SUSTAINABILITY
Balancing Energy, Water and Food

NEUROSCIENCE
Electrical Stimulation Eases Depression

INFOTECH
Neuronlike Computing

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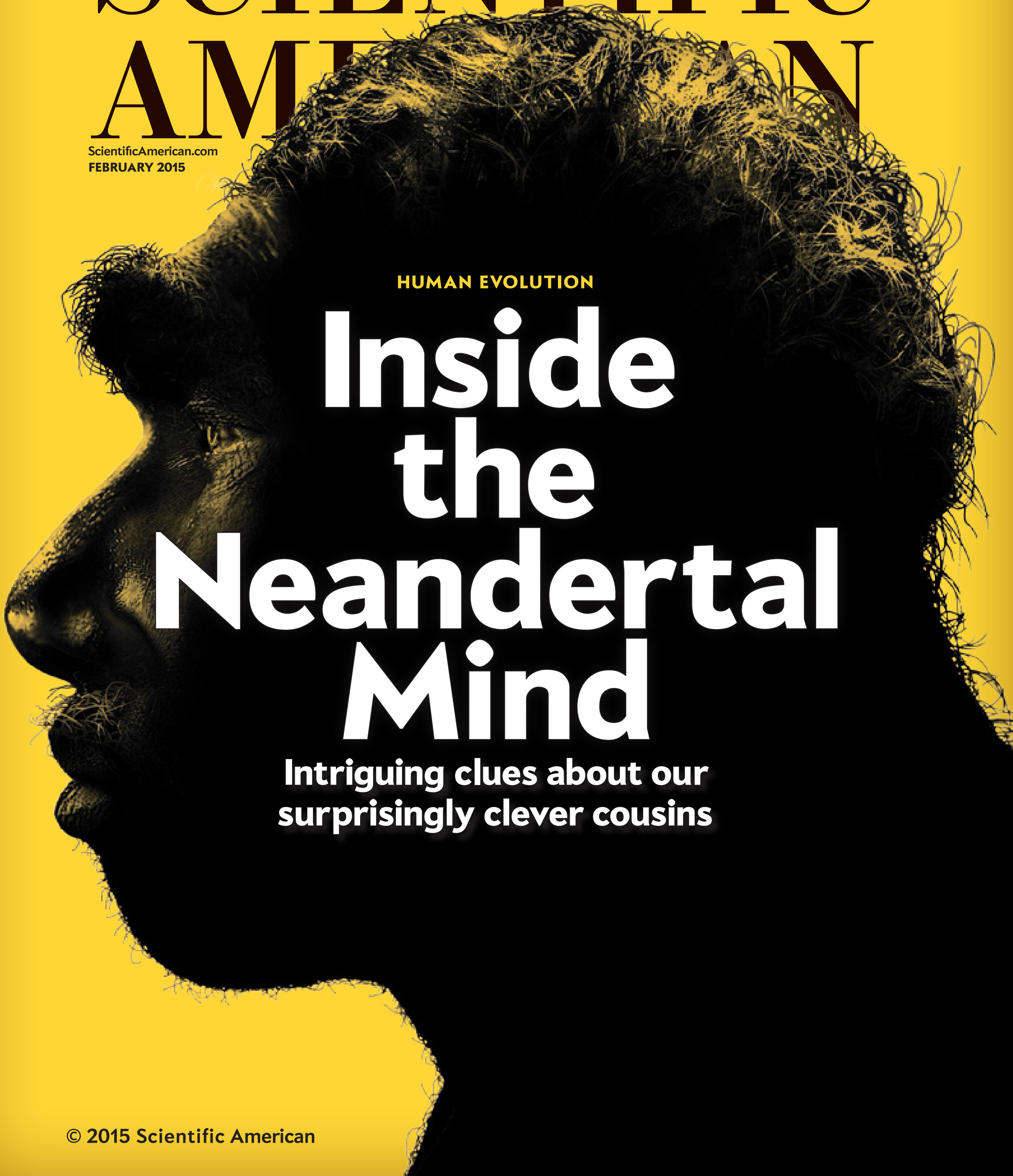


HUMAN EVOLUTION

Inside the Neandertal Mind

Intriguing clues about our surprisingly clever cousins

How a Changing Climate Triggers Earthquakes, Tsunamis and Volcanoes

An astonishing transformation over the last 20,000 years has seen our planet flip from a frigid wasteland into the temperate world. Now there are signs that human-induced climate change is causing another turnaround. Could we bequeath to future generations not only a far hotter world, but also a more geologically fractious one?

Surviving Armageddon: Solutions For a Threatened Planet

Our world is constantly under threat, both from geological processes and from the cosmic forces that rage beyond our atmosphere. Can we use our scientific understanding and our technology to make the world a safer place? We'll discuss volcano monitoring, earthquake prediction, asteroid spotting and other efforts underway.

Architecture & Engineering

Speaker: Stephen J. Ressler, P.E., Ph.D.

A Field Guide to Great Structures

Many of the world's greatest works of architecture have been profoundly influenced by the principles of engineering mechanics that underlie their design. Learn how to see, analyze, and understand the many fascinating structures we will encounter during our cruise, from the Hallgrímskirkj in Reykjavik to the great bridges of the Norwegian fjords.

The Norwegian Stave Church

The stave church is a medieval building that was once common throughout northwestern Europe. Today the few surviving examples are found almost exclusively in Norway. Learn to see the stave church not just as an iconic architectural form, but as a sophisticated technological system as well.

Saint Paul's Cathedral: Evolution of the First Modern Dome

Learn about the development of the dome as a structural and architectural element from the Classical Era through the 18th century. We'll focus on the extraordinary structural innovations devised by Sir Christopher Wren for the dome of Saint Paul's, and we'll see how these innovations overcame the inherent structural limitations of earlier domes.

A Structural Retrospective

We'll examine interesting structures photographed by Bright Horizons participants during our trip, analyzing the structural system, discerning the underlying engineering principles, and assessing how structural considerations influenced the architectural design. Learn how your appreciation of great architectural works can be enriched through an understanding of basic structural mechanics principles.

Anthropology

Speaker: Kenneth Harl, Ph.D.

Why Was There a Viking Age?

Learn how the harsh climate and daunting geography of Scandinavia shaped the unique culture and religion of the Nordic peoples of the Viking Age. The Scandinavians produced superb ships, excelled in warfare, celebrated ancestral heroes and worshiped frightening gods. We'll look at how the many strands of Viking life tied together.

Viking Voyages of Discovery

Learn how Vikings braved the North Atlantic in spectacular voyages of discovery that led to the colonization of the Faroe Islands, Iceland, Greenland, and Newfoundland. Hear about the exploits of Erik the Red, Leif Eriksson and other Nordic explorers, their remarkable ships and seamanship, and the peculiar legacy of faked Viking artifacts from this time.

The Icelandic Republic: A Frontier Society

Learn how Icelanders created the first overseas European colonial society and established a remarkably successful form of government and a rich literary tradition. We'll examine records of family sagas to learn about the lives, loves and disputes of ordinary men and women in Viking Age Iceland.

Poetry and Saga of the Viking Age

Viking Age Icelanders developed a genius for reciting poetry and storytelling—skills prized for entertainment during the long winters. We'll read poems replete with subtle metaphors and composed in an array of alliterative verses, as well as prose narratives that stand among the finest vernacular literature of Medieval Europe.

Vikings in Hollywood

We'll take an entertaining look at novels, comics and movies that have popularized the image of barbaric Vikings sporting horned helmets. While it is easy to dismiss Hollywood for sensationalism, it is remarkable how well some examples have recreated the spirit of the Viking Age.

Neuroscience

Speaker: Martha J. Farah, Ph.D..

Cognitive Enhancement: the Neuroscience of Boosting Your Brainpower

Can a pill make you smarter? Hear the latest on the neural bases of intelligence and methods for enhancing it, including psychopharmacology, transcranial brain stimulation and "brain-training" programs. We'll also consider the ethical, legal, and societal impact of these practices.

Wellbeing and the Brain

Whatever wellbeing means to you, chances are the brain plays an important role in attaining and maintaining it. Learn about the neural bases of mood and resilience, and how exercise, sleep, social connectedness and meditation can improve these functions and the brain systems that support them.

Neurolaw

"Ladies and gentlemen of the jury, do not condemn my client for his actions. He had no choice in the matter; events set in motion at the time of the big bang resulted in his brain functioning as it did on that fateful day." Would you be persuaded by this lawyer's defense? We'll explore the fascinating intersection of ethics, law and neuroscience.

How Genes and Experience Make Us Who We Are

From prenatal processes of cell creation and migration in the fetal brain to the sculpting of neural connections in adolescence, human brain development is a complex and prolonged process. We'll discuss genetic influences on intelligence, personality and other reflections of brain function, and how each individual's life experiences influence the development and function of the brain.

SCIENTIFIC AMERICAN Travel HIGHLIGHTS LONDON (HARWICH)

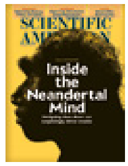
Saturday, August 1st

Find your own version of London amidst its many layers and neighborhoods. Museums and parks, tradition and innovation, urban vitality and peaceful corners are all up for your exploration.

SCIENTIFIC AMERICAN

February 2015 Volume 312, Number 2

ON THE COVER



Neandertals have a reputation for having been slow-witted. But were our extinct cousins truly that different from us? Studies of their anatomy and DNA have yielded limited information about Neandertal cognition. New insights from the cultural remains they left behind hint that they were far cleverer than they have been given credit for. Image by Jean-François Podevin.

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Our Neandertal cousins were much more intelligent than you probably think. *By Kate Wong*

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If a future civilization ever considered trying to extract energy from a black hole, it would have some formidable obstacles to surmount. *By Adam Brown*

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The human body does not have just one biological clock. It has many. *By Keith C. Summa and Fred W. Turek*

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Electrical stimulation deep within the brain may deliver a much needed treatment for severe mood disorders.
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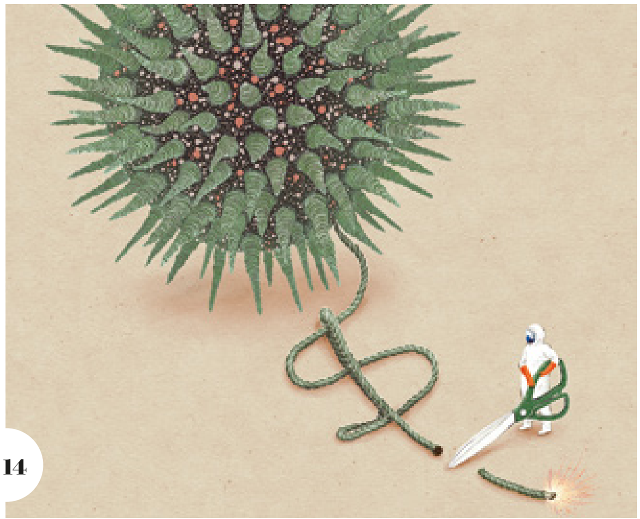
We know surprisingly little about what low-dose radiation does to organisms and ecosystems. Four years after the disaster in Fukushima, scientists are beginning to get some answers.
By Steven Featherstone

Photograph by Steven Featherstone



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ON THE WEB

Top 10 Stories of 2014
Scientific American reviews the most important events in science and technology from the past year, including the Ebola outbreak and the Rosetta spacecraft's comet landing. *Go to www.ScientificAmerican.com/feb2015/top-10*

COURTESY OF NEW YORK STATE THRUWAY AUTHORITY (*bridge*)

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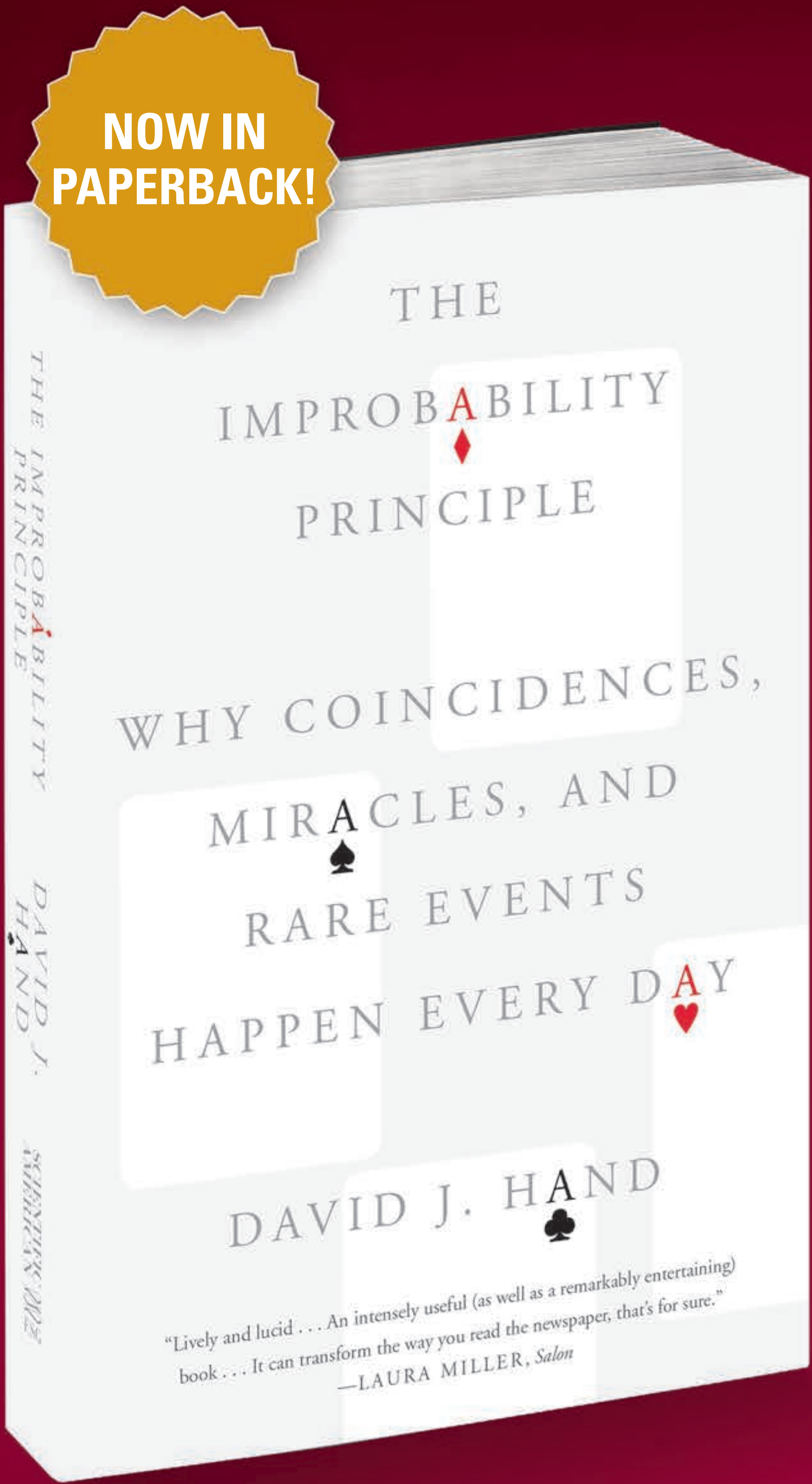
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—LAURA MILLER, Salon
THE IMPROBABILITY PRINCIPLE
DAVID J. HAND

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

Different yet Alike

PERHAPS IT IS BECAUSE WE *HOMO SAPIENS* ARE TODAY THE only remaining members of the various human species whose feet have trod this world, we believe ourselves to be completely unique in multiple ways. Of course, we think, we survived where others failed because we must have been the most collaborative, the most intelligent, the most creative of all human species. *Of course.*

Yet for every time we have come to feel so sure of ourselves about anything, it seems to me, science patiently provides the evidence and the rejoinder: "It's never that simple." Case in point: the new findings about "Neandertal Minds," in this issue's cover story by senior editor Kate Wong.

With heavy brows and stockier physiques than today's humans, Neandertals, who inhabited Eurasia between 350,000 and 39,000 years ago, nonetheless left intriguing clues that showed them to be far from the brutish simpletons of pop culture. Although they have long been thought to be mentally inferior to modern humans, they demonstrated the impressive ability to make skillful use of tools, to value aesthetically pleasing body ornaments such as feathers, to engrave caves with symbols.

What, then, truly distinguishes us? And how did humans continue when Neandertals went extinct? In search of answers, researchers are studying skulls and other evidence for clues about the brain features from which emerged the Neandertal mind. Their quest may yield some profound insights into our own heritage as well. Turn to page 36.

Our continued survival on Earth will require solving some interleaving challenges—among them how to manage energy, food and water at once to serve a growing population. In "A Puzzle for the Planet," starting on page 62, Michael E. Webber of the University of Texas at Austin explores efforts to come up with an integrated system for juggling those three essentials. When I attended last year's World Economic Forum meeting at Davos, Switzerland, I was impressed that a record 23 sessions focused on climate, which will no doubt have been an important theme this year as well. Let's hope that our species' cleverness will be up to the challenge of determining—while there is still time—how to live sustainably on a finite planet. SA

DELVE DEEPER

Readers of *Scientific American*'s award-winning journalism can now enjoy deeper insights into the research we cover, straight from the scientific journal articles themselves. In a one-year pilot, Nature Publishing Group (our parent company) will enable free content sharing for this magazine, along with some 100 white-listed journalists and media outlets, as well as for nature.com subscribers, for 49 owned journals, including the *Nature* family. An online link in a related story will give the reader access to the full journal article. The functionality on nature.com is powered by ReadCube (which is backed by a sister company, Digital Science). *—M.D.*

Illustration by Nick Higgins

October 2014

"Pharmaceutical companies have spent millions of dollars in directly advertising testosterone treatment to consumers."

NAYVIN GORDON *OAKLAND, CALIF.*

LIGHT AND THE BIG BANG

In "A Beacon from the Big Bang," Lawrence M. Krauss suggests that, if verified, possible observation of gravitational waves from the early universe could provide evidence for a theory in which the universe underwent a period of explosive expansion, or inflation, shortly after the big bang.

Because so much of the described event occurs within an infinitesimal fraction of a second, would not the early universe's components have to have been moving at many multiples of the speed of light?

Richard C. Betancourt
New York City

How can we see something from the origin of the universe? If light was emitted from that origin, it would travel out from it at the speed of light. Our galaxy and solar system and Earth would evolve billions of years later, meaning the light of the big bang has long since passed us by.

Ken Parker
Fort Collins, Colo.

KRAUSS REPLIES: In response to Betancourt: one has to be careful when parsing the phrase "nothing can travel faster than light." Nothing can travel through space faster than light, but space can expand without limit. This is because, locally, objects in an expanding universe are not moving through nearby space. It is the space that is carrying them apart, like a wave carrying a surfer, who is not moving with respect to the water but moving with respect to the shore.

Concerning Parker's question: the big bang didn't happen at a single point in our universe but throughout all of space, which was at that time contracted to a single point. Therefore, light is not traveling "outward" from a single "center" but rather from all of space.

SELLING OF TESTOSTERONE

In "The Other T Party" [The Science of Health], Carina Storrs was quite thorough but neglected one point relating to how many men in the U.S. have received needless testosterone treatment in recent years: she failed to mention the role of the pharmaceutical companies and their extensive promotion of testosterone directly to consumers. These companies have spent millions of dollars in direct advertising to consumers through television.

Nayvin Gordon
Oakland, Calif.

SIMIAN SECURITY

In "Know the Jargon" on the "human shield effect" [Advances], Jason G. Goldman reports that a study found that samango monkeys in a South African research center feel safe when a human is behind them. Are these monkeys familiar with humans and thus "know" that humans won't harm them? Or is it that humans "look" safe and that the monkeys "think" they will make a commotion and deflect predators? Or might this attitude exist for some other reason?

