corporation documentary that I participated in called *Conspiracy Rising,* for example, featured theories behind the deaths of JFK and Princess Diana, UFOs, Area 51 and 9/11, as if there were a common thread running throughout. According to radio host and conspiracy monger Alex Jones, also appearing in the film, "The military-industrial complex killed John F. Kennedy" and "I can prove that there's a private banking cartel setting up a world government because they admit they are" and "No matter how you look at 9/11 there was no Islamic terrorist connection—the hijackers were clearly U.S. government assets who were set up as patsies like Lee Harvey Oswald."

Such examples, along with others in my years on the conspiracy beat, are emblematic of a trend I have detected that people who believe in one such theory tend to believe in many other equally improbable and often contradictory cabals. This observation has recently been confirmed empirically by University of Kent psychologists Michael J. Wood, Karen M. Douglas and Robbie M. Sutton in a paper entitled "Dead and Alive: Beliefs in Contradictory Conspiracy Theories," published in the journal *Social Psychological and Personality Science* this past January. The authors begin by defining a conspiracy theory as "a proposed plot by powerful people or organizations working together in secret to accomplish some (usually sinister) goal" that is "notoriously resistant to falsification … with new layers of conspiracy being added to rationalize each new piece of disconfirming evidence." Once you believe that "one massive, sinister conspiracy could be successfully executed in near-perfect secrecy, [it] suggests that many such plots are possible." With this cabalistic paradigm in place, conspiracies can become "the default explanation for any given event—a unitary, closed-off worldview in which beliefs come together in a mutually supportive network known as a monological belief system."

This monological belief system explains the significant correlations between different conspiracy theories in the study. For example, "a belief that a rogue cell of MI6 was responsible for [Princess] Diana's death was correlated with belief in theories that HIV was created in a laboratory … that the moon landing was a hoax … and that governments are covering up the existence of aliens." The effect continues even when the conspiracies contradict one another: the more participants believed that Diana faked her own death, the more they believed that she was murdered.

The authors suggest there is a higher-order process at work that they call global coherence that overrules local contradictions: "Someone who believes in a significant number of conspiracy theories would naturally begin to see authorities as fundamentally deceptive, and new conspiracy theories would seem more plausible in light of that belief." Moreover, "conspiracy advocates' distrust of official narratives may be so strong that many alternative theories are simultaneously endorsed in spite of any contradictions between them." Thus, they assert, "the more that participants believe that a person at the centre of a death-related conspiracy theory, such as Princess Diana or Osama [bin] Laden, is still alive, the more they also tend to believe that the same person was killed, so long as the alleged manner of death involves deception by officialdom."

As Alex Jones proclaimed in *Conspiracy Rising:* "No one is safe, do you understand that? Pure evil is running wild everywhere at the highest levels."

On his Infowars.com Web site, Jones headlines his page with "Because There Is a War on for Your Mind." True enough, which is why science and reason must always prevail over fear and irrationality, and conspiracy mongering traffics in the latter at the expense of the former. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/sep2012

Illustration by Brian Taylor

The ongoing search for fundamental farces

Steve Mirsky has been writing the Anti Gravity column since Derek Jeter had a total of 12 base hits in the major leagues. He also hosts the *Scientific American* podcast Science Talk.

Bring Out Your Dead

A member of the species describes how *Homo sapiens* could go out

The scene occurs very near the end (there's your spoiler alert) of what may be the best sports novel ever written, *End Zone,* by Don DeLillo. (The book came out in 1972, but I'm not clear on the expiration dates for spoiler alerts.) The protagonist, college football running back Gary Harkness, tells a teammate about his hobby: "I like to read about mass destruction and suffering.... Horrible diseases, fires raging in the inner cities, crop failures, genetic chaos, temperatures soaring and dropping, panic, looting, suicides, scorched bodies, arms torn off, millions dead. That kind of thing."

The fictional Gary Harkness would love the new nonfiction book *The Fate of the Species,* by Fred Guterl. (Disclosure: Guterl is *Scientific American*'s executive editor, but I'm not holding that against him.) Harkness would adore the first part of the subtitle—*Why the Human Race May Cause Its Own Extinction*—although he would probably be less enthused about the concluding phrase—*and How We Can Stop It.*

Guterl covers all of Harkness's interests and more, although the sundered limbs are merely implied. "What I'm aiming to do," Guterl writes, "is tell some stories about real dangers we face. I won't give you a balanced view. I will intentionally ignore the bright side of these issues and focus on the question of how bad can it be." The answer: Really bad. Not millions of dead but billions, including, of course, you and me and/or all our progeny, depending on the timing of the day of reckoning.