Ted Grinthal
Berkeley Heights, N.J.

GOLDMAN REPLIES: These monkeys are well habituated to human presence because they live on the land of South Africa's Lajuma Research Center. It is precisely because the center's monkeys are familiar with humans and are not hunted by them that the monkeys have learned to rely on humans for cover from natural predators that are around them. In areas where humans do represent a threat or where monkeys are uncertain of human intentions, you would not expect a similar pattern of behavior.

METHANE AND CLIMATE

In "An Inconvenient Ice," Lisa Margonelli discusses the potential of methane hydrates, large deposits of methane gas trapped in ice below the seafloor, as both an energy source and a danger in its potential to exacerbate climate change.

It occurs to me that the last Ice Age may have ended when sea levels got low enough to cause massive outpouring of methane from methane hydrates. Are there data that would support this idea?

Harry Walker
Pitman, N.J.

MARGONELLI REPLIES: According to earth scientist Gerald R. Dickens of Rice University, "the answer is somewhat complex," but "it is unlikely that there has been a significant release of methane over the past 100,000 years" from falling sea levels. He explains: "Here's a bit of background: The gas hydrate stability window below the seafloor increases with pressure, and hence depth, but does so nonuniformly. Consequently, even large-amplitude changes in sea level and pressure have a minimal effect on gas hydrate stability at most deep locations.

"But the relatively shallow-water continental slopes that are affected by falling sea levels have experienced many large-amplitude changes in sea level over the past 700,000 years. Gas hydrate deposits take a long time to form and require continuous high pressures to accumulate. This upper zone contains very little gas hydrate because it has been in a continual state of transition over a long period."

INSPIRED BY GARDNER

"Let the Games Continue," by Colm Mulcahy and Dana Richards, celebrates the

late Martin Gardner, the longtime author of the Mathematical Games column in *Scientific American*.

I was a high school freshman when I discovered Gardner's genius in your publication. From then on, I never missed his column while it ran. His ability to grasp complex scientific and mathematical concepts and recast them to be understandable to the layperson was extraordinary. At his death in 2010, humanity lost a great teacher. Gardner was a true inspiration to me. I encourage you to keep celebrating his life and works every October ad infinitum.

William R. Peebles, Jr.
via e-mail

SAVING THE MONARCH

"Saving 'Bambi,'" by Roger Drouin [Advances], reports on efforts that have been suggested to save the monarch butterfly, whose population has greatly declined, including the creation of more milkweed habitat in the U.S.

As a native plant professional, I can confirm that ecological restoration of native grassland ecosystems that contain milkweed plants is the only method to keep the monarchs from going extinct. At a minimum, between $100 billion and $200 billion is necessary for purchasing land for thousands of milkweed patches, restoring the native ecosystems and performing annual maintenance to keep weeds out.

The monarch must be granted an emergency listing as a threatened species. In addition to buying and restoring the milkweed sites, the U.S. Fish and Wildlife Service and each state in the U.S. that the butterflies migrate through should approve a recovery plan and maps of the needed critical habitat areas. Anything less, and the monarch will go the way of another migrating species that we lost 100 years ago: the passenger pigeon.

Craig Dremann
Redwood City, Calif.

CLARIFICATION

In the "Test Yourself" box in "Let the Games Continue," by Colm Mulcahy and Dana Richards, the wording of the first puzzle, related to lightbulbs, was potentially misleading. In the sentence "then go to the third floor to see the bulb," the text should have said "check" instead of "see."

LETTERS TO THE EDITOR

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Letters may be edited for length and clarity. We regret that we cannot answer each one. Post a comment on any article at ScientificAmerican.com/feb2015

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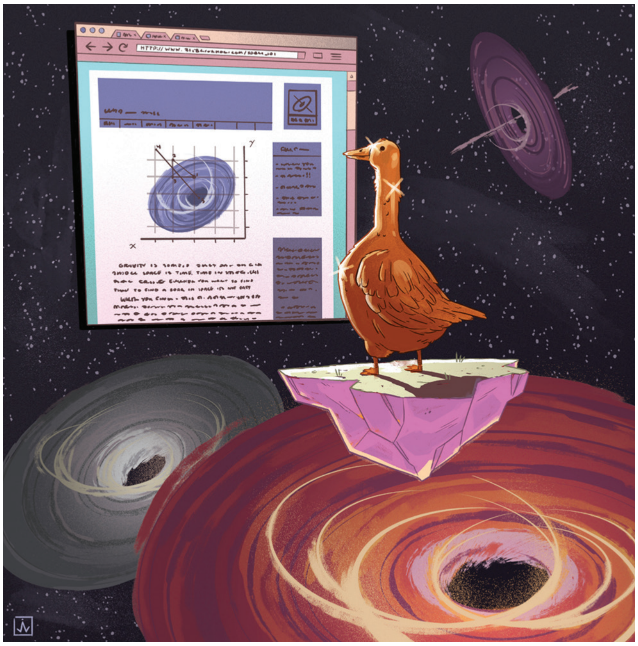


Don't Kill the Goose

The new Congress has a chance to reverse years of stinting on fundamental research

The 114th U.S. Congress, infused with 71 new members elected last fall, will begin to hammer out a federal budget this month. In an era of tight spending and lingering economic malaise, this Congress—and the White House—might be tempted to limit funding for basic science in favor of applied research that has more direct payoffs. Politicians of both major parties have done so before. We urge them not to do it again and to instead renew a law that is vital to basic research.

It is easy to make fundamental science sound wasteful and silly. Representative Lamar Smith of Texas, chair of the House Committee on Science, Space, and Technology, has made recent headlines by questioning National Science Foundation grants he deems "frivolous," such as studies of the mechanics of bicycle riding or the chemistry of plant gases.

But even a cursory look at the facts demonstrates that basic research drives innovation. The pages of this magazine have featured abundant examples of purely theoretical work that have led to practical gains. Albert Einstein was simply curious about the nature of space and time, for instance, when he developed his general theory of relativity; now we rely on that theory to synchronize the clocks on GPS satellites. The late senator William Proxmire of Wisconsin famously lambasted "wasteful spending" on a study of the sex life of the parasitic screwworm fly. But that research saved the U.S. cattle industry about $20 billion by helping to control the insect, a livestock pest. Proxmire later apologized.

So many seemingly esoteric studies have led to practical benefits that Representative Jim Cooper of Tennessee began celebrating them in 2012 with the Golden Goose Awards. Last year a physicist won because his computer simulations of black holes led to software advances that, in the 1990s, produced the first easy-to-use Web browser—followed by a new economy of Web-based businesses.

The $3.8-billion federal investment in the Human Genome Project between 1990 and 2003 added $796 billion to the economy, estimates Battelle Technology Partnership Practice. Economists have calculated that a third to a half of U.S. economic growth since World War II has come from basic research.

This is why recent spending trends are worrying. A growing share of U.S. research is funded by the private sector, whose money shifts around quickly based on short-term corporate needs and tends to focus on applied, rather than basic, research. Government investment, in contrast, is considered crucial to the success of basic research because it is continuous. Yet it has generally declined for a decade as Congress has tried to squeeze budgets. In 2013 cuts from congressionally mandated budget sequestration caused the largest reduction in federal R&D spending in 40 years, according to the American Association for the Advancement of Science. Both political parties are to blame: federal science budgets declined during periods when Democrats controlled both chambers (2007–2011) and when Republicans did so (2005–2007).

This reduction is hurting the ability of the U.S. to compete with other countries. As charted by the World Bank, Sweden, Japan, Israel, Austria, South Korea and Germany, among others, each invest a larger share of their gross domestic product on research than the U.S. does. China is on track to overtake the U.S. by the early 2020s, reports the "2014 Global R&D Funding Forecast" by Battelle and *R&D Magazine*.

There is a way to fix this. It starts with a law, the America COMPETES Act, signed by then president George W. Bush in 2007. The law sets up funding goals for several agencies, including three that support much of the basic science in this country: the NSF, the Department of Energy's Office of Science, and the National Institute of Standards and Technology. Yet Congress has never appropriated enough money to meet the act's targets, and the financing has now expired.

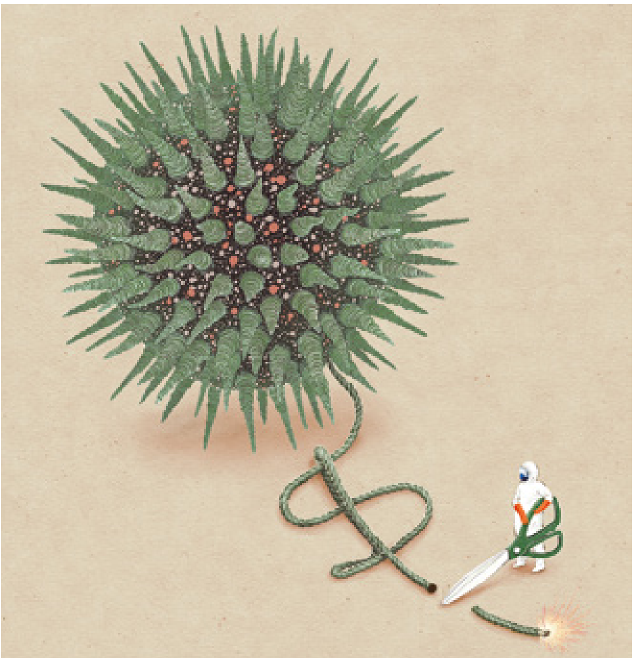
This spring lawmakers in Congress should reauthorize the act and fund it completely. Action now, history tells us, will produce impressive long-term returns on this investment. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/feb2015

Illustration by Justin Volz

Commentary on science in the news from the experts

Marc Lipsitch is a professor of epidemiology and director of the Center for Communicable Disease Dynamics at the Harvard School of Public Health.



Defusing a Biological Bomb

A pause on risky pathogen research should be made permanent

Last October the White House announced a pause in federal funding for so-called gain-of-function experiments that increase the contagiousness or virulence of influenza viruses or of the coronaviruses that cause severe acute respiratory syndrome (SARS) or Middle East respiratory syndrome (MERS). With the announcement began a yearlong "deliberative process"; in the coming months a committee led by the National Science Advisory Board for Biosecurity and the National Research Council must advise the U.S. government on whether to continue funding research of this kind.

The pause was long overdue. Mishaps in federal laboratories last summer reminded us that accidents happen in even the best facilities. Most dangerous pathogens under study in labs such as these are not highly transmissible, so the risk is largely confined to on-site workers. Gain-of-function experiments, especially those involving flu, are a different story.

Since at least 2005, researchers have been deliberately creating influenza viruses that are both highly virulent (killing several percent or more of those infected) and spread easily among humans. The most dangerous experiments involve strains that are unfamiliar to our immune systems; neither our natural defenses nor existing vaccines can protect us against them. They are called potential pandemic pathogens (PPPs) because an accident involving their release could cause a global catastrophe.

We must study dangerous pathogens if we want to defeat them. As scientists and as a society, we accept the low probability that a handful of people may become accidentally infected and even die doing necessary science. But experiments involving PPPs massively increase the stakes: they place the world's population at risk.

The chances of a catastrophic event such as an accidental pandemic are hard to estimate, but preliminary work puts the risk at 0.01 to 0.1 percent per laboratory year of research on transmissible, virulent flu. Such a pandemic could claim millions of lives. We have never before knowingly accepted such risks for the sake of scientific experiments, and we need an exceptionally compelling rationale before we consider doing so now.

Proponents of PPP experiments argue that by studying the properties of transmissible, virulent flu in the lab, we can better prepare for strains that become pandemic naturally—for example, by developing "prepandemic" vaccines. This idea is highly problematic. We are nowhere near being able to predict from a flu virus's genetic sequence whether it will be transmissible or virulent, and our surveillance of flu strains in the wild is extremely limited. The impact of a particular change to the genetic sequence of a flu virus depends, in ways we have barely begun to understand, on the rest of the flu genome. Our current approaches for pandemic risk prediction are largely untested, and they have never succeeded in identifying a strain as risky before a pandemic occurred.

Researchers began discussing the novel risks of PPP experiments a decade ago, but the conversation quickly stalled; thereafter, PPP research steamed ahead. The pause in U.S. funding at last gives us an opportunity to have that debate. The U.S. is not the only funder of this type of research, but it is a major one, and the rest of the world will be watching carefully.

The scientists and policy makers involved in the White House's deliberative process must carefully consider the risks and benefits of potential pandemic pathogens. The choice is not between studying these pathogens and ignoring them. The choice is between a portfolio of research, technology development and surveillance that includes PPP studies and a portfolio that excludes PPP research and uses the freed-up resources for alternatives.

The creation of novel, transmissible, virulent influenza strains is exceptionally risky and has little public health benefit; such research should be stopped. Other types of experiments included in the funding pause, among them those that alter MERS and SARS viruses to adapt them to lab animals, might be different. For all such studies, however, objective, credible, disinterested and quantitative risk-benefit analysis is needed before further experiments continue. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/feb2015

Illustration by Julia Yellow

Dispatches from the frontiers of science, technology and medicine

The Tappan Zee Bridge's replacement should be completely finished in 2018.

COURTESY OF NEW YORK STATE THRUWAY AUTHORITY

ENGINEERING

The Rise of the Cable-Stayed Bridge

As U.S. bridges fall into disrepair, a European span design comes into favor

New York State's longest bridge is in dire straits. "At times, you can see the river through the cracks in the pavement," President Barack Obama said at a press conference in front of the Tappan Zee Bridge in May 2014. "Now, I'm not an engineer, but I figure that's not good."

It's not. The three-mile-long Tappan Zee carries 138,000 vehicles a day over the Hudson River. It is also "functionally obsolete" and as such exemplifies America's crumbling infrastructure: about one in 10 bridges in the country merits the disturbing designation of "structurally deficient," according to a 2013 report by the U.S. Department of Transportation. Built in 1955, the Tappan Zee has aged beyond its 50-year design life, like many of the steel crossways constructed during the nation's most fervent bridge-building days in the 1950s and 1960s. And now the cantilever bridge—a structure that distributes weight over beams anchored to the shore—costs $50 million a year to maintain. It is in such bad shape that Obama fast-tracked a replacement: a cable-stayed bridge, which distributes weight with cables and towers.

The cable-stayed bridge debuted in its full form in the U.S. in the 1970s, decades after engineers in Europe honed the design. Today, because of improvements in structural modeling, this method is often a civil engineer's first choice for bridges up to 3,000 feet long. They go up faster than alternative approaches and cost less because they use less material. The Tappan Zee's replacement, currently

Continued on page 19

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ENERGY & TRANSPORT

New Paradigms in Innovation

By Ronan Stephan & Robert Plana

LIKE MANY SCIENTIFIC DOMAINS, THOSE ADDRESSING ENERGY AND TRANSPORT ARE TODAY INTERTWINED with global issues linked to urbanization, climate change and the rarefaction of fossil resources.

These interwoven planetary issues call today for systemic responses. Consequently, the increasing use of renewable sources requires new solutions for both energy transmission and storage, and dynamic balancing between production and consumption. This translates into new, more complex architectures (smart grids, multimodal mobility systems, etc.) and systems whose performance needs to be optimized on a global, rather than individual, piecemeal, basis.

This new complexity can be compared to architectures found in the living world and inspires analogies with biology, a domain in which everything is based on a dynamic equilibrium between systems.

From the many angles provided by various disciplinary perspectives, these new scientific questions sometimes produce glimmers of understanding, lifting the veil on hidden properties. These may potentially lead to new solutions for modeling these architectures and predicting their behavior. Knowing how to detect these early, weak, buried and evanescent signals, born of paradoxical observations, that stimulate thinking and create flashes of insight, has become vital.

NEW SOCIAL AND COGNITIVE PARADIGMS

This is the key to an analogical reasoning that will, on the one hand, spark understanding -and therefore allow us to mas-

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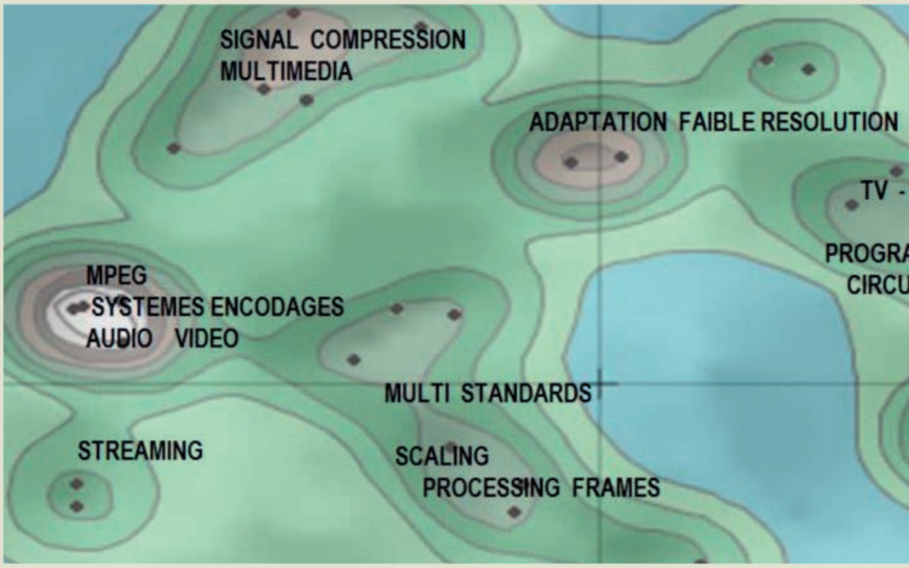
This technology mapping helps companies locate their patents in relation to those of their competitors and shows dynamic areas of opportunities and risk



Left: CNRS-DAE 2004. Right: FIST s.a.

ter these issues- and, on the other hand, break new ground for innovative ways of doing things that allow us to approach problems from a new angle. For example, the knowledge derived from research into the immune system can inspire ideas for improving signal transmission and, above all, protecting the integrity and security of data transmission networks.

These new systems increasingly are embedding more and more human-oriented technologies, with usages, ergonomics and user's expectations being integrated right from the design phase. This brings with it new paradigms whose determining factors are no longer exclusively technological but also social and cognitive, resulting in a contextual adaptation in terms of culture, geopolitics and environment. As far as energy and transport are concerned, the ONE universal solution is replaced by MANY tailored solutions depending on the particular specifications, country and dominant energy source. This does not include determining the usages, which also vary from place to place.

In the energy and transport fields, these forced major changes are changing the way research, development and innovation are carried out. People now talk about reconfigurable and flexible solutions (for example, using dynamic pricing); real-time control solutions (for recharging electric vehicles); proactive monitoring of equipment and systems (in aeronautics); proactive service quality monitoring (via the Internet); and real-time energy production, transmission and storage optimization (using genuine smart grid operating systems).

TOOLS FOR A NEW ORGANIZATION

In these periods of major change, the established points of reference are being swept away, even in so-called "traditional" industries. Conventional instruments are replaced by more intelligent tools, tools that are shared, distributed, cooperative, and being continually improved. This revolution, largely sustained by the new digital era, is just as profound as the Internet revolution twenty years ago. The potentialities of these new tools, abundantly described in the corpus of open innovation, are defining a new approach to manufacturing (using robotics and cobotics), mediation in exchanges and new social ergonomics (through collaborative social networks) and new processes for analysis and supervision (using data screening, mining, and pattern recognition solutions). These tools, which have begun to modify companies' organization and their relationship to their markets, are also able to provide early and disruptive guidelines concerning existing and future competitiveness. They will complement the current arsenal used to detect the emerging signals and corresponding "what if " scenarios, in other words, devise the strategy.

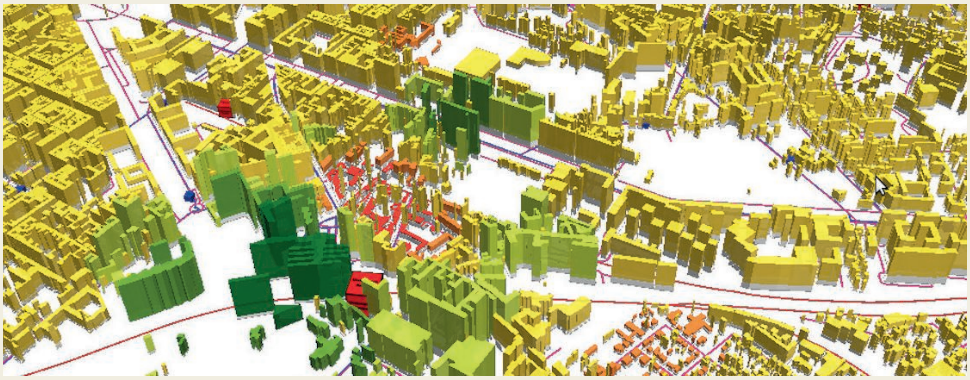
Today, we collect – or capture – these weak, or missed, signals in various ways: analogically, digitally, or through collective knowledge.

The analogical method involves establishing and developing open partnerships with universities, research bodies and, more generally, with all the stakeholders in major, innovative ecosystems. These spaces, within which scientists and engineers share ideas and present concepts, stimulate scientific exploration and shed light on industrial issues wherever they may lie on the scale of technological maturity. When maintained over time, these overlapping perspectives and discussions fertilize relationships and produce new ideas, sometimes even accelerating the appearance of new fields of scientific research.

SIMULATION

Modeling the City

The CoSMo Company is a French start-up founded in 2010 that provides modeling and simulation tools for multi-scale, dynamic and heterogeneous complex systems. With offices in Lyon and San Francisco, the company develops dedicated software for the energy and urban planning sectors. In October 2013, it produced a scalable model of the city of Versailles that simultaneously integrated the transportation, land and real estate development factors. The aim was to predict the impact of public policy on the quality of life in the city and the attractiveness of its various neighborhoods over the next 20 years. In December 2013, the tool designed for Versailles was applied to San Francisco. Using the same kind of extremely varied and detailed data, and on a neighborhood scale, the city was able to compare different policy impact scenarios.



Impact at twenty years of public policy decisions on the quality of life in Versailles: the changes are not always where they were expected to be. Negative: red; positive: green

The digital method makes use of the wealth of data available today (on users, their usage patterns, equipment performance characteristics, etc.) using fast and relevant processes to extract relevant data indicators on emerging topics. This technique obviously opens the door to new approaches in terms of economic intelligence, allowing organizations to respond more quickly in their strategic analysis and decision-making.

The third method is collective intelligence, a hybrid of the first two combining the best of each. It will, for example, aim to build physical communities engaged on strategic problems, and to enrich their available information through advanced processing of digital contents. For example, Alstom has used this new concept in a new system based on a corporate social network dedicated to innovation. The system brings together, in communities, physical and reconfigurable virtual users, who are sort of avatars able to derive, from analysis of community topics, relevant queries whose results are then fed back into the discussions. This results in the creation of dynamic and totally unique bodies of knowledge that will both provide an initial mapping of the weak signals, and allow innovative scenarios to be formulated for addressing strategic issues.

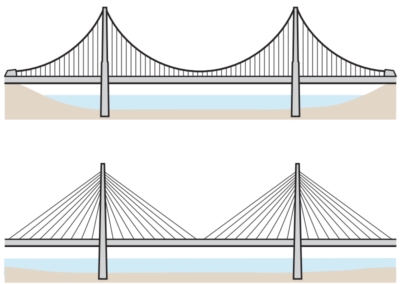
MASTERING NEW ABILITIES

Subsequently, dealing with future challenges in the energy and transport fields will no longer rely only on technological advances, but also, and increasingly, on new capacities for analyzing, predicting and designing future architectures (systems of systems), taking into account a complexity augmented by sociological and organizational aspects from the very beginning.

In such a context, the simulation of complex systems (see the example of The Cosmo Company in the box above) and the use of “serious games” will play a key role in defining future products and will involve completely revamped and more flexible marketing techniques able to integrate user expectations further upstream. These new –and fuzzy, as yet unspecified-systems will need to be sufficiently adaptable and modifiable for clients to make them their own, leading to “co-developed” products. This general trend, guided by –among other things-design thinking, which reintroduces a measure of abstraction into new product design by taking inspiration also from users’ wishes, is a new form of co-creativity.

In conclusion, the digital revolution brings with it new features that will have an impact on companies: internally, by changing the way processes and exchanges are carried out, in particular through access to information and externally, where products will be replaced by solutions. Raw materials will be sourced from big data, and the competitive edge will be gained from the ability to treat the data and extract meaningful patterns, or, in other words, to separate the wheat from the chaff. This new and vital resource will undoubtedly draw in other digital technologies stakeholders to act as competitors in markets that previously were the stronghold of the industry’s establishment.

THE COSMO COMPANY/ESRI



Suspension (*top*) and cable-stayed (*bottom*) bridges differ in their cables.

Continued from page 15
called the New NY Bridge, will take shape this spring as crews begin to work above the water on the steel underpinnings of the road. Cable-stayed bridges are also under construction in Portland, Ore., Louisville, Ky., and Los Angeles. "They're becoming a go-to type in the U.S.," says Andrew Herrmann, a former president of the American Society of Civil Engineers.

The design's closest relative is the suspension bridge—the difference between the two lying largely in how the cables are strung (*above*). In a suspension structure, such as the Golden Gate Bridge, there are two sets of cables: primary cables that connect the towers to one another and secondary cables that hang from the first set and hold the roadbed in place. A cable-stayed bridge, in contrast, has only cables that run directly from the towers to the road. Suspension bridges also require large anchors—typically huge blocks of concrete—at either end to hold them in place, whereas the weight of the road deck of a cable-stayed bridge is balanced evenly on each side of its towers and so does not need anchors.

When completed, the New NY Bridge will have eight traffic lanes and be the widest cable-stay in the world at a cost of approximately $3.9 billion. Its erection is long overdue. Bridges throughout the Northeast, which have tolerated 50 or more years of harsh winters, are in worse shape than most. "Even though this bridge will be the first cable-stay in New York State, it won't be the last," says David Capobianco, a project manager for the new bridge. "Cable-stays are definitely here to stay." The construction company expects that the structure will last for 100 years and that the first vehicles will cross it in late 2016. —*Amy Nordrum*

LOCOMOTION

Hadrosaur Gave *T. rex* a Run for Its Money

Pity the hadrosaur. The duck-billed dinosaur had no horns, armor or tusks for defense when *Tyrannosaurus rex* was on the hunt. And it was too big to escape by climbing a tree or burrowing into the ground. To top it all off, the herbivore was slow of foot. Luckily, the layout of a hadrosaur's leg and tail muscles may have helped it escape the massive jaws of tyrannosaur predators.

T. rex would win in a sprint, but a hadrosaur would outrun it in a longer race, paleontologist W. Scott Persons argues in a study about the dinosaurs' caudofemoralis muscles, published in November 2014 by Indiana University Press. The left and right caudofemoralis of theropod dinosaurs were large tail muscles anchored to the upper leg bones. Contractions would swing a hind limb backward, propelling the dinosaur forward. *T. rex* fossil impressions show that its caudofemoralis muscles were attached to the femur near the hip socket. Extrapolating from 3-D computer modeling of modern-day reptiles "means the physical distance the muscle has to contract to swing the leg through a single arc is very, very short," Persons says. Short contractions allowed it to take fast, long strides.

The only chance *T. rex* had to nab a hadrosaur was to take it by surprise.

In contrast, the hadrosaur's similarly sized caudofemoralis muscle was attached much farther down on the femur, making the muscle contraction considerably longer, which in turn made its strides shorter and slower. Advantage: *T. rex*.

An extended race, however, would yield a different result. The proximity of *T. rex*'s caudofemoralis muscle to its femur also meant the carnivore had to expend enormous amounts of energy to swing its leg, so it tired quickly. (Imagine the effort required to open and close a door if the doorknob were positioned three inches from the hinge.) For the hadrosaur, superior leverage and slower muscle contractions would mean that it tired less over great distances.

Thus, the only chance *T. rex* had to nab a hadrosaur was to take it by surprise, Persons notes. But unlike a big, agile cat, which can slink through high grass to sneak up on its prey, *T. rex*'s size would have easily given it away. With a head start and the push of its leveraged legs, the duck-billed dino would live to run another day. —*David Godkin*

COURTESY OF NIROOT PUTTAPIPAT (*dinosaurs*)

Illustration by George Retseck (bridges)

BIOLOGY

The Origin of Power

A new hypothesis about the debut of mitochondria

Mitochondria, the organelles known to every junior high school student as "the powerhouses of the cell," go back some two billion years. Although these energy producers were identified in the 1800s, how they became fixtures in cells is still under debate.

Mitochondria's ancestor was a free-living bacterium that another single-celled organism ingested. Most biologists think that the bacterium benefited the host: in one hypothesis, these premitochondria supplied hydrogen to make energy. Other researchers think that when atmospheric oxygen rose sharply in that era, anaerobic cells needed the bacteria to clear out the gas, which is toxic to them. However the match was made, the two lived so harmoniously that they eventually became mutually dependent and formed a long-term relationship.

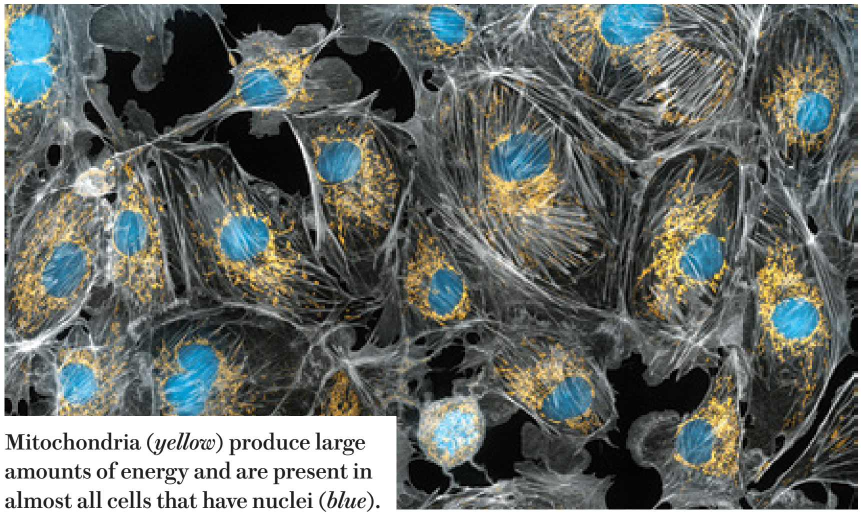
A new analysis of evolutionary relationships by Martin Wu and Zhang Wang, both then at the University of Virginia, brings up the possibility that the mitochondrial progenitor was actually a parasite. Their claim derives from their recently constructed evolutionary tree for mitochondria, which resolves ancestral relationships among the organelles and their closest living bacterial

Illustrations by Thomas Fuchs

relatives based on their genomes. Those DNA data led Wu to deduce that mitochondria sit within an order of parasitic and pathogenic bacteria called Rickettsiales and that they evolved from an ancestor that produced an energy-stealing protein. At some point, this parasitic predecessor lost the klepto gene and gained another that enabled it to supply energy to its host, as mitochondria do today. The researchers published their findings in October 2014 in the journal *PLOS ONE*.

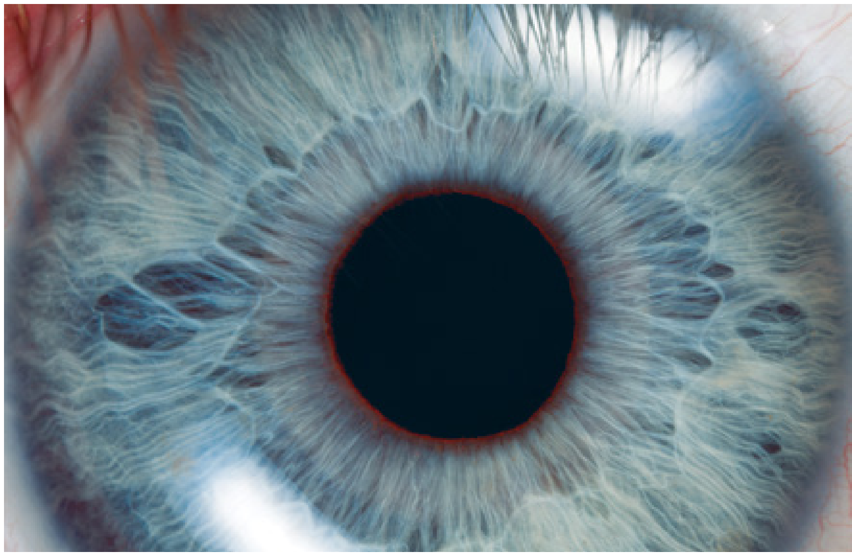
But other scientists take issue with the paper's conclusions. Dennis Searcy, who studies the origin of mitochondria at the University of Massachusetts Amherst, says the authors interpreted their evolutionary tree wrongly when they decided that mitochondria descended from Rickettsiales. Such a miscalculation would clearly corrupt their analysis. And Michael Gray, who researches mitochondrial evolution at Dalhousie University in Nova Scotia, thinks that the rapid evolution of the organelles makes it difficult to say with certainty where the once free-living entities sit within their branch of the tree.

Wu maintains that the study minimized errors as much as possible, while acknowledging that better models are necessary to assign definitive relationships. "There is definitely more work to be done," he says. "There are still very large gaps in the tree." —*Annie Sneed*



Mitochondria (*yellow*) produce large amounts of energy and are present in almost all cells that have nuclei (*blue*).

TORSTEN WITTMANN *Science Source*



HEALTH

Advance Warning

An eye-tracking test enters the running for a prognostic Alzheimer's screen

One in nine Americans aged 65 and older has Alzheimer's disease, a fatal brain disorder with no cure or effective treatment. Therapy could come in the form of new drugs, but some experts suspect drug trials have failed so far because compounds were tested too late in the disease's progression. By the time people show signs of dementia, their brains have lost neurons. No therapy can revive dead cells, and little can be done to create new ones.

So researchers running trials now seek participants who still pass as cognitively normal but are *on the verge* of decline. These "preclinical" Alzheimer's patients may represent a window of opportunity for therapeutic intervention. How to identify such individuals before they have symptoms presents a challenge, however.

Today most Alzheimer's patients are diagnosed after a detailed medical workup and extensive tests that gauge mental function. Other tests, such as spinal fluid analyses and positron-emission tomography (PET) scans, can detect signs of approaching disease and help pinpoint the preclinical window but are cumbersome or expensive. "There's no cheap, fast, noninvasive test that can identify people at risk of Alzheimer's," says Brad Dolin, chief technology officer of Neurotrack in Palo Alto, Calif.—a company developing a computerized visual screening test for Alzheimer's.

Unlike other cognitive batteries, the Neurotrack test requires no language or motor skills. Participants view images on a monitor while a camera tracks their eye movements. The test draws on research by co-founder Stuart Zola of Emory University, who studies learning and memory in monkeys. When presented with a pair of images—one novel, the other familiar—primates fixate longer on the novel one. But if the hippocampus is damaged, as it is in people with Alzheimer's, the subject does not show a clear preference for the novel images.

The findings seem to hold in people. In a study published in 2013, Zola and his colleagues gave the half-hour test to 92 seniors. Scores predicted who would develop Alzheimer's three years in advance. The company has since developed a five-minute Web-based test that uses webcams and is launching a three-year study of the test with up to 3,000 seniors in Shanghai this winter. Additional studies in the U.S. will evaluate the tool alongside PET and other measures for preclinical Alzheimer's. And a number of pharmaceutical companies will include Neurotrack in clinical trials of Alzheimer's therapies in the next few years, according to Neurotrack's CEO Elli Kaplan. Experts not involved with Neurotrack think it shows promise. The test paradigm has "an excellent base of supporting literature," says Peter Snyder of Brown University.

Blood tests, retinal scans and computerized cognitive tests are also in the running as simple screens for presymptomatic Alzheimer's. It is unclear which is most accurate, and doctors likely would use several to assess the disease's progression.

—Esther Landhuis

PETER A. KEMMER *Getty Images*

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PLANT SCIENCE

Bloody Beetroot

Sugar beets are the latest in a long line of plants found to produce hemoglobin

ISTOCKPHOTO

Hemoglobin is best known as red blood cells' superstar protein—carrying oxygen and other gases on the erythrocytes as they zip throughout the bodies of nearly all vertebrates. Less well known is its presence in vegetables, including the sugar beet, in which Nélida Leiva-Eriksson recently discovered the protein while working on her doctoral thesis at Lund University in Sweden. In fact, many land plants—from barley to tomatoes—contain the protein, says Raúl Arredondo-Peter, an expert on the evolution of plant hemoglobins, or leghemoglobins, at the Autonomous University of the State of Morelos in Mexico. "Hemoglobins are very ancient proteins," he notes. Scientists first discovered them in the bright-red nodules of soybean roots in 1939 but have yet to determine the proteins' role in plants in most cases. One popular idea is that hemoglobin binds with and delivers nitric oxide to cells, sending signals to regulate growth.

Researchers are now investigating ways to leverage leghemoglobins. For example, Robert Hill, a plant biologist at the University of Manitoba, found that genetically engineering alfalfa to produce more of the proteins boosted the crop's survival rate during a flood from 20 to 80 percent. Plant hemoglobins might even serve as a blood substitute for humans someday—an idea that Arredondo-Peter says is conceivable but far off because they do not carry and release oxygen at the same rates as human hemoglobins. Or they could be exploited to trick our senses: food scientists at Stanford University are experimenting with plant hemoglobins as an ingredient in veggie burgers to make them taste more like bloody steaks. *—Amy Nordrum*

DESIGN

Fit for Play

Type of school yard influences how much children exercise

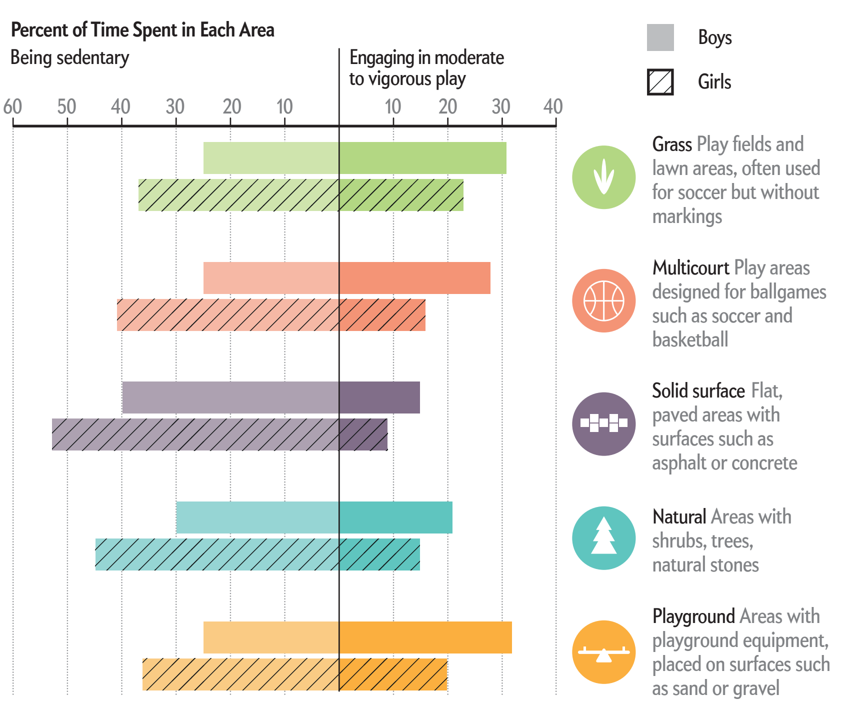
Kids should exercise at least one hour a day, according to the Centers for Disease Control and Prevention. But in the U.S., less than half of six- to 11-year-olds and only 8 percent of 12- to 19-year-olds meet that target. Schools help to promote physical activity, with recess accounting for up to 40 percent of a child's daily exercise needs. So how exactly do kids spend that welcome break from their desks?