Guterl takes us on a tour of various apocalypses, starting with viruses, especially flu. Every infectious disease expert I've spoken to in the past two decades is terrified of a new strain that could rival the horrific 1918 flu outbreak in killing efficiency. Today we face an adjunct disease threat: wackos with radio programs telling millions of devout listeners that any public health actions taken by officials are mere smoke screens for nefarious policies. (Google "2009 flu" and "Limbaugh.")

The book goes on to give due respect to the civilization-upheaval potential of climate change, ecosystem collapses, bioterror and artificial evil intelligence—that Stuxnet computer virus designed to mess up Iranian nuclear enrichment operations could return tweaked to take down the U.S. power grid. Any of those cases could wipe out significant portions of the world's population. And the subsequent societal breakdown would then sweep away vast numbers of the survivors. Hey, a blown transformer down the street took out my electricity for three hours last week, and I was about to start burying flash drives full of Bach for aliens to find in the distant future.

Despite the gruesome subject matter, Guterl maintains a sunny disposition. "I tend toward the techno-optimistic side of the spectrum," he writes. "I also think optimism is our best weapon."

I'm less sanguine. (Google "climate change" and "Inhofe.")

Guterl also talks about the get-it-over-in-one-shot scenario, an extinction-event asteroid impact. In comes one of those Chicxulub crater makers, and we're cooked. Former astronaut Edward Lu says we could send a telescope into a Venus-like orbit around the sun that in weeks would double our information about potentially Earth-rattling asteroids. If an inbound killer rock were spotted, we would theoretically mount a mission to deflect the thing.

Lu's Sentinel Mission has to raise a few hundred million hard-to-find bucks to get off the ground. Meanwhile, as I write in early July, the National Hockey League's Minnesota Wild has announced the signing of free agents Ryan Suter and Zach Parise for a combined cost of just under $200 million. Yay.

The book's last chapter is called "Ingenuity." As Guterl muses, "We've beaten the odds so far. To continue beating them will take every good idea." Yet even the best ideas may not be foolproof, because, as has been said, fools are so ingenious. Many years ago I happened on a quotation that went something like this: "If all the world's oceans were filled with gasoline, sooner or later some lunatic would throw in a lit match." The match may already be lit. SA

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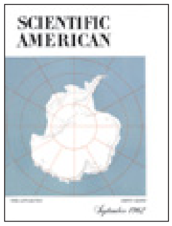
Illustration by Matt Collins

50, 100 & 150 Years Ago compiled by Daniel C. Schlenoff

Innovation and discovery as chronicled in *Scientific American*



September 1962

Antarctic Fauna

"As for the vast regions of water that underlie the great ice shelves of the Antarctic continent, such as those of the Ross and Weddell seas, it has long been held that these are quite deficient in life. This supposition has been upset recently by the finding of large fishes—mostly Nototheniids—together with bottom invertebrates frozen in situ and exposed well above sea level on the wind-scoured surface of the Ross Ice Shelf near the U.S. base at McMurdo Sound. These remains, on top of ice more than 100 feet thick, had apparently been trapped by freezing at the bottom of the shelf when ice touched the sea floor. Preliminary carbon-14 dating indicates that it may have required about 1,100 years for these specimens to work their way up through the ice."

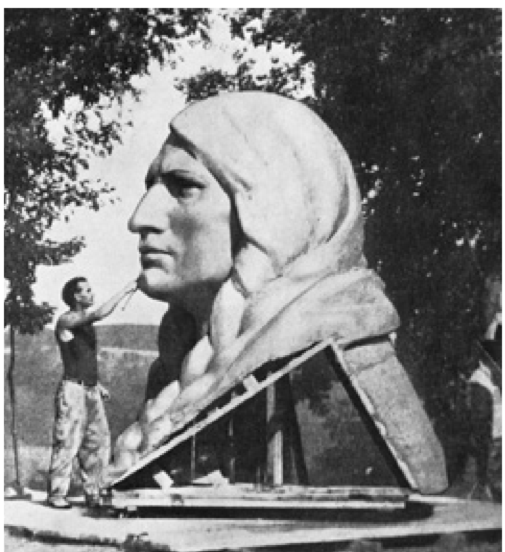
Scrapped Telescope

"Secretary of Defense Robert S. McNamara has canceled construction of the Navy's 600-foot radio telescope because of rising costs and a decline in its potential military value. The 30,000-ton structure at Sugar Grove, W.Va., would have been by far the world's largest fully steerable radio telescope. More than $41.7 million had already been spent on it. According to a report in the *New York Times,* its primary purpose was to pick up radio messages transmitted elsewhere in the world by detecting their reflections from the moon. Although the Navy did not confirm this, it explained that such missions can now be carried out by satellites and new electronic instruments."