Over in Denmark, a longitudinal study of how schoolchildren move through urban environments provided an opportunity to find out by outfitting hundreds of students with accelerometers and GPS trackers during their waking hours. Henriette Bondo Andersen, a research assistant in the department of sports science and clinical biomechanics at the University of Southern Denmark, used some of the collected data to analyze how children spent their recess time and whether various school yards—including those made up of grassy areas, playgrounds or asphalt lots—influenced activity levels.

The researchers found that children were significantly more active when playing on grassy areas and at sites featuring playground equipment. Concrete lots elicited the least energy expenditure, and in all five areas studied, girls spent more time being sedentary than boys. The findings (*below*) were published this month in *Landscape and Urban Planning*.

Insights into which schoolyard elements work best to promote physical activity could help developers around the world create more exercise-friendly spaces. "We're working with seven schools that are renovating their playgrounds by adding dancing, climbing, skating and trampoline areas," Andersen says. "The goal is to make it so kids can more easily choose to be active." *—Rachel Nuwer*

ALL PLAYGROUNDS ARE NOT CREATED EQUAL



GETTY IMAGES (*top*); SOURCE: "OBJECTIVELY MEASURED DIFFERENCES IN PHYSICAL ACTIVITY IN FIVE TYPES OF SCHOOLYARD AREA," BY HENRIETTE BONDO ANDERSEN ET AL., IN *LANDSCAPE AND URBAN PLANNING*, VOL. 134; FEBRUARY 2015 (*bottom*)

Graphic by Tiffany Farrant-Gonzalez

IN THE NEWS

Quick Hits

U.S.

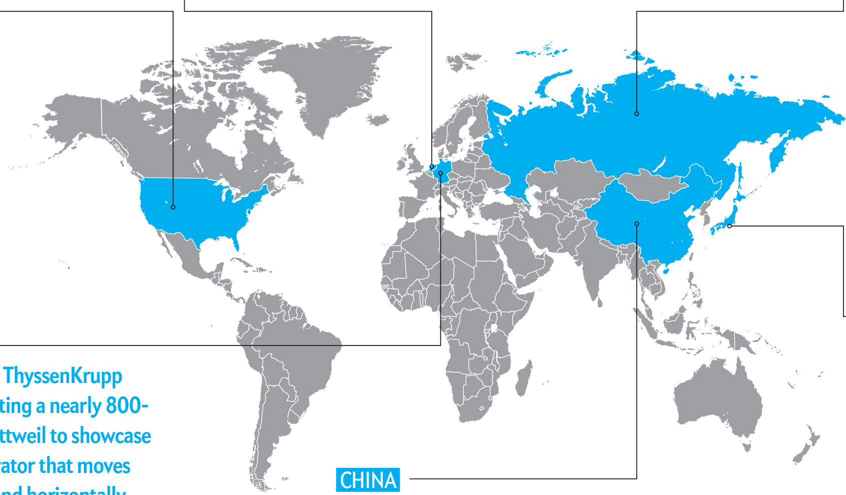
U.S. Army officials announced they will build an airport for drones at Fort Bliss in Texas. The unmanned aerial vehicles will get two runways and a 50,000-square-foot hangar—all planned for completion by April 2016.

THE NETHERLANDS

Dutch railways mounted lasers onto commuter trains in a pilot test this winter to detect and then obliterate leaves on the tracks, which can trigger anticollision software and cause delays.

RUSSIA

The government will submit a proposal to the United Nations this spring claiming a large section of the continental shelf in the Arctic Ocean. Denmark claimed a part of the Arctic, including the North Pole, in December.



GERMANY

The corporation ThyssenKrupp has started erecting a nearly 800-foot tower in Rottweil to showcase a prototype elevator that moves both vertically and horizontally. Maglev will propel the cars, which are set to begin operation in 2016.

CHINA

Sony's PlayStation 4 appeared in stores as of January, joining Xbox One, which did so in September, after a 14-year ban on the sale of personal game consoles was lifted. The content of video games, however, is still subject to government approval.

JAPAN

The Muscle Suit exoskeleton went on sale for about $5,000. Marketed to factory workers and nurses, it enables wearers to lift heavy loads with a third of the typical effort.

For more details, visit www.ScientificAmerican.com/feb2015/advances

ANIMAL BEHAVIOR

Cry "Havoc" and Let Slip the Bees of War

Jane Goodall discovered 40 years ago that chimpanzees wage war. Until then, she thought they were "rather nicer" than humans. But her shocking observation of animal warfare was not the first. It was the second. By then scientists had known for at least 80 years that we were not the only species to kill others of our own kind. Some insects do it, too.

The Australian stingless bee *Tetragonula carbonaria* is notorious for inciting war, usually to usurp the hive of another. Instead of wasting time building their own hives, they just steal one and redecorate. The fights between stingless bee colonies are epic in scale, according to John Paul Cunningham of Queensland University of Technology in Australia, with "swarms from the attacking and defending hives colliding midair and fighting bees falling to the ground locked in a death grip from which neither combatant survives."

While studying such skirmishes, Cunningham and his colleagues were surprised to find that the stingless bees were being attacked not only by other colonies of their own species but also by colonies of a different species entirely, *Tetragonula hockingsi*. This insight marks the first known description of interspecies warfare in bees—the only other instance of this type of conflict observed throughout the animal kingdom occurs among some ant species.

The stingless bees' aggression against others was so remarkable that the researchers monitored approximately 260 colonies of *T. carbonaria* in Queensland over five years to make sure they were not wrong. Because the bees are hard to distinguish by sight, Cunningham's team identified instances of usurpation of one species by the other by assessing the structure of the hives each year when they were opened for honey extraction. The hives of *T. carbonaria* are made up of well-organized cells built in a spiral pattern. Those of *T. hockingsi* contain

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cells that look haphazardly arranged. If a hive known to hold *T. carbonaria* had the structure of a *T. hockingsi* hive the following year, then that was the site of a successful seizure of territory. The researchers recorded evidence of 46 such interspecies usurpations, with victors coming from either species in equal proportion. The findings were detailed last December in the *American Naturalist.*

When the reproductive capacity of the royal class is at stake, the potential benefits to either colony may outweigh the risks of massive casualties.

Cunningham also observed the daily activities of a *T. carbonaria* hive over a single winter, witnessing three major battles and collecting the dead for later genetic analyses. By the end of the winter, the hive had been successfully commandeered by *T. hockingsi,* with the invaders dragging out all remaining occupants, including larvae, and installing a new queen.

What induces thousands of bees to go into battle and risk death? One clue comes from the genetic analysis of the dead conducted by University of Queensland researcher James Hereward. He found that the new queen was most likely the daughter of the attacking hive's own queen—brought to her new home to continue the ruling species' lineage. When the reproductive capacity of the royal class is at stake, the potential benefits to either colony may outweigh the risks of massive casualties.

The trigger for a war is uncertain, Cunningham says, "especially because beekeepers can have many hives of both species living harmoniously in close proximity." As Christoph Grüter of the University of Lausanne in Switzerland, who was not involved in the work, points out, this study highlights how much is still unknown about insect warfare and how it evolved. "The entire colony of the attacked species is wiped out, and a substantial number of attackers die as well," he explains. "It's very unusual to have these kinds of costs among both attackers and defenders."

Long live the queen.

—Jason G. Goldman

BY THE NUMBERS

DOES MATHEMATICAL ABILITY PREDICT CAREER SUCCESS?

In the early 1970s researchers identified a large sample of U.S. 13-year-olds who were exceptionally talented in math—landing in the top 1 percent of mathematical reasoning scores on SAT tests. Forty years later those wunderkinder are now midcareer and have accomplished even more than expected, according to a recent follow-up survey. Researchers at Vanderbilt University's Peabody College published the update in the December 2014 issue of *Psychological Science,* writing: "For both males and females, mathematical precocity early in life predicts later creative contributions and leadership in critical occupational roles." *—Amber Williams*

1,037
MEN

613
WOMEN

25%–40%
EARNED DOCTORATES
Compared with less than 2% of U.S. population

4.1%
TENURED AT A MAJOR RESEARCH UNIVERSITY

7,572
ACADEMIC ARTICLES WRITTEN
25% of participants

2.3%
TOP EXECUTIVES

2.4%
ATTORNEYS

85
BOOKS PUBLISHED
3% of participants

681
PATENTS SECURED
8% of participants

CRYPTOGRAPHY

Insecure Skies

Thousands of commercial and spy satellites in space present ongoing coordination challenges, but a surprising obstacle is privacy

In February 2009 the U.S.'s Iridium 33 satellite collided with the Russian Cosmos 2251, instantly destroying both communications satellites. According to ground-based telescopes tracking Iridium and Cosmos at the time, the two should have missed each other, but onboard instrumentation data from even one of the satellites would have told a different story. Why weren't operators using this positional information?

Orbital data are actually guarded secrets: satellite owners view the locations and trajectories of their on-orbit assets as private. Corporations fear losing competitive advantage—sharing exact positioning could help rivals determine the extent of their capabilities. Meanwhile governments fear that disclosure could weaken national security. But even minor collisions can cause millions of dollars' worth of damage and send debris into the path of other satellites and spacecraft carrying humans, such as the International Space Station, which is why the Iridium-Cosmos crash prompted those in the field to find an immediate fix to the clandestine problem.

In the current working solution, the world's four largest satellite communications providers have teamed up with a trusted third party: Analytical Graphics. The company aggregates their orbital data and alerts participants when satellites are at risk. This arrangement, however, requires that all participants maintain mutual trust of the third party, a situation often difficult or impossible to arrange as more players enter the field and launch more satellites into orbit.

Now experts are thinking cryptogra-

SOURCE: "LIFE PATHS AND ACCOMPLISHMENTS OF MATHEMATICALLY PRECOCIOUS MALES AND FEMALES FOUR DECADES LATER," BY DAVID LUBINSKI, CAMILLA P. BENBOW AND HARRISON J. KELL, IN *PSYCHOLOGICAL SCIENCE,* VOL. 25, NO. 12; DECEMBER 2014 (*math survey stats*); ISTOCKPHOTO (*satellite*)

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Even minor collisions can cause millions of dollars' worth of damage and send debris into the path of other satellites.

phy, which can eliminate the need for mutual trust, may be a better option. In the 1980s specialists developed algorithms that allowed many people to jointly compute a function on private data without revealing any number of secrets. In 2010 DARPA tasked teams of cryptographers to apply this technology to develop so-called secure multiparty computation (MPC) protocols for satellite data sharing. In this method, each participant loads proprietary data into its own software, which then sends messages back and forth according to a publicly specified MPC protocol. The design of the protocol guarantees that participants can compute a desired output (for example, the probability of collision) but nothing else. And because the protocol design is public, anyone involved can write their own software client—there would be no need for all parties to trust one another.

One of the current drawbacks of cryptography for orbital data is speed. Calculating the probability of collision between two satellites requires intense calculations: insecure computations take milliseconds, whereas these protocols take 90 seconds when performed on commodity hardware. As computing power improves, however, the MPC protocols will become more practical to use. Now DARPA's efforts are wrapping up, and a proof-of-concept algorithm is ready. At present, no one is using the protocols in practice, but cryptographers are looking for adopters of the technology.

—Brett Hemenway and Bill Welser

Brett Hemenway is a research assistant professor at the University of Pennsylvania focusing on cryptography and an adjunct researcher at RAND Corporation. William Welser IV is director of the engineering and applied sciences department at RAND and an expert in space policy.

CHEMISTRY

New Vibrations

Chemists confirm the existence of a "vibrational" chemical bond predicted in the 1980s

Chemistry has many laws, one of which is that the rate of a reaction speeds up as temperature rises. So, in 1989, when chemists experimenting at a nuclear accelerator in Vancouver observed that a reaction between bromine and muonium—a hydrogen isotope—slowed down when they increased the temperature, they were flummoxed.

Donald Fleming, a University of British Columbia chemist involved with the experiment, thought that perhaps as bromine and muonium co-mingled, they formed an intermediate structure held together by a "vibrational" bond—a bond that other chemists had posed as a theoretical possibility earlier that decade. In this scenario, the lightweight muonium atom would move rapidly between two heavy bromine atoms, "like a Ping Pong ball bouncing between two bowling balls," Fleming says. The oscillating atom would briefly hold the two bromine atoms together and reduce the overall energy, and therefore speed, of the reaction. (With a Fleming working on a bond, you could say the atomic interaction is shaken, not stirred.)

At the time of the experiment, the necessary equipment was not available to examine the milliseconds-long reaction closely enough to determine whether such vibrational bonding existed. Over the past 25 years, however, chemists' ability to track subtle changes in energy levels within reactions has greatly improved, so Fleming and his colleagues ran their reaction again three years ago in the nuclear accelerator at Rutherford Appleton Laboratory in England. Based on calculations from both experiments and the work of collaborating theoretical chemists at Free University of Berlin and Saitama University in Japan, they concluded that muonium and bromine were indeed forming a new type of temporary bond. Its vibrational nature lowered the total energy of the intermediate bromine-muonium structure—thereby explaining why the reaction slowed even though the temperature was rising.

The team reported its results last December in *Angewandte Chemie International Edition,* a publication of the German Chemical Society. The work confirms that vibrational bonds—fleeting though they may be—should be added to the list of known chemical bonds. And although the bromine-muonium reaction was an "ideal" system to verify vibrational bonding, Fleming predicts the phenomenon also occurs in other reactions between heavy and light atoms.

—Amy Nordrum

COMMENT AT ScientificAmerican.com/feb2015

David Noonan is a freelance science writer and former *Newsweek* senior editor.

Marijuana's Medical Future

As more states legalize treatment, scientists are learning how the plant's chemicals may help conditions ranging from brain injuries to cancer

Edward Maa did not plan to become a marijuana researcher. But a few years ago, when the neurologist and epilepsy specialist surveyed his patients about their use of alternative medicines, he discovered that more than a third had turned to marijuana to try to control their seizures. "I had no idea," says Maa, who is chief of the Comprehensive Epilepsy Program at Denver Health.

Now he is trying to impose some scientific rigor on what has become a very big and unscientific ad hoc experiment in his state, where medical marijuana use is legal. According to the Epilepsy Foundation of Colorado, the widely reported case of Charlotte Figi, a child whose nearly constant seizures were dramatically curtailed with cannabidiol, a marijuana ingredient, has helped trigger an influx of families from around the U.S. seeking similar treatment for their children with seizure disorders. Maa wants to move beyond anecdote and into data. He is monitoring 150 epilepsy patients who all take a product derived from the same strain of marijuana that Figi used, provided by the same source. Over the course of a year, he intends to compare dosage to seizure activity and side effects, as well as patient characteristics, to see if any patterns suggest the drug is effective—or not—in particular situations. "My position is, let's see what's going on," Maa says. "Let's see if this is helpful and try to understand what we are seeing."

Understanding the biology and chemistry behind marijuana's claimed medical benefits is becoming extremely important now that 23 states and the District of Columbia allow the use of marijuana to treat some medical conditions, including pain, nausea and glaucoma. Other states are expected to follow suit. Four states and the District of Columbia have legalized it for recreational use as well. Although the federal government still lists marijuana as a Schedule I drug, a class "with no currently accepted medical use," a body of recent research—most of it done in test tubes and animals, but some done in people—suggests that cannabinoids, which are the active ingredients in marijuana, may have medicinal uses even beyond the approved ones. They might protect the brain from the effects of trauma, ease the spasms of multiple sclerosis and reduce epileptic seizures. Further preliminary work indicates that the chemicals may slow the growth of tumors and reduce brain damage in Alzheimer's disease.

THIS IS YOUR BRAIN ON POT

THE CHEMICAL THAT INDUCES marijuana's trippy effects, delta-9 tetrahydrocannabinol (THC), was isolated in 1964. Several other components have been described since, including cannabidiol, the compound used by the epilepsy patients, which does not make people high. In the late 1980s and early 1990s scientists began to identify and map two groups of molecules, known as receptors, in the central nervous system and immune system that help cannabinoids bind to cells. That interaction appears to play a critical role in marijuana's various effects. (The brain

Illustration by Aleks Sennwald

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CB1, the more common of the two main receptors, is widely distributed in the brain, with high concentrations in the cortex and the hippocampus (a region important to forming new memories). CB1 receptors also occur in parts of the brain involved in pain perception. There are low levels of CB1 in the brain stem, where cardiac and respiratory functions are regulated; their relative scarcity in this region may explain why, unlike opioids, even heavy doses of cannabinoids do not pose acute threats to the heart or your ability to breathe.

CB2, the other main cannabinoid receptor, is found mostly in the immune system. Its presence there interests scientists because the immune system triggers inflammation, and studies show marijuana can have an anti-inflammatory effect.

In the brain, when the psychoactive component THC links up with CB1, it slows down or blocks the release of a variety of neurotransmitters—signaling molecules released by neurons—including glutamate and dopamine. The result is the high that marijuana is best known for, often along with temporary impairment of short-term memory. Two other well-known effects of the THC-CB1 linkage are the stimulation of appetite, a boon for AIDS patients and others who need to maintain body weight, and the suppression of nausea, a benefit for some cancer patients receiving chemotherapy. THC has also been shown to disrupt the transmission of pain signals.

Recent research suggests that THC might also protect neurons from trauma. Early test-tube studies pointed to this effect, and so has one clinical trial published last October. In it, trauma surgeon David Plurad and his colleagues did a retrospective review of 446 traumatic brain injury (TBI) cases treated at Harbor-UCLA Medical Center from January 2010 through December 2012. Their study, reported in the journal *American Surgeon,* found that 82 of those patients tested positive for THC and two of them died, for a mortality rate of 2.4 percent. The mortality rate among the 364 patients who did not have THC in their system was 11.5 percent, nearly five times higher. After taking into account other factors, such as age, severity of injury and blood alcohol level, the researchers concluded that the link between THC and a lower death rate in these patients stood up. Although the mechanisms are not fully understood, previous research suggests that both THC and cannabidiol may increase blood flow in the brain, bringing needed oxygen as well as nutrients to endangered neurons. Because they inhibit glutamate, they may also prevent toxic effects that occur after brain trauma, when neurons can get overstimulated by the neurotransmitter.

Marijuana, of course, impairs perception and reaction time, so it may have contributed to the accidents that Plurad studied at the same time that it helped some people survive them. The irony is not lost on the surgeon. "There is never going to be one answer for marijuana," Plurad says. "It's good for you, it's bad for you. It will never be one or the other. It will always be somewhere in between." Some research, including a recent study funded by the National Institute on Drug Abuse, has shown that heavy use of marijuana (at least four times a week for the past six months in the paper) can lead to adverse changes in parts of the brain associated with reward and decision making. Plurad warns against such heavy use and use by teenagers. "As a clinical person," he says, "what's interesting to me is that when you get down to the nitty-gritty of taking care of patients, it's cheap. And if it has valuable applications, then we should pursue it."

DEVELOPING A DRUG

DRUG COMPANIES are already in pursuit, working on compounds that show the benefits without the cognitive problems. GW Pharmaceuticals, a British firm, has developed two marijuana-derived drugs, Epidiolex and Sativex. Epidiolex, a purified form of cannabidiol, is intended to treat seizures and is being tested in an international clinical trial led by the University of California, San Francisco, Epilepsy Center. It has already been granted orphan drug status—a path to approval based on smaller clinical studies than normal—by the Food and Drug Administration. Sativex, a mouth spray that contains THC and cannabidiol, is approved in Canada and several other countries, but not the U.S., for the treatment of muscle spasticity in multiple sclerosis. It is also being tested as a pain treatment. As Maa and others point out, pharmaceutical cannabinoid medicines offer consistent potency and make dosage easier to control—critical factors in many cases, especially with pediatric patients.