September 1912

Cement Colossus

"Many articles of literary merit have been written on Mr. Lorado Taft's concrete statue to the American Indian [*see photograph*]. The writer, as builder, has been requested to set forth in simple technical terms the methods used in the building of this—so far as the writer is aware—the first heroic cement statue, which was dedicated near Oregon, Illinois, on July 1st, 1911, and which has been open to the public view and criticism ever since the huge plaster mold was taken off in the early spring. —John G. Prasuhn"



CLAY MODEL for a colossal cement monument to the American Indian in northern Illinois; from an article by the artist's assistant, 1912

The monumental statue stands 48 feet tall. For a slide show on the intersection of science and the arts in 1912, see **www.ScientificAmerican.com/sep2012/science-and-art**

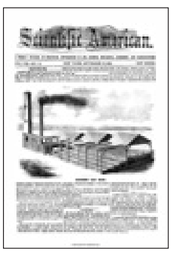
Problem of Life

"There are other fundamental problems, which have exercised the minds of thinkers of all ages, and which still remain to baffle the most advanced workers in the fields of modern science. Of such is the problem of the nature and origin of life. Prof. E. A. Schaefer in his inaugural address before the British Association at Dundee, Scotland, is careful to avoid entanglement in hopeless 'philosophical' quibble. He attempts no definition of life, but says, 'recent advances in knowledge

SCIENTIFIC AMERICAN, VOL. CVII, NO. 10; SEPTEMBER 7, 1912 have suggested the probability that the dividing line between animate and inanimate matter is less sharp than it has been regarded, so that the difficulty of finding an inclusive definition is correspondingly increased.' "

Battlefield Medicine

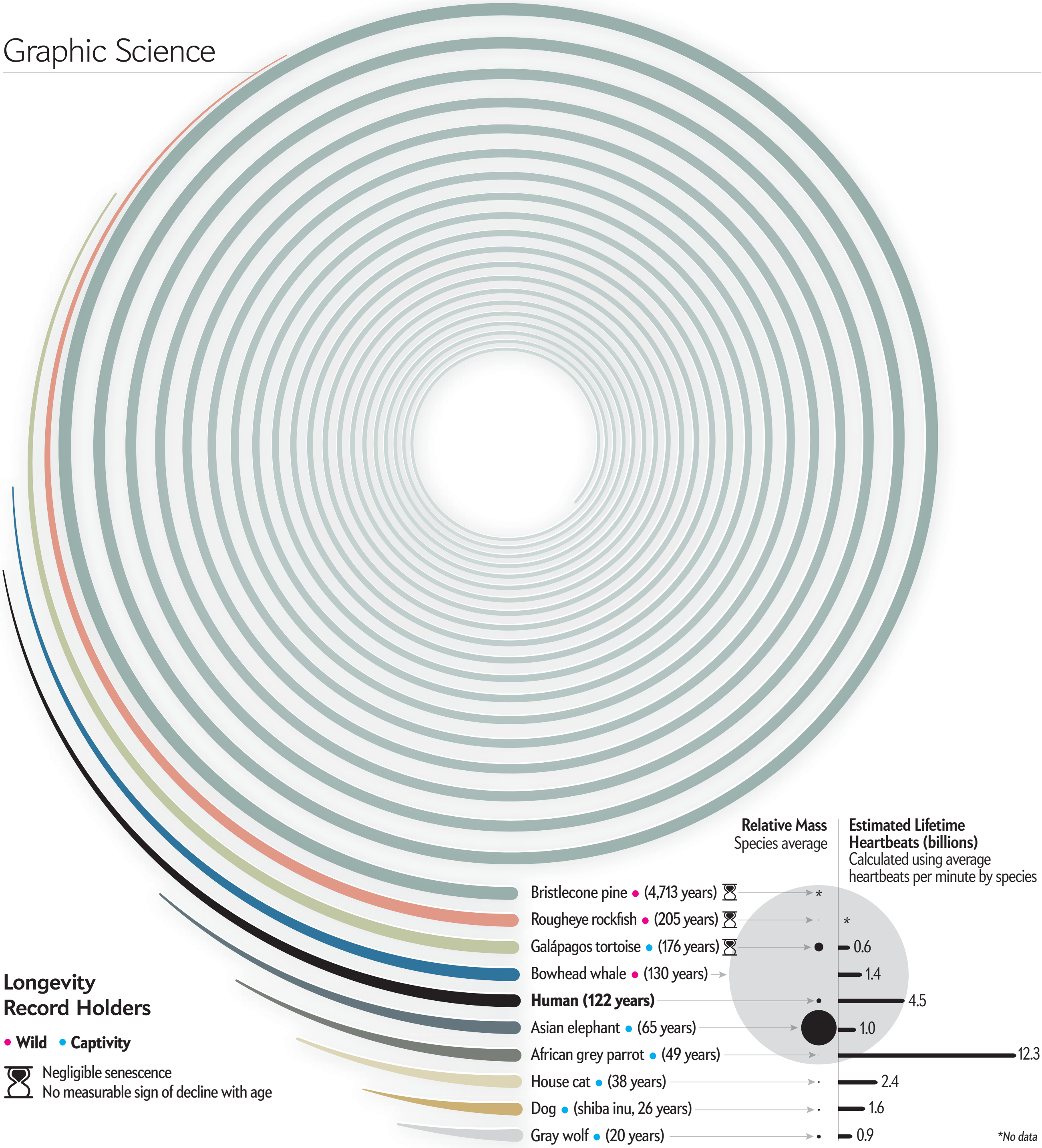
"The annual maneuvers of the sanitary department of the military government of Paris were unusually interesting this year. The exercises included the establishment of a rescue service by automobile, in addition to curious experiments in training dogs to search for wounded men. The most remarkable specimen of the new equipment is an automobile operating room, in which surgical operations can be performed at the battle-front in conditions as favorable as those afforded by a hospital. Severe abdominal wounds, which are very common in modern warfare, cannot be operated upon properly by the ordinary field service, and in many cases the removal of the patient is equivalent to a sentence of death."



September 1862

Steam Irrigation

"About twenty years ago Ibrahim Pasha of Egypt erected a steam engine of 100 horse power to take the place of 500 wheels which supplied water from the Nile to market gardens in the neighborhood of Boulac. When the natives saw the machinery put together, and were told its object, they pronounced the governor mad. But when they saw the huge machine belching out columns of water, they at once said the Franks [Westerners] had brought a devil, to empty the Nile. Such is the fertilizing power of the Nile water, that when the Cornish engine just mentioned was erected, 700 or 800 acres of land were brought under cultivation in the immediate vicinity of Cairo. These are now covered with market gardens and sugar fields."



Which Creatures Live the Longest?

The key indicator for animals may be total energy expended over a lifetime

Conventional wisdom in longevity studies used to be that the life span of a creature was roughly proportional to its body mass and heart rate—the big, slow elephant outlives the quick, small mouse. New research, however, presents a more complicated picture. Bats and birds, for instance, are small but tend to live longer than many larger creatures. Moreover, when scientists look within particular species, size does not correlate well with life span, although fast growth is often associated with reduced longevity. To some degree, resting metabolic rate does correlate, but for animals total energy expended over a lifetime may be the best indicator of all. Definitive answers in this field can be slow in coming, partly because the studies take a long time to do—a typical Galápagos tortoise, for instance, can outlast a scientist's career. And don't hold your breath for insights into the extreme life span of the bristlecone pine. *—Fred Guterl*

SCIENTIFIC AMERICAN ONLINE
More data in an interactive graphic at ScientificAmerican.com/sep2012/graphic-science

RECORD-HOLDER SOURCES: JOÃO PEDRO DE MAGALHÃES *AnAge online database, Institute of Integrative Biology, University of Liverpool;* "PATENTED HARPOON PINS DOWN WHALE AGE," BY AMANDA LEIGH HAAG, IN *NATURE*, PUBLISHED ONLINE JUNE 19, 2007 *(whale); GUINNESS WORLD RECORDS 2010 (cat); GUINNESS WORLD RECORDS 2011 (dog)*