In addition to these conditions, studies in animals and in cells, published in 2014, suggest that cannabinoids might eventually play a helpful role in treating three other kinds of disease. After inducing human breast cancer tumors in mice, researchers in the U.K. found they could shrink the tumors by administering THC. The chemical may disrupt cancer cell growth as it binds to CB2 receptors, which are much more abundant on cancer cells than on healthy ones. At the University of South Carolina, a team discovered that THC could reduce the inflammation associated with autoimmune diseases by suppressing the activity of certain genes involved in the immune response. And at the University of South Florida, researchers working with cells in a lab showed that extremely low concentrations of THC could reduce production of beta amyloid, the protein that forms the plaque abundant in the brains of Alzheimer's patients. It will, however, be several years before scientists learn how well THC will work, if at all, in patients with the condition.

For Lester Grinspoon, the new findings are gratifying but not surprising. Grinspoon, associate professor of psychiatry emeritus at Harvard Medical School, is the American godfather of medical marijuana. Now 86, Grinspoon used marijuana to treat his young son's chemotherapy-related nausea in the 1960s. He wrote a book about marijuana's benefits in 1971 and, after decades of research and controversy, continues to endorse them (see his Web site: RxMarijuana.com). He is pleased the nation at last appears to be catching up with him. "It's about time," he says. He notes that before World War II, marijuana was listed as a medicine in the country's encyclopedia of drugs, the *United States Pharmacopeia*. "When marijuana is finally readmitted to the *U.S. Pharmacopeia,* a place it lost in 1942, it will be seen as one of the safest, least toxic, most versatile drugs of that whole compendium," he predicts. SA

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David Pogue is the anchor columnist for Yahoo Tech and host of several *NOVA* miniseries on PBS.

The Future Is Plastic

Why mobile payments are stalled—and the credit card is here to stay

It really is time for credit cards to go. We're still using a payment technology that hasn't changed in more than 50 years. We carry around a piece of plastic with an easily demagnetized stripe, whose account number is all too easily hacked or stolen. (Just ask Target, Home Depot or TJ Maxx.)

Why not allow people to pay by waving their cell phones? It works well in Europe. It uses a device we are already carrying. It can be convenient, fast and secure.

That, surely, is what Google was thinking when it introduced Google Wallet in 2011. You hold your Android phone near the cash register's wireless credit-card terminal, tap in a security code, and boom: you just paid. You charged your credit-card account without actually needing your card. But Google Wallet was a bust—the first sign that phone-payment nirvana won't be simple to attain.

The biggest problem: Verizon, AT&T and T-Mobile didn't like the Wallet initiative one bit. They refused to sell Android phones containing the Wallet app.

Why? Because they were cooking up their own, competing phone-payment system, originally called Isis. (The name changed to Softcard after the word "Isis" became better known as an Islamic extremist group.)

But Softcard seems stalled, too. It works directly with only a handful of credit cards from Chase, Wells Fargo or American Express. As with Google Wallet, you have to tap in a security code with each purchase; a credit-card swipe looks speedy by comparison.

A third initiative, Apple Pay, doesn't require a code. Instead the Home button on iPhone 6 models reads your fingerprint, so the identification process is instantaneous and effortless. Merchants like Apple Pay because it doesn't cost them anything. Banks like it because Apple Pay transactions are extremely secure; the merchant never stores, or even receives, your credit-card number. (The phone transmits a one-time transaction code to the merchant.)

Sounds great, right? Then why doesn't Apple Pay work at Walmart, Lowe's, Old Navy, Target, Southwest Airlines, 7-Eleven, Best Buy, CVS, Dunkin' Donuts, Sunoco, Shell, ShopRite, Wendy's, Banana Republic, Bed Bath & Beyond or the Gap?

Because those chains are backing yet a fourth phone-payment system. In this scheme, called CurrentC, your purchases are deducted directly from your bank account. No credit card is involved—meaning that the stores do not have to pay the banks the usual 2 to 4 percent card fees on each sale. For a national chain, that's big money.

Four immense corporate initiatives, each vying to be the first American phone-payment success story. They're attacking the credit-card problem separately, as enemies—and we, the people, are the losers.

Which one will win? Maybe none of them.

Credit cards make all parties happy. They bring money to the banks, sales to the stores and convenience to the consumers. In other words, everybody has an interest in solving the fraud problem.

And while the corporate interests quarrel away their window of opportunity, traditional cards are about to fix their own vulnerability. Credit cards are about to become much more secure.

This year EMV cards (for Europay-MasterCard-Visa) are coming to America in a big way. Each contains a chip, not a magnetic stripe. You type in a PIN code instead of signing your name. EMV is far more secure than mag-stripe codes. To encourage retailers to install EMV-compatible card readers, Visa, MasterCard, Amex and Discover have announced that this October, they will no longer accept liability for fraudulent purchases made on magnetic cards. They will shift that responsibility to the merchants.

For tech fans and younger audiences, paying by waving the phone is fun, fast and secure. Someday all we'll carry while shopping will be a phone—but thanks to squabbling and corporate greed, that day is about to slip even farther into the future. SA

SCIENTIFIC AMERICAN ONLINE
Five newfangled ways to pay: ScientificAmerican.com/feb2015/pogue

Illustration by Paulo D. Campos

HUMAN EVOLUTION

NEANDERTAL MINDS

Analyses of anatomy, DNA and cultural remains have yielded tantalizing insights into the inner lives of our mysterious extinct cousins

By Kate Wong

IN BRIEF

Long-standing view of Neandertals, our closest relatives, holds that they lagged far behind anatomically modern *Homo sapiens* in terms of cognitive ability.

Studies show that they did differ from *H. sapiens* in their brain anatomy and DNA, but the functional significance of these differences is unclear.

Cultural remains provide clearer insights into the Neandertal mind—and narrow the supposed mental gap between them and us.

The findings suggest that factors unrelated to intelligence drove Neandertals to extinction and allowed *H. sapiens* to flourish.

Illustration by Giordano Polini

Kate Wong is a senior editor at *Scientific American.*

ON A CLEAR DAY IN GIBRALTAR, LOOKING OUT OF GORHAM'S CAVE, YOU can see the rugged northern coast of Morocco looming purple above the turquoise sea. Inside the cave, quiet prevails, save for the lapping of waves against its rocky beach. But offshore, the strait separating this southernmost tip of the Iberian Peninsula from the African continent bustles with activity. Fishing vessels troll the waters for tuna and marlin, cruise ships carry tourists gawking at Gibraltar's hulking limestone massif, and tankers ferry crude oil from the Mediterranean to points west. With its swift, nutrient-rich currents, mild climate and gateway location, the area has attracted humans for millennia.

One impressive group dwelled in the region for tens of thousands of years, weathering several ice ages here. During such times lower sea levels exposed a vast coastal plain in front of the cave, land that supported a variety of animals and plants. These individuals cleverly exploited the local bounty. They hunted large animals such as ibex and seals and small ones such as rabbits and pigeons; they fished for bream and gathered mussels and limpets from the distant shore; they harvested pine nuts from the surrounding evergreens. Sometimes they took ravens and eagles for their plumage to bedeck themselves with the beautiful black flight feathers. And they engraved their cave floor with symbols whose meaning has since been lost to time.

In all these ways, these people behaved just like our own *Homo sapiens* ancestors, who arose in Africa with the same anatomy we have today and later colonized every corner of the globe. But they were not these anatomically modern humans. They were Neandertals, our stocky, heavy-browed cousins, known to have lived in Eurasia between 350,000 and 39,000 years ago—those same Neandertals whose name has come to be synonymous in pop culture with idiocy and brutishness.

The scientific basis for that popular pejorative view has deep roots. Back in the early 1900s the discovery of the first largely complete Neandertal skeleton, from the site of La Chapelle-aux-Saints in France, gave rise to the group's image problem: deformities now known to reflect the old age of the individual were seen as signs of degeneracy and subhumanness.

Since then, the pendulum of paleoanthropological opinion has swung repeatedly between researchers who see Neandertals as cognitively inferior to *H. sapiens* and those who see them as our mental equals. Now a rash of new discoveries is fanning the debate. Some fossil and ancient DNA analyses seem to suggest that Neandertal brains were indeed different—and less capable—than those of *H. sapiens.* Yet mounting archaeological evidence indicates that Neandertals behaved in many of the same ways that their anatomically modern contemporaries did.

As scientists advance into the Neandertal mind, the mystery of why our closest relatives went extinct after reigning for hundreds of thousands of years is deepening. The race is on to solve this extinction riddle: such insight will help reveal what it was that distinguished our kind from the rest of the human family—and set anatomically modern humans on the path to becoming the enormously successful species we are today.

BONY INKLINGS

PALEOANTHROPOLOGISTS have long sought clues to Neandertal cognition in the fossilized skulls they left behind. By studying casts of the interior of the braincase, researchers can reconstruct the external form of an extinct human's brain, which reveals the overall size as well as the shape of certain of its regions. But those analyses have failed to turn up much in the way of clear-cut differences between Neandertal brains and those of *H. sapiens.* (Some experts think Neandertals were just another population of *H. sapiens.* This article treats the two groups as different human species, albeit very closely related ones.) Neandertal brains were a little flatter than ours, but they were just as big—indeed, in many cases they were larger, explains paleoneurologist Ralph Holloway of Columbia University. And their frontal lobes—which govern problem solving, among other tasks—were almost identical to those of *H. sapiens,* judging from the impression they left on the inside of the braincase. That impression does not reveal the internal extent or structure of those key brain regions, however. "Endocasts are the most direct evidence of brain evolution, but they are extremely limited in terms of giving you solid information about behavior," Holloway admits.

In a widely publicized study published in 2013, Eiluned Pearce of the University of Oxford and her colleagues purportedly got around some of the limitations of endocasts and provided a way of estimating the size of internal brain areas. The team used eye-socket size as a proxy for the size of the visual cortex, which is the brain region that processes visual signals. They found that the Neandertal skulls they measured had significantly larger eye sockets than modern humans have—the better for coping with the lower light levels available in their high-latitude homes, according to one theory—and thus larger visual cortices. With more real estate dedicated to processing visual information, Neandertals would have had less neural tissue left over for other brain regions, including the ones that help us maintain extensive social networks, which can buffer against hard times, the researchers argued.

Holloway is not convinced. His own endocast work indicates that there is no way to delineate and measure the visual cortex. And Neandertal faces are larger than those of anatomically modern humans, which might explain their larger eye sockets. Moreover, people today are hugely variable in the proportion of visual cortex they have relative to other brain regions, he observes, and this anatomical variability does not appear to correspond to differences in behavior.

Other fossil analyses have yielded similarly equivocal signals about the Neandertal mind. Studies of limb asymmetry and wear marks on tools as well as on the teeth (from using them to grasp items such as animal hides during processing) indicate that Neandertals were as right-handed as we moderns are. A strong tendency toward favoring the right hand is one of the traits that distinguishes *H. sapiens* from chimpanzees and corresponds to asymmetries in the brain that are believed to be related to language—a key component of modern human behavior. Yet studies of skull shape in Neandertal specimens representing a range of developmental stages indicate that the Neandertals attained their large brain size through a different developmental pathway than that of *H. sapiens*. Although Neandertal brains started off growing like modern brains in the womb, they diverged from the modern growth pattern after birth, during a critical window for cognitive development.

Those developmental differences may have deep evolutionary roots. An analysis of some 17 skulls dated to 430,000 years ago from the fossil site of Sima de los Huesos, in the Atapuerca Mountains in northern Spain, has shown that members of the population there, believed to have been Neandertal precursors, had smaller brains than later members of the lineage. The finding suggests that Neandertals did not inherit their large brain size from the last common ancestor of Neandertals and modern humans; instead the two species underwent a parallel brain expansion later in their evolution. Although Neandertal brains ended up approximately as large as ours, their independent evolution would have left plenty of opportunities for the emergence of brain differences apart from size, such as those affecting connectivity.

GENETIC HINTS

GLIMPSES OF SOME OF THOSE differences have come from DNA analyses. Since the publication of a draft of the Neandertal genome in 2010, geneticists have been mining ancient DNA to see how Neandertals and *H. sapiens* compare. Intriguingly, the Neandertals turn out to have carried a very similar variant we have of a gene called *FOXP2* that is thought to play a role in speech and language in humans. But other parts of the Neandertal genome appear to contrast with ours in significant ways. For one thing, Neandertals seem to have carried different versions of other genes involved in language, including *CNTNAP2*. Further, of the 87 genes in modern humans that differ significantly from their counterparts in Neandertals and another archaic hominin group, the Denisovans, several are involved in brain development and function.

Differences in the genetic codes of Neandertals and modern humans are not the whole story, however. The switching on and off of genes could have distinguished moderns from Neandertals, too, so that the groups differed in how robustly and under what circumstances they produced the substances encoded by their genes. Indeed, *FOXP2* itself appears to have been expressed differently in Neandertals than in *H. sapiens,* even though the protein it made was the same. Scientists have begun studying gene regulation in Neandertals and other extinct humans by examining the patterns of chemical tags known as methyl groups in ancient genomes. These tags are known to influence gene activity.

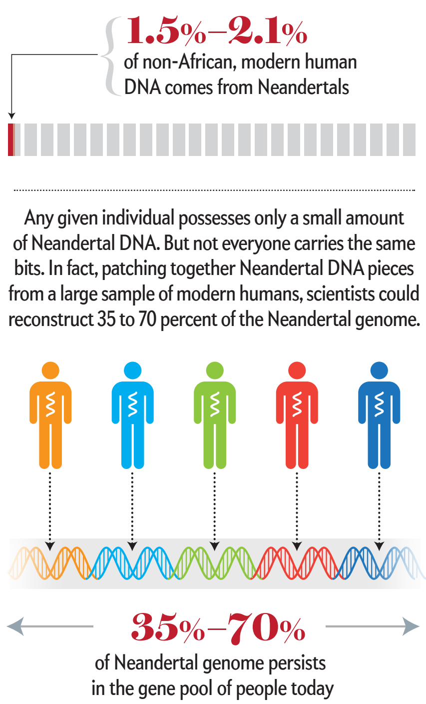
But whether or not differences in DNA sequences and gene activity translate to differences in cognition is the big question. To that end, intriguing clues have emerged from studies of people today who carry a small percentage of Neandertal DNA as a result of long-ago interbreeding between Neandertals and *H. sapiens*.

Geneticist John Blangero of the Texas Biomedical Research Institute runs a long-term study of extended families in San Antonio aimed at finding genes involved in complex diseases such as diabetes. In recent years he and his colleagues had begun looking at brain structure and function in the study participants. A biological anthropologist by training, Blangero started at one point to wonder how he could use living humans to answer such questions as what cognitive abilities Neandertals had.

A plan began to take shape. Over the course of their disease research, Blangero and his team had obtained whole-genome sequences and MRI scans of the brains of hundreds of patients. And they had developed a statistical method to gauge the effects of certain disease-linked gene variants on observable traits. Blangero realized that with the aid of their statistical tool, they could use the Neandertal genomes and his group's genetic and MRI data from living people to estimate the effects of the full complement of Nean-

Neandertal Legacy

Analysis of DNA recovered from several Neandertal fossils has revealed that Neandertals interbred with *Homo sapiens* after our species left Africa. Neandertal DNA lives on in many people today as a result of this long-ago mixing.

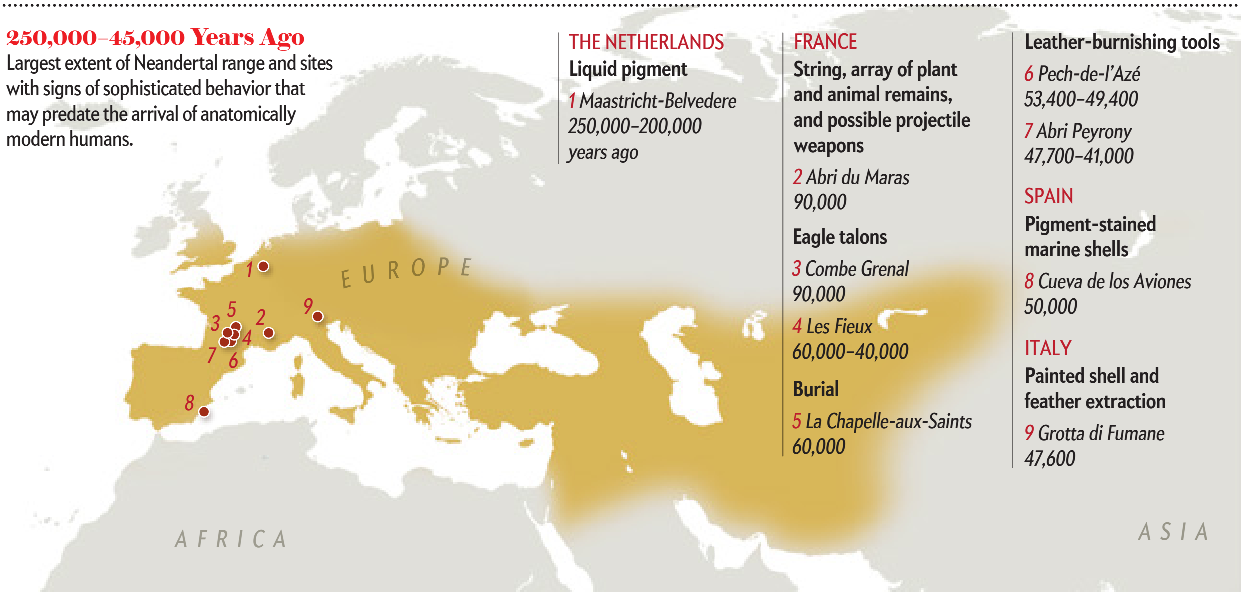


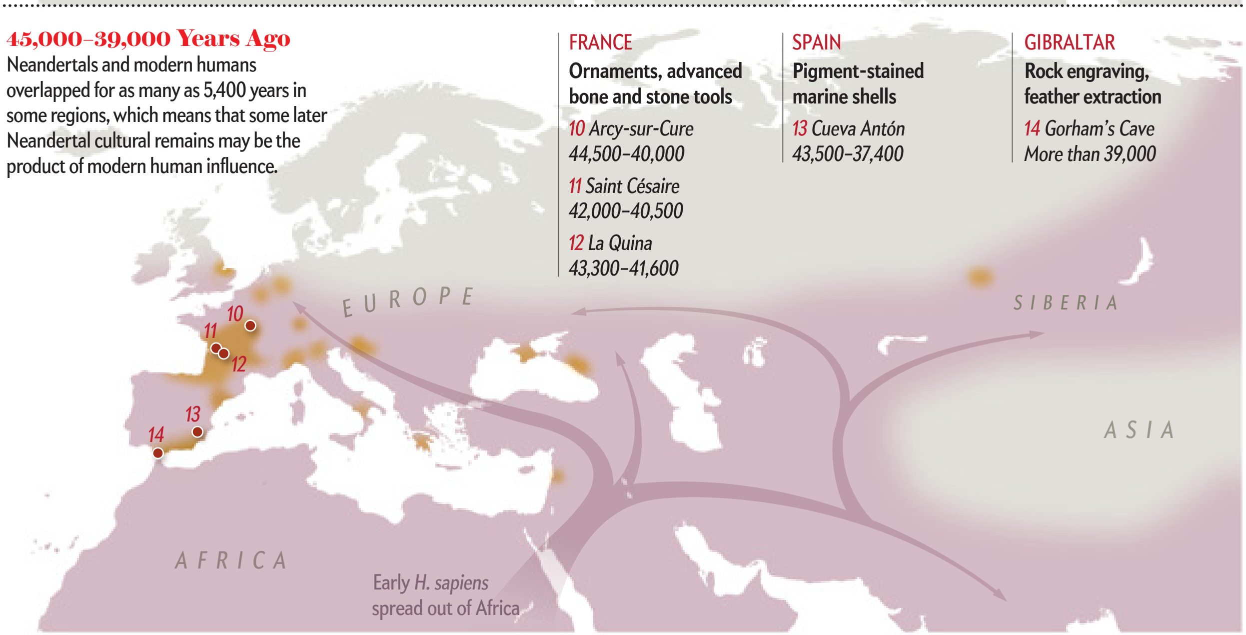
Graphic by 5W Infographics

The *Homo sapiens* Effect

Neandertals ruled Eurasia for hundreds of thousands of years until anatomically modern *H. sapiens* from Africa invaded their turf. Then the Neandertals faded away. Some experts have proposed that Neandertals lost out to the moderns because they lacked the language and social skills, technological ingenuity and foraging savvy that the newcomers had. Any hints of Neandertal sophistication from late Neandertal archaeological sites were chalked up to the influence of *H. sapiens.* Recent efforts to pinpoint the timing of Neandertal extinction, by redating a number of sites in Europe, indicate that Neandertals overlapped with *H. sapiens* for thousands of years in some places—ample time for Neandertals to have learned the ways of the interlopers. Yet over the past few years a flurry of discoveries attesting to Neandertal sophistication—from symbolic items and advanced tools to a wide variety of food remnants—have emerged from sites that clearly predate the arrival of *H. sapiens.* The question that scientists now face is whether the new arrivals were just better at these things or whether some other factor drove the Neandertals' demise.