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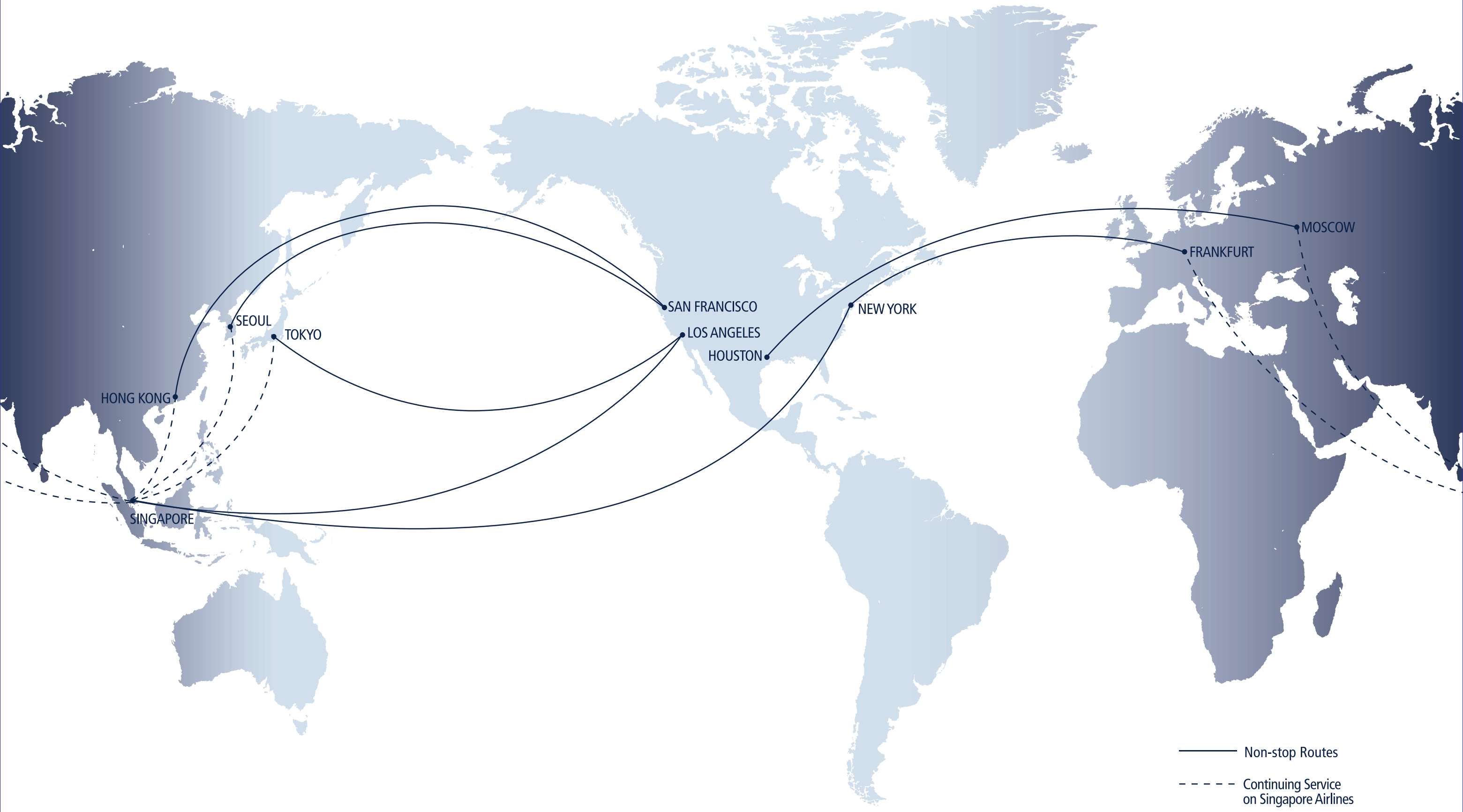
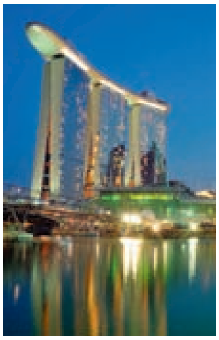


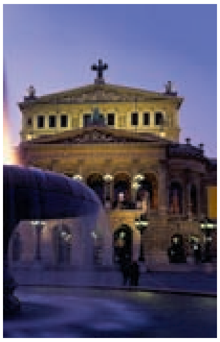


SINGAPORE

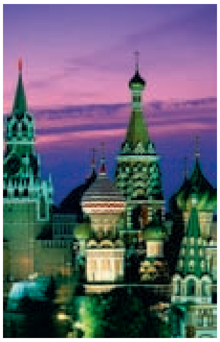
HONG KONG

SEOUL

TOKYO



FRANKFURT



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