Neandertal range · Early *Homo sapiens* range · ● Representative sites of Neandertal finds indicative of advanced behavior



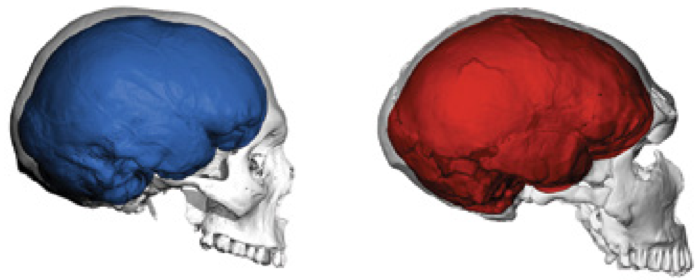


SOURCE: "THE TIMING AND SPATIOTEMPORAL PATTERNING OF NEANDERTHAL DISAPPEARANCE," BY TOM HIGHAM ET AL., IN *NATURE*, VOL. 512; AUGUST 21, 2014 (*Neandertal range*)

Maps by 5W Infographics

dertal genetic variants—the so-called polygenotype—on traits related to cognition.

Their results suggest that several key brain regions were smaller in Neandertals than in modern humans, including the gray matter surface area (which helps to process information in the brain), Broca's area (which seems to be involved in language) and the amygdala (which controls emotions and motivation). The findings also indicate that Neandertals would have had less white matter, translating to reduced brain connectivity. And other traits would have compromised their ability to learn and remember words. "Neandertals were almost certainly less cognitively adept," asserts Blangero, who presented his preliminary findings at the annual meeting of the American Association of Physical Anthropologists in Calgary last April. "I'm willing to bet on that one."



BRAIN SHAPE differs between a Neandertal (*right*) and a modern human (*left*), but how this difference might have affected thought is unknown.

FROM "A UNIQUELY MODERN HUMAN PATTERN OF ENDOCRANIAL DEVELOPMENT: INSIGHTS FROM A NEW CRANIAL RECONSTRUCTION OF THE NEANDERTAL NEWBORN FROM MEZMAISKAYA," BY PHILIPP GUNZ, SIMON NEUBAUER, LUBOV GOLOVANOVA, VLADIMIR DORONICHEV, BRUNO MAUREILLE AND JEAN-JACQUES HUBLIN, IN *JOURNAL OF HUMAN EVOLUTION*, VOL. 62, NO. 2; FEBRUARY 2012

Of course, without living Neandertals around today, Blangero cannot conduct cognitive assessments that would confirm or refute his inference. But there is, in theory, another way to put his hunch to the test. It would be possible, using existing technology, to study Neandertal brain cell function by genetically modifying modern human cells to have Neandertal DNA sequences, programming them to become neurons and observing the Neandertalized cells in petri dishes. Scientists could then examine the abilities of the neurons to conduct electrical impulses, to migrate to different brain regions and to produce projections (neurites) that aid in cell communication, for instance. Blangero notes that although there are ethical issues to consider where the creation of Neandertal cells is concerned, such work might actually help researchers identify genes involved in modern human brain disorders if the genetic changes compromise neuron function. Such findings could, in turn, lead to the discovery of new drug targets.

Not everyone is ready to draw conclusions about the Neandertal mind from DNA. John Hawks of the University of Wisconsin–Madison observes that Neandertals may have carried gene variants that affected their brain function but that have no counterparts in people today for comparison. He notes that if one were to predict Neandertal skin color based on the genes they share with modern humans, one would surmise that they had dark skin. Yet scientists now know Neandertals had some genes no longer in circulation that probably lightened their skin. But a bigger problem with attempting to suss out how Neandertal brains worked from their genes, Hawks says, is that for the most part researchers do not know how genes affect thought in our own kind. "We know next to nothing about Neandertal cognition from genetics because we know next to nothing about [modern] human cognition from genetics," he asserts.

ARCHAEOLOGICAL INSIGHTS

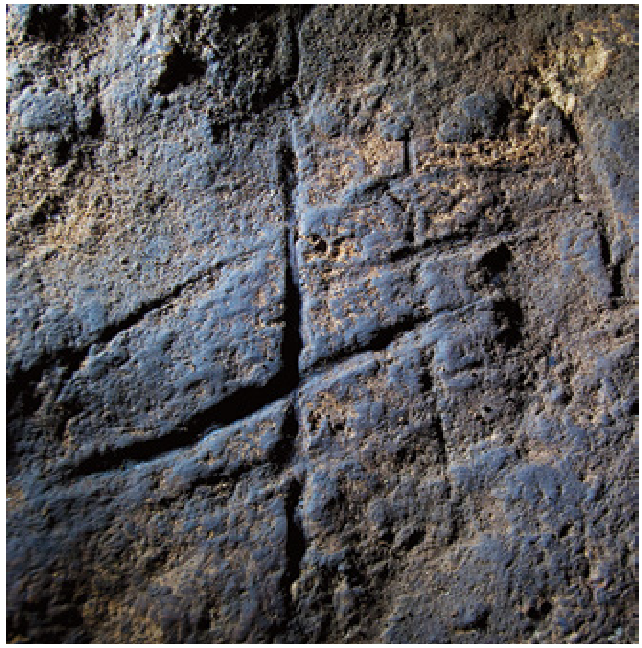
GIVEN THE LIMITATIONS of the fossil anatomy and the fact that ancient DNA research is still in its infancy, many researchers say the clearest window on the Neandertal mind is the cultural record these extinct humans left behind. For a long time, that record did not paint a particularly flattering picture of our vanished cousins. Early modern Europeans left behind elegant art, complex tools and remainders of meals attesting to an ability to exploit a wide variety of animals and plants that enabled them to adapt to new environments and shifting climate. Neandertals, in contrast, seemed to lack art and other symbolic remains; their tools were comparatively simple; and they appeared to have had a foraging strategy narrowly focused on large game. Stuck in their ways, the thinking went, the Neandertals simply could not adapt to deteriorating climate conditions and competition from the invading moderns.

In the 1990s, however, archaeologists began to find evidence contradicting that scenario—namely, a handful of decorative items and advanced tools attributed to Neandertals. Ever since, researchers have been at loggerheads over whether these items are Neandertal inventions as claimed; doubt has arisen because the items date to the end of the Neandertal dynasty, by which time *H. sapiens* was in the area, too. (Anatomically modern humans appear to have reached Europe by around 44,000 to 41,500 years ago, hundreds of thousands of years after Neandertals settled there.) Some skeptics think that *H. sapiens* made the sophisticated artifacts, which later got mixed in with the Neandertal remains. Alternatively, they offer, Neandertals may have copied the ingenious moderns or stolen their goods.

But that position is becoming harder to uphold in the face of a raft of discoveries over the past few years that evince Neandertal savvy prior to the spread of anatomically modern humans throughout Europe. "There's been a real sea change. Every month brings something new and surprising that Neandertals did," observes David Frayer of the University of Kansas. "And the new evidence is always that they were more sophisticated, not hicks."

Some of the most surprising discoveries reveal aesthetics and abstract thought in Neandertal cultures that predated the arrival of *H. sapiens*. These finds include the engraving and signs of feather use from Gorham's Cave. In fact, artifacts of this nature have turned up at archaeological sites across Europe. At the Grotta di Fumane in Italy's Veneto region, archaeologists found signs of feather use and a fossil snail shell collected from at least 100 kilometers away that had been stained red, suspended on a string and worn as a pendant at least 47,600 years ago. Cueva de los Aviones and Cueva Antón in southeastern Spain have also yielded seashells bearing traces of pigment. Some seem to have served as cups for mixing and holding red, yellow and sparkly black pigments that may have been cosmetics; others bear holes indicating that they were worn as jewelry. The modified shells date to as many as 50,000 years ago.

Other Neandertal leavings indicate that their yen for decorating reaches back further still. Sites in France and Italy document a tradition of harvesting eagle talons that spans from 90,000 to 40,000 years ago. Cut marks on the bones show that the Nean-



GIBRALTAR CAVES (*above*) **housed sophisticated Neandertals. An engraving** (*right*) **found in one of the caves adds to evidence that Neandertals thought symbolically.**

dertals focused their efforts on obtaining the claws, not the flesh. This finding led investigators to conclude that the Neandertals exploited the eagles for symbolic reasons—probably to adorn themselves with the impressive talons—rather than dietary ones.

Even older hints of Neandertal aesthetics come from the site of Maastricht-Belvedere in the Netherlands, where archaeologists have found small splatters of red ochre, or iron oxide, in deposits dating to between 250,000 and 200,000 years ago at minimum. The scarlet pigment had been finely ground and mixed into a liquid that then dripped onto the ground. Researchers cannot know for sure what those Neandertals were doing with the red liquid, but painting is one obvious possibility. Indeed, when red ochre turns up at early modern human sites, investigators assume that it was used for decorative purposes.

In addition to rendering a far more resplendent portrait of our much maligned cousins, these new discoveries provide crucial insights into the Neandertal mind. Archaeologists have long considered art, including body decoration, to be a key indicator of modern cognitive abilities because it means that the makers had the capacity to conceive of something in the abstract and to convey that information in symbols. Symbolic thinking underpins our ability to communicate via language—one of the defining traits of modern humans and one that is seen as critical to our success as a species. If Neandertals thought symbolically, as they appear to have done, then they probably had language, too. In fact, abstract thought may have dawned in the human lineage even before the last common ancestor of Neandertals and *H. sapiens:* in December researchers unveiled a mussel shell from Indonesia that they contend was engraved with a geometric pattern by a more primitive ancestor, *Homo erectus,* around 500,000 years ago.

Symbolic thought is not the only component of behavior believed to have helped *H. sapiens* get ahead, however. The manufacture of tools with specialized uses is another element, one that Neandertals appear to have mastered as well. In 2013 Marie Soressi of Leiden University in the Netherlands and her collaborators announced their discovery of bone tools known as *lissoirs*—implements that leather workers today use to render animal hides more pliable, lustrous and impermeable to the elements—at two Neandertal sites in the Dordogne region of France dating to between 53,000 and 41,000 years ago. Judging from the wear marks on the artifacts, Neandertals used them for the same purpose. The Neandertals made the *lissoirs* from deer ribs, shaping the end of the bone that attaches to the sternum to form a rounded tip. To wield the tool, they pressed the tip into a dry hide at an angle and pushed it across the surface repeatedly, smoothing and softening the skin.

Fresh evidence of Neandertal ingenuity has also come from the site of Abri du Maras in southern France, which sheltered Neandertals around 90,000 years ago. Microscopic analyses of stone tools from the site, conducted by Bruce Hardy of Kenyon College and his colleagues, revealed traces of all manner of activities once thought to be beyond the ken of the species. For instance, the team found remnants of twisted plant fibers that would have been used for making string or cords, which then could have been fashioned into nets, traps and bags. Traces of wood turned up as well, suggesting that the Neandertals crafted tools from that material.

Residue analysis additionally gives the lie to the notion that Neandertals were perilously picky eaters. Studies of the chemical makeup of their teeth, along with analyses of animal remains from Neandertal sites, have suggested that Neandertals relied heavily on large, dangerous prey such as mammoth and

DAVID LIITTSCHWAGER *National Geographic* (cave); COURTESY OF STEWART FINLAYSON *The Gibraltar Museum* (cave marking)

BONE TOOL for leatherwork, shown here in four views, is among the advanced implements that Neandertals made.

bison rather than an array of animals depending on availability, as anatomically modern humans did. The Abri du Maras Neandertals apparently exploited a veritable menagerie of creatures, including small, fast animals such as rabbits and fish—all species previously thought to be out of reach for Neandertals, with their low-tech gear.

Some scholars have argued that an ability to live partly on plant foods gave *H. sapiens* an edge over Neandertals, allowing them to reap more sustenance from the same area of land. (Subsisting on plants is trickier for humans than for other primates because our big brains demand a lot of calories, and yet our small guts are poorly suited to digesting large quantities of raw roughage—a combination that requires intimate knowledge of plant foods and how to prepare them.) But the Abri du Maras Neandertals gathered edible plants, including parsnip and burdock, as well as edible mushrooms. And they were not alone.

According to studies led by Amanda Henry of the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany, Neandertals across a broad swath of Eurasia—from Iraq to Belgium—ate a variety of plants. Examining the tartar in Neandertal teeth and residues on stone tools, she determined that Neandertals consumed species closely related to modern wheat and barley, cooking them to make them palatable. She also found bits of starch from tubers and telltale components of date palms. The similarities to findings from early modern human sites were striking. "Any way we broke up the data, there were no significant differences between the groups," Henry remarks. "The evidence we have now does not suggest that the earliest modern humans in Eurasia were better at accessing plant foods."

A LONG FAREWELL

IF NEANDERTALS actually behaved in ways once thought to distinguish anatomically modern humans and fuel their rise to world domination, that likeness makes their decline and eventual extinction all the more puzzling. Why did they die out while *H. sapiens* survived? One theory is that moderns had a bigger tool kit that may have boosted their foraging returns. Modern humans evolved in Africa, where their population size was larger than that of Neandertals, Henry explains. With more mouths to feed, preferred resources such as easy game would have declined, and the moderns would have had to develop new tools to obtain other kinds of food. When they brought this cutting-edge technology with them out of Africa and into Eurasia, they were able to exploit that environment more effectively than the resident Neandertals could. In other words, moderns honed their survival skills under more competitive circumstances than Neandertals had faced and thus entered Neandertal territory with an advantage over the incumbents.

Not only did the large population size of *H. sapiens* spur innovation, but it helped to keep new traditions alive rather than letting them fizzle out with the last member of a small, isolated group. The bigger, more connected membership of *H. sapiens* "increasingly provided a more efficient ratchet effect to maintain and build on knowledge compared with earlier humans, including the Neandertals," offers Chris Stringer of the Natural History Museum in London. Still, the arrival of moderns did not spell instant doom for Neandertals. The latest attempt to track their decline, carried out by Thomas Higham of Oxford and his colleagues, applied improved dating methods to pinpoint the ages of dozens of Neandertal and early modern European sites from Spain to Russia. The results indicate that the two groups shared the continent for some 2,600 to 5,400 years before the Neandertals finally disappeared, around 39,000 years ago.

That lengthy overlap would have left plenty of time for mating between the two factions. DNA analyses have found that people today who live outside Africa carry an average of least 1.5 to 2.1 percent Neandertal DNA—a legacy from dalliances between Neandertals and anatomically modern humans tens of thousands of years ago, after the latter group began spreading out of Africa.

Maybe, some experts offer, mixing between the smaller Neandertal population and the larger modern one led to the Neandertal's eventual demise by swamping their gene pool. "There were never very many of them, there were people coming in from other areas and mixing with them, and they faded out," Frayer surmises. "The history of all living forms is that they go extinct," he adds. "That's not necessarily a sign that they were stupid, or culturally incapable, or adaptively incapable. It's just what happens." SA

MORE TO EXPLORE

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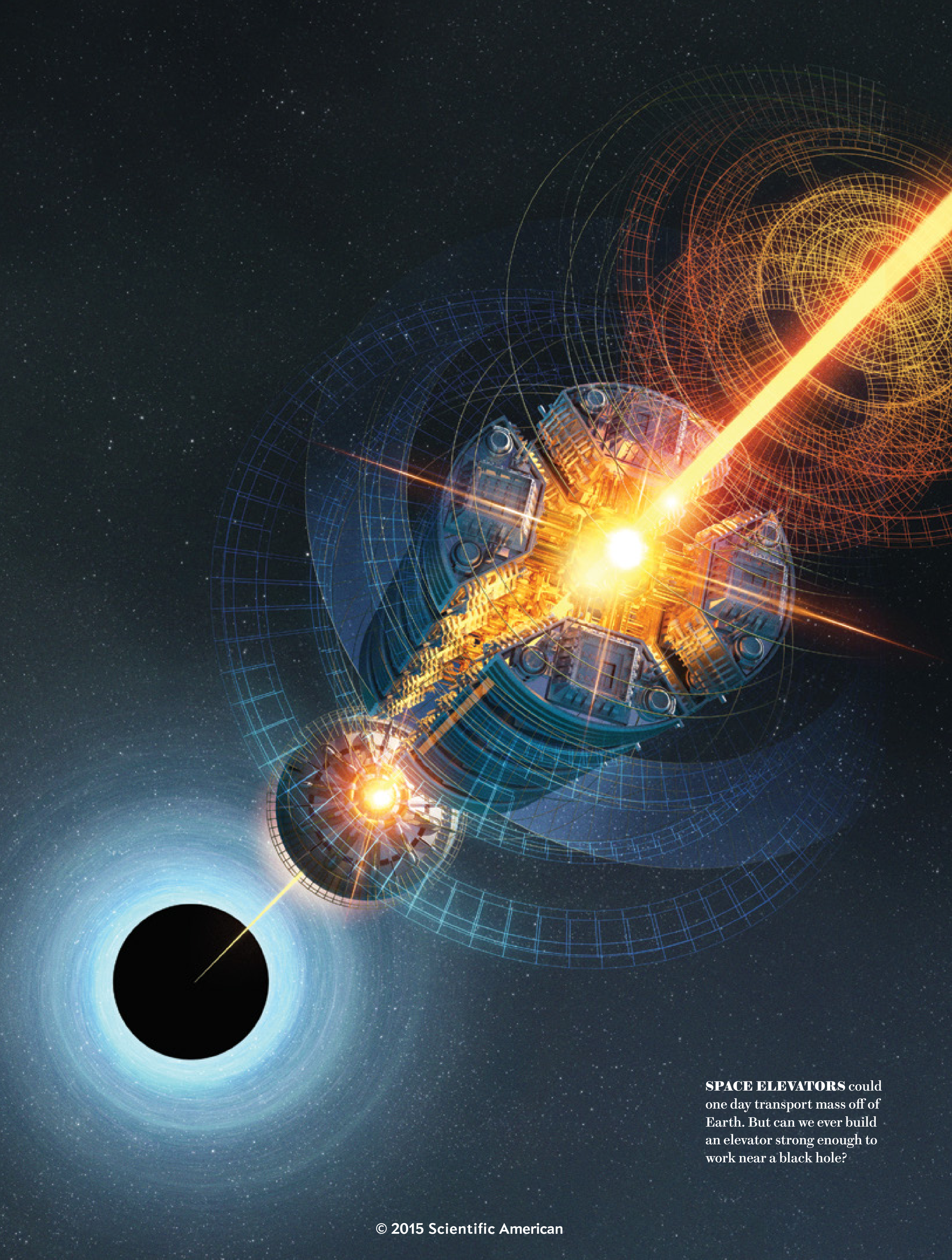


SPACE ELEVATORS could one day transport mass off of Earth. But can we ever build an elevator strong enough to work near a black hole?

ASTROPHYSICS

CAN WE MINE A BLACK HOLE?

Let's say some future civilization wanted to get energy out of a black hole. The first step would be to build a space elevator that defies the laws of physics

By Adam Brown

Illustration by Kenn Brown, Mondolithic Studios

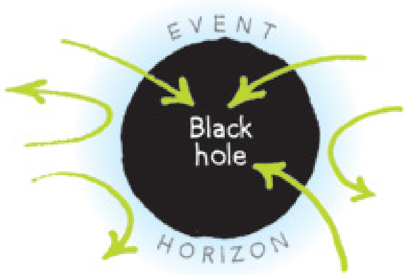
Adam Brown is a theoretical physicist at Stanford University. When not thinking about black holes, he thinks about the big bang and about bubbles of nothing.

One day the sun will fail. The fuel powering its nuclear fusion will run out, the sky will grow cold and, if Earth survives at all, humankind will be plunged into perpetual winter. To stay alive, our descendants will need to make alternative arrangements. They will first exhaust the resources of Earth, then the solar system, and eventually all the stars in all the galaxies in the visible universe. With nothing left to burn, they will surely cast their gaze on the only remaining store of energy: black holes. Might they be able to harvest this energy and save civilization?

I'm here with some bad news. The plan is not going to work. The reasons come down to the physics of such exotic entities as quantum strings and that venerable science-fiction favorite: the space elevator.

FALSE HOPE

ON THE FACE OF IT, extracting energy (or indeed anything at all) from a black hole sounds impossible. Black holes, after all, are shrouded by an "event horizon," a sphere of no return where the gravitational field becomes infinite. Anything that strays inside this sphere is doomed. Hence, a wrecking ball intended to demolish a hole and release its energy would itself be wrecked, swallowed by the black hole, along with its unfortunate operator. A bomb tossed into the hole, far from destroying it, would merely enlarge it—by an amount equal to the mass of the bomb. What goes into a black hole never comes out: not asteroids, not rockets, not even light.



Or so we used to think. But then, in what is to me the most shocking and delightful physics paper ever written, in 1974 Stephen Hawking showed that we were wrong. Building on earlier ideas of Jacob D. Bekenstein, now at the Hebrew University of Jerusalem, Hawking showed that black holes leak small amounts of radiation. You are still going to die if you fall in, but although you yourself will never make it out, your energy eventually will. This is good news for would-be black hole miners: energy can escape.

The reason that energy escapes lies in the shadowy world of quantum mechanics. One of the signature phenomena of quantum physics is that it allows particles to tunnel through otherwise impassable obstacles. A particle rolling toward a tall barrier sometimes appears on the other side. Do not try this at home—fling yourself at a wall, and you are unlikely to rematerialize unscathed on the other side. But microscopic particles tunnel more readily.

Quantum tunneling is what permits

IN BRIEF

When the sun dies in a few billion years, humanity must find another power source to survive. One candidate may be black holes, which are full of energy.

A thought experiment suggests using the science-fiction concept of a space elevator to "mine" the thermal radiation from a black hole.

A space elevator would use a box attached to a rope dangling down near the black hole's event horizon to scoop up radiation. It turns out, however, that even the strongest material in the world—a fundamental string—would not yield a rope able to withstand the intense gravitational pull near a black hole horizon.

Illustrations by Nigel Holmes

an alpha particle (a helium nucleus) to escape the clutches of a radioactive uranium nucleus, and quantum tunneling is what permits "Hawking radiation" to leak from a black hole. Particles escape the event horizon's infinite gravitational field not by blasting past but by tunneling through. (No one has ever seen a black hole leak, of course. But it is such a compelling mathematical consequence of applying quantum mechanics to curved spacetime that no one doubts it.)

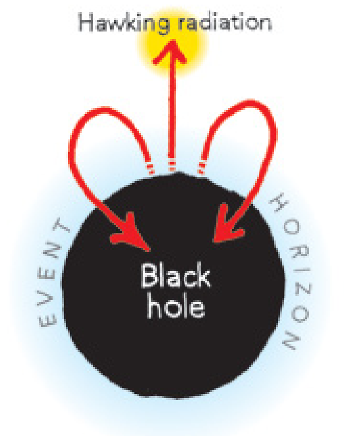
Because black holes leak, we may hope to feast off their energy. But the devil is in the details. No matter how we try to extract this energy, we will see that we encounter problems.

One simple approach would be to just wait. After enough time, the black hole should disgorge its energy, photon by photon, back into the universe and into our waiting hands. With each bit of energy lost, the black hole shrinks, until eventually it dwindles away to nothing. In that sense, a black hole is like a delicious cup of coffee whose surface you are forbidden to touch on pain of gravitational dismemberment. There is still a way to consume the cataclysmic coffee: wait for it to evaporate and breathe in the fumes.

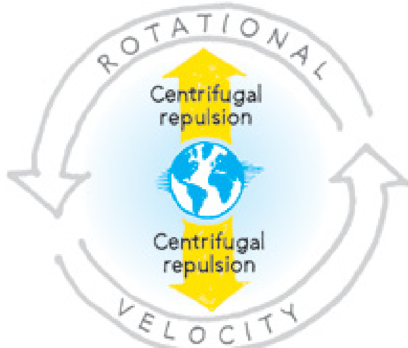
There is a catch. Although waiting is simple, it is also achingly slow. Black holes are extremely dim—one with the mass of the sun glows at 60 nanokelvins; until the 1980s we did not even know how to make something that cold in a laboratory. To evaporate a solar-mass black hole takes 10^{57} times the current age of the universe, a stupendously long time. In general, the lifetime of a black hole is the cube of its mass, m^3. Our shivering descendants will be motivated to speed things up.

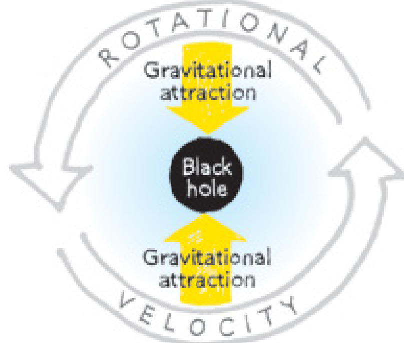
Initial cause for optimism on their behalf is that not every Hawking particle that escapes the event horizon goes on to escape to infinity. In fact, practically none of them do. Almost every particle that tunnels past the event horizon is later recaptured by the gravitational field and reclaimed by the black hole. If we could somehow pry these photons from the black hole's grasp, rescuing them after they have escaped the horizon but before they were recaptured, then maybe we could gather the energy of black holes faster.

To understand how we can liberate these photons, we must first investigate the extreme forces at work near a black hole. The reason most particles get recaptured is that they are not emitted straight out. Imagine shining a laser from just outside the horizon. You must aim directly overhead for the light to escape; the closer you are to the horizon, the more carefully you have to aim. The gravitational field is so strong that even if you are just a little bit off vertical, the light will circle around and fall back in.



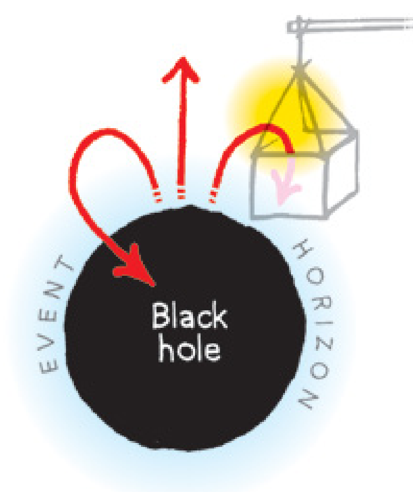
It might seem strange that rotational velocity can hurt a particle's escape prospects. After all, it is precisely orbital velocity that keeps the International Space Station aloft—it provides the centrifugal repulsion that counteracts gravity. Get too close to a black hole, however, and the situation reverses—rotational velocity impedes escape. This effect is a consequence of general relativity, which states that all mass and energy are subject to gravity—not just an object's rest mass but also its orbital kinetic energy. Close to a black hole (more precisely, within one and a half times the event horizon radius), the gravitational attraction of the orbital kinetic energy is stronger than the centrifugal repulsion. Inside this radius, more angular velocity makes particles fall faster.





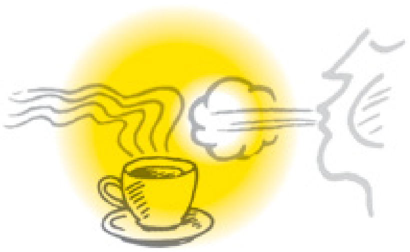
This effect means that if you slowly rappel down toward a black hole horizon, you will soon become very hot. You will be bathed not just by the photons that would have escaped to infinity as Hawking radiation but also by those that would never have made it. The black hole has a "thermal atmosphere"; the closer you get to the event horizon, the hotter it gets. This heat carries energy.

The fact that energy is stored outside of the event horizon has given rise to the clever proposal that we can "mine" a black hole by reaching in, grabbing the thermal atmosphere and carting it off. Dangle a box close to, but not over, a black hole horizon, fill the box with hot gas, and then drag it out. Some of the contents would have made it out unaided, as conventional Hawking radiation, but most of the gas, had we not intervened, was destined to fall back in. (Once the gas is out of the near vicinity of the event horizon, transporting it the rest of the way to Earth is relatively easy: simply pack it onto a rocket and fly it home or convert the gas into a laser and beam it back.)



The closer you get to the event horizon, the hotter it gets. This heat carries energy.

This strategy is like blowing on our delicious but dangerous coffee. Unassisted, most of the water vapor emitted falls back in, but blowing across the surface removes the freshly escaped vapor before it has a chance to be recaptured. The con-



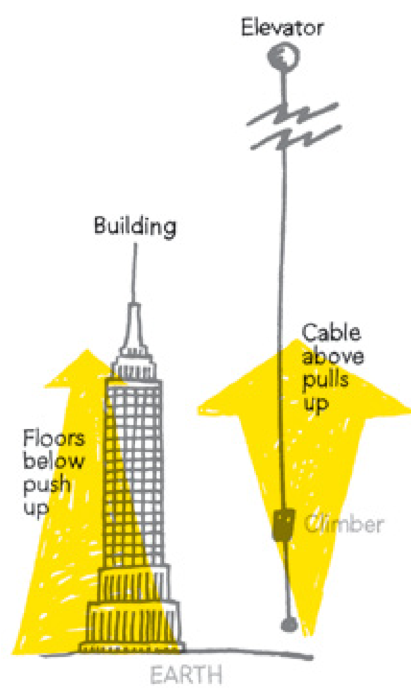
jecture is that by stripping a black hole's thermal atmosphere, we can rapidly devour the hole in an amount of time that scales not like the m^3 needed for evaporation but like the considerably faster m.

In recent work, however, I showed that this conjecture is false. The problem does not come from any elevated musing on quantum mechanics or on quantum gravity. Instead it arises from the most unsophisticated of considerations: you cannot find a strong enough rope. To mine the thermal atmosphere, you need to be able to dangle a rope near a black hole—you need to create a space elevator. But, I discovered, constructing an effective space elevator near a black hole is impossible.

ELEVATOR TO THE SKY

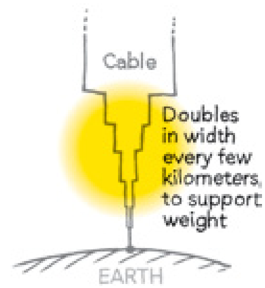
A SPACE ELEVATOR (sometimes known as a sky hook) is a futuristic structure, made famous by science-fiction author Arthur C. Clarke in his 1979 novel *The Fountains of Paradise.* He imagined a rope that dangles from outer space down toward the surface of Earth. It is held up not with a push from below (as in a skyscraper, where each floor supports the floors above) but with a pull from above (each segment of rope supports the one below). The far end of the rope is moored to a huge, slowly orbiting mass way out beyond geostationary orbit that tugs the rope outward, keeping the whole thing aloft. The near end of the rope dangles down to just above the planet's surface, where it stops—the balancing of the various forces ensures that it just floats there, as if by magic (magic, Clarke once remarked, being indistinguishable from sufficiently advanced technology).

The point of this advanced technology is that with the rope in place, putting cargo in orbit becomes much easier. No longer do we need the danger, inefficiency or waste of a rocket, which, for the first part of its journey, mainly lifts fuel. Instead we would attach to the rope an electrically powered elevator. Once the marginal cost of moving cargo to low-Earth orbit is just the cost of the electricity, getting a kilogram into space drops from the tens of thousands of dollars that the Space Shuttle charged to a couple of bucks—a journey to space for less than a subway ride.



The technological obstacles to building a space elevator are formidable, and the greatest of them is finding a suitable material for the rope. The ideal material needs to be both strong and light—strong so that it does not stretch or break under the strain and light so that it does not unduly burden the rope above.

Steel is not strong enough, not even nearly. In addition to the weight of everything beneath, a segment of steel must also bear its own weight, so the cable must get thicker and thicker the higher up you go. Because steel is so heavy, compared with its strength, near Earth the cable must double in thickness every few kilometers. Long before it reaches the geostationary point, it has become impractically thick.



Building a space elevator around Earth with 19th-century building materials just will not work. But 21st-century materials are already showing promise. Carbon nanotubes, long ribbons of carbon arranged in a hexagonal honeycomb lattice, are 1,000 times stronger than steel. Carbon nanotubes are excellent candidates to build an extraterrestrial space elevator.

It would cost many billions of dollars, be by far the largest megaproject ever undertaken, require figuring out how to spin the nanotubes into threads tens of thousands of kilometers long, and face many other obstacles besides. But for a theoretical physicist like me, once you have decided that a proposed structure does not actually violate the known laws of physics, everything else is just engineering. (By this measure, the problem of building a fusion power plant is also "solved," even though there is a conspicuous absence of fusion power plants fueling our civilization, with the commendable exception of the sun.)

BLACK HOLE ELEVATOR

AROUND A BLACK HOLE, of course, the problem is much harder. The gravitational field is more intense, and what works

SCIENTIFIC AMERICAN ONLINE Learn about the latest research on space elevators at ScientificAmerican.com/feb2015/brown

around Earth is pathetically inadequate for the task.

It is possible to show that even using the much vaunted strength of carbon nanotubes, a hypothetical space elevator that reached down close to a black hole horizon would either have to be so thin near the black hole that a single Hawking photon would break it or so thick far out from the black hole that the rope itself would collapse under its own gravity and become a black hole of its own.

These limitations rule out carbon nanotubes. But just as the Iron Age followed the Bronze Age, and just as carbon nanotubes will some day follow steel, so, too, might we expect that materials scientists will invent stronger and stronger and lighter and lighter materials. And so they might. But the progress cannot go on indefinitely. There is a limit to progress, a limit to engineering, a limit to the tensile-strength-to-weight ratio of any material—a limit imposed by the laws of nature themselves. This limit is a surprising consequence of Albert Einstein's famous formula $E = mc^2$.

The tension in a rope tells you how much energy you must expend to make it longer: the tenser the rope, the more energy it costs to lengthen. An elastic band has tension because to make it longer you must spend energy rearranging its molecules: when the molecules are easy (energetically cheap) to rearrange, the tension is small; when the molecules are expensive to rearrange, the tension is large. But rather than just rearranging bits of the existing rope, we could always just manufacture a whole new section of rope and stick it on the end. The energy cost to extend a rope in this way is equal to the energy contained in the mass of the new rope segment and is given by the formula $E = mc^2$—the mass (m) of the new segment of rope times the speed of light squared (c^2).

This is a very energy-expensive way to lengthen a rope, but it is also a fail-safe way. It provides an upper limit on the energy cost of extending a rope and thus a limit on the tension of a rope. The tension can never be greater than the mass per unit length times c^2. (You might think that two ropes woven together would be twice as strong as one. But they are also twice as heavy and so will not improve the strength-to-weight ratio.)

This fundamental limit on the strength of materials leaves a lot of room for technological progress. This limit is hundreds of billions of times stronger than steel and, pound for pound, still hundreds of millions of times stronger than carbon nanotubes. Still, it means we cannot improve our materials indefinitely. Just as our efforts to propel ourselves ever faster must end at the speed of light, so our efforts to build stronger materials must end at $E = mc^2$.

There is a hypothetical rope material that precisely reaches the limit—that is as strong as any material can be. This material has never been seen in a lab, and some physicists doubt whether it even exists, but others have devoted their life to its study. The strongest rope in nature may never have been seen, yet it already has a name: a string. Those who study strings—string theorists—hope they are the fundamental constituents of matter. For our purposes, what matters is not their fundamentalness but their strength.

Strings are strong. A section of rope made of strings the same length and weight as a shoelace can suspend Mount Everest. Because the toughest engineering challenges call for the toughest materials, if we want to build a space elevator around a black hole our best shot is to use strings; where nanotubes failed, perhaps fundamental strings will succeed. If anything can do it, strings can; conversely, if strings cannot, black holes are safe.

It turns out that while strings are strong, they are not quite strong enough. Rather they are tantalizingly on the edge of being strong enough. Any stronger, and it would be easy to construct a space elevator even around a black hole; any weaker, and the project would be hopeless—the string itself would break under its own weight. Strings are exactly marginal in that whereas a rope that is made of strings dangling toward the surface of a black hole does have just enough strength to support its own weight, it has none left over to support the elevator's cargo. The rope supports itself but only at the expense of dropping the box.

This, then, is what shields black holes from prying. The laws of nature themselves limit our building materials, which means that although a rope can reach the dense thermal atmosphere of a black hole, it cannot expeditiously plunder it. Because the strength of a string is borderline, we would be able to extract a limited amount of energy from the rarified upper atmosphere using a shorter rope.

But this thin and insubstantial diet is not much better than just waiting: the lifetime of the black hole still scales like m^3, the same as the unaided evaporation lifetime. By poaching the occasional photon here and there, we may be able to shorten the lifetime of a black hole by some small factor, but we will not achieve the kind of industrial extraction required to feed a hungry civilization.

In this particular, the finite speed of light is our constant enemy. Because we cannot travel faster than light, we cannot escape a black hole's event horizon. Because we cannot extract more than mc^2 worth of energy from our fuel, we are destined to cast our gaze on black holes. And because a rope can never be stronger than the speed of light squared times its mass per unit length, we will not be able to feast off the hole's contents.

With the sun gone, we will be living in perpetual winter. We may look to the great trove of energy in the thermal atmosphere of a black hole, but we will grasp for it at our peril. Reach too eagerly or too deep, and rather than our box robbing the black hole of its radiation, the black hole will instead rob us of our box. It is going to be a cold winter. SA

MORE TO EXPLORE

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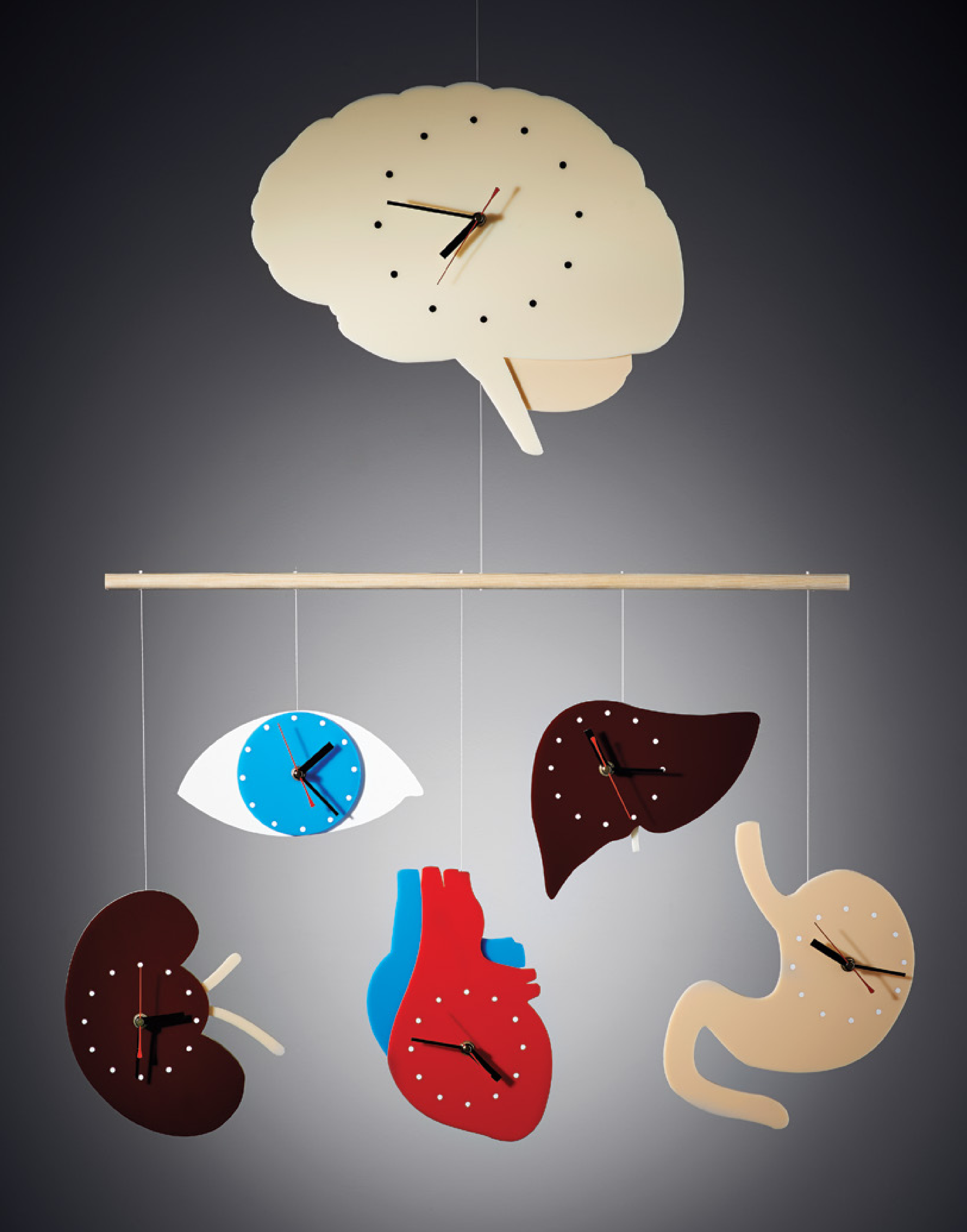

CHRONOBIOLOGY

THE CLOCKS WITHIN US

Genes in the liver, pancreas and other tissues (not just the brain) keep the various parts of the body in sync. Timing miscues may lead to diabetes, depression and other illnesses

By Keith C. Summa and Fred W. Turek

Illustration by Kyle Bean

Keith C. Summa is an M.D.-Ph.D. student at the Northwestern University Feinberg School of Medicine and is interested in understanding how to apply research findings about circadian rhythms to clinical medicine.

Fred W. Turek is a neurobiologist and director of the Center for Sleep and Circadian Biology at Northwestern. He is founding president of the Society for Research on Biological Rhythms.

ANYONE WHO HAS EVER FLOWN EAST OR WEST AT 500 knots for more than a few hours has experienced firsthand what happens when the body's internal clock does not match the time zone in which it finds itself. Up to a week may be needed to get over the resulting jet lag—depending on whether the master clock, which is located deep inside the brain, needs to be advanced or slowed to synchronize when the body and brain want to sleep with when it is dark outside. Over the past several years, however, scientists have learned, much to our surprise, that, in addition to the master clock in the brain, the body depends on multiple regional clocks located in the liver, pancreas and other organs, as well as in the body's fatty tissue. If any one of these peripheral clocks runs out of sync with the master clock, the disarray can set the stage for obesity, diabetes, depression or other complex disorders.

The two of us have dedicated ourselves to exploring the ins and outs of how these peripheral clocks work and to identifying the genes that regulate their activity. The first clock gene was isolated, or cloned, from fruit flies in 1984. One of us (Turek) was part of the team that in 1997 cloned and identified a different clock gene, the first discovered in mammals. As of the last count, researchers around the globe have identified dozens of genes that help the body keep time, including those going by such names as *Clock, Per* (for period) and *Tim* (for timeless).

Studies in our laboratory have focused on mice, but circadian clock genes have been identified in an amazing range of living organisms, from bacteria to fruit flies to humans. Many of these genes appear to be similar in a wide range of species—a sign that they have been central to survival throughout evolution.

The greatest progress so far has come in deciphering the role of clocks in disorders of metabolism, which is the set of processes by which the body converts food into energy and stores fuel for later use. (Among the more surprising finds: when you eat appears to be as important as what you eat in the regulation of weight gain.) Circadian rhythms do not explain every aspect of these complex conditions, of course, but we ignore our body's various clocks at our peril. Rapidly growing knowledge of these rhythms could radically change the ways diseases are diagnosed and treated in the future and improve people's ability to maintain their health.

MASTER CLOCK

FROM THE MOST COMPLEX organisms to the simplest ones, all of life on earth is governed by circadian rhythms that match the 24-hour day. Circadian rhythms are found even among the earliest life-forms to emerge: cyanobacteria, single-celled blue-green algae now widespread throughout diverse habitats. These organisms derive energy from the sun through photosynthesis, using light to power the production of organic molecules and oxygen from carbon dioxide and water.

An internal clock enables each cyanobacterium to prime its photosynthetic machinery before sunrise, which enables it to start harvesting energy as soon as light starts to shine and gives

IN BRIEF

Embedded deep within the brain is a master clock that regulates the timing of many of the biological processes that occur in the human body.

Researchers have shown over the past few years that cellular (or regional) clocks can be found in the liver, pancreas and other parts of the body as well.

Routinely eating or sleeping at the wrong times may throw these peripheral clocks out of sync with the master clock in the brain.

A growing body of evidence suggests that these chronobiological disruptions predispose individuals to the development of obesity, diabetes, depression and other disorders. Resynchronizing the body's many clocks may, in the coming years, help to restore health and proper functioning.

PAGE 50: PHOTOGRAPH BY MITCH PAYNE

it a leg up on cellular organisms that merely respond to light. Similarly, the clock enables the cyanobacteria to turn off photosynthesis when the sun sets. In this manner, they can avoid wasting energy and other resources on systems that do not work at night. Instead resources can be diverted to reactions better suited for darkness, such as DNA replication and repair, which may be compromised by ionizing radiation from the sun's rays.

Bacterial strains carrying mutations in different clock genes may switch from the usual 24-hour cycles for turning genes on and off to periods, or "clock lengths," of 20, 22 or sometimes even 30 hours. In studies that grouped cells according to their altered cycles, Carl Johnson and his colleagues at Vanderbilt University showed in 1998 that cyanobacteria with a clock length that matched the environmental light cycle outcompeted those with a mismatch. For example, in a 24-hour light-and-dark cycle, normal cyanobacteria grow more quickly and divide more successfully than mutants with a 22-hour clock length. But when Johnson's team artificially set the light-and-dark cycle to 22 hours, those same mutants survived better than the normal bacteria. These experiments demonstrated clearly, for the first time, that the ability to properly coordinate internal metabolic rhythms to environmental cycles enhances fitness.

Although the human clock mechanism depends on different genes from those found in cyanobacteria, our circadian machinery shares many other similarities with that of these blue-green algae, suggesting that both processes arose separately during evolution to address the same biological needs and functions.

PERIPHERAL CLOCKS

RESEARCHERS ORIGINALLY assumed that there was but a single clock that acted like a metronome and regulated myriads of biological processes throughout the body. In the 1970s they traced this putative clock to the suprachiasmatic nucleus of the brain, just above where the optic nerves cross. But about 15 years ago signs began emerging that subordinate timing mechanisms existed in other organs, tissues and individual cells as well. Investigators started finding evidence that the same clock genes that were active in the brain were periodically turning on and off in the individual cells of the liver, kidneys, pancreas, heart and other tissues. These cellular clocks, we now know, regulate the activity of 3 to 10 percent—and in some cases perhaps as much as 50 percent—of genes in various tissues.

At about the same time, a number of scientists began wondering whether circadian rhythms played any role in the process of aging. Turek asked Amy Easton, then a graduate student at Northwestern University, to conduct a few experiments on mice that had mutations in the *Clock* gene. While examining daily running behavior in older mice, she realized that they tended to be fat and to have difficulty climbing into the running wheels in their cages. This observation inspired us to focus some of our research efforts on metabolism and circadian rhythms. In a series of tests, published in *Science* in 2005, we demonstrated a relation between alterations in the *Clock* gene and the development of obesity and metabolic syndrome, which is a cluster of physiological abnormalities that puts individuals at higher risk of heart disease and diabetes. To receive a diagnosis of metabolic syndrome, a person must experience at least three of the following conditions: excess fat in the abdominal area, as opposed to on the hips; high amounts of triglyceride fats in the

HOW IT WORKS

The Body's Many Cellular Clocks

Life on earth moves to the rhythms of a 24-hour day. In humans, a master clock in the brain synchronizes subordinate clocks in various cells of the body. Specifically, certain genes direct the production of proteins at different times of day, which ramp up or inhibit biological processes. Health problems may occur if these clocks fall out of sync.

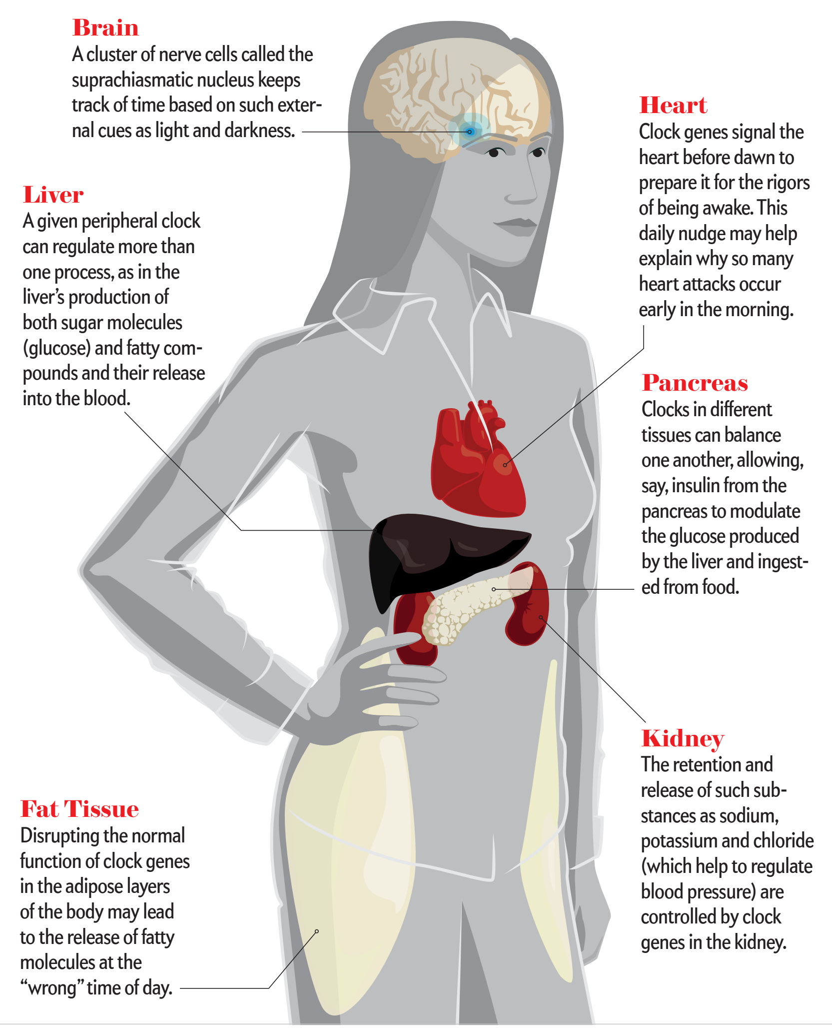

Illustration by Josy Conklin

blood; low levels of HDL, the so-called good cholesterol, in the blood; high blood pressure; and high levels of glucose in the blood (indicating a difficulty in processing sugar).

This work triggered an explosion of interest in the effects of circadian rhythms on metabolism. Previous studies of shift workers—who experience chronic misalignment between their internal clocks and the solar day—had shown that they have a greater risk of developing metabolic, cardiovascular and gastrointestinal diseases, among others. But shift workers commonly exhibit other unhealthy behaviors, such as insufficient sleep, poor diet and lack of exercise. Thus, researchers had trouble distinguishing between cause and effect. By providing genetic evidence linking the internal clock and metabolic health, the *Clock* mutant mice helped to propel the study of circadian rhythms into a more precise, molecular era that allows more definitive conclusions.

CLOCKS AND METABOLISM

SOON AFTER investigators realized that circadian rhythms help to regulate metabolism, they began studying the peripheral clock found in the liver, which plays a pivotal role in metabolism. In 2008 Katja Lamia, Kai-Florian Storch and Charles Weitz, all then at Harvard Medical School, conducted experiments using mice in which a critical circadian clock gene had been deleted only in liver cells. (Unlike people, mice are active primarily at night and sleep during the day, but the sleep-wake cycle is otherwise similarly regulated.) In essence, these mice had no clock in the liver and normal clocks elsewhere in the body. During their daytime rest period (when mice do not eat as much), they experienced extended bouts of low blood sugar levels, or hypoglycemia. This drop is dangerous because the brain can begin to shut down within minutes if it does not receive enough glucose to meet its energy demands.

Further experiments showed that the low glucose levels occurred because the rhythms that usually control when the liver produces and secretes the sugar molecule into the blood had disappeared. Thus, the liver clock contributes to the maintenance of normal blood glucose levels over the course of the day, ensuring a constant and adequate source of energy to support the ongoing functions of the brain and the rest of the body.

Not surprisingly, an opposing counterregulatory system is required to limit excessive blood glucose in response to feeding. The primary hormone responsible is insulin, which is produced by so-called beta cells, found in the pancreas. After a person eats a meal, glucose enters the bloodstream, triggering the secretion of insulin. This hormone, in turn, acts like a brake on rising sugar levels by promoting the removal of glucose and its storage in the muscles, liver and other tissues.

As a follow-up, Billie Marcheva and Joseph T. Bass (an original member, along with Turek, of the circadian metabolism research team at Northwestern) carried out a series of studies to determine the role of the biological clock in the pancreas. They found that the pancreatic clock is critical to maintaining normal blood sugar levels and that disruption of the clock severely compromises pancreatic function, resulting in diabetes. Diabetes is a metabolic disorder in which the body produces too little insulin or is insensitive to it. Too much sugar ends up locked out of cells and floating in the bloodstream.

Marcheva and Bass began by examining isolated pancreatic tissue from mice that had mutations in circadian clock genes. They saw that the amount of insulin secreted in response to glucose stimulation was reduced drastically. Next, they generated mice in which the clock was deleted only in the pancreas. The animals developed diabetes early in life and exhibited a profound reduction in insulin secretion.

Rapidly growing knowledge of circadian rhythms could radically change the way diseases are diagnosed and treated in the future.

These examples illustrate a key point about the function of clocks in different tissues: they may have drastically different roles. In cases such as the liver and pancreas, they even regulate opposing physiological processes. Yet when they are integrated into a functioning system, these tissue clocks precisely synchronize their timing to maintain the body's homeostasis; that is, they provide for relatively stable levels of key molecules in the face of varying conditions in the external environment. Taken a step further, the master circadian clock can be conceptualized as a conductor of an orchestra that keeps multiple peripheral tissues—the instruments—properly timed relative to one another and to the environment, thus optimizing the function of the system.

MULTIPLE ROLES

ANOTHER OVERARCHING discovery is that the clock in a given tissue can affect more than one process in that tissue. Indeed, each clock can regulate multiple processes. For example, the liver clock regulates entire networks of genes necessary for the production and metabolism of glucose. In addition, in 2011 Mitch Lazar of the University of Pennsylvania and his colleagues demonstrated that the liver clock also determines how much fat accumulates in liver cells.

In this instance, Lazar and his co-workers determined that a clock gene called *Rev-erbα* acts like a timer for an enzyme that controls access to the genetic instructions found within the DNA molecule. The target enzyme in question—histone deacetylase 3 (HDAC3)—affects the process by which certain strands of DNA are wound into coils so tight that the hereditary information inside cannot be used by the cell to drive its biological processes.

Using a genetic trick, Lazar and his team showed that blocking the *Rev-erbα* clock gene, which in turn prevented HDAC3's activity, resulted in the development of a condition known as hepatic steatosis, or fatty liver. It turns out that one of HDAC3's functions is to turn off the genes that control the production of fatty

SCIENTIFIC AMERICAN ONLINE Watch a video about biological clocks in mammals at ScientificAmerican.com/feb2015/clock-genes

molecules during the night (when mice are active and need to use their fat stores for energy). The loss of the clock gene causes the amount of HDAC3 to decline, which in turn leaves the genes responsible for the synthesis of fats in the liver stuck in the on position. This hyperactivity, in turn, causes abnormal accumulation and deposition of fat (adipose) in liver cells, a process that disrupts liver function and commonly accompanies obesity and diabetes.

Clock genes also function in adipose tissue and affect multiple metabolic processes from there. In addition to serving as an energy storage depot, fat functions as an endocrine organ through its production of the hormone leptin; that is, it secretes hormones into the blood that alter the activities of other organs in the body. Georgios Paschos and Garret FitzGerald, both then at the University of Pennsylvania, and their colleagues recently engineered mice lacking an intact clock in fat cells (adipocytes) and found that the animals developed obesity and shifted their normal patterns of food intake to the daytime. As a result, fatty molecules were coursing through their body at the "wrong" time, disrupting their brain's ability to regulate the timing and intake of food. This change in feeding behavior appears to be specific for animals lacking an adipocyte clock because mice with deleted pancreatic or liver clocks retain normal feeding rhythms.

The observation that these animals shifted their feeding patterns and gained excess weight without clocks in adipocytes agrees with prior studies demonstrating that the timing of food intake can have a significant effect on how efficiently the body stores and utilizes the fuel it consumes. Indeed, in 2009 Deanna Arble, then a graduate student working with us at Northwestern, reported that mice given access to a high-fat diet only during the "wrong" time of day gained significantly more weight than animals fed the same diet only during the dark phase. These weight differences persisted despite similar overall caloric intake and physical activity in each group.

More recently, Satchidananda Panda and his group at the Salk Institute for Biological Studies in La Jolla, Calif., have extended these findings, showing that restricting intake of a high-fat diet in mice to an eight-hour window during their normal time for eating (the dark phase) prevented obesity and metabolic dysfunction without any reduction in caloric intake. In fact, these animals had metabolic health profiles similar to mice that ate just a low-fat diet. The benefit appears to stem from improved coordination of the metabolic cycles in the liver and other tissues.

Interestingly, these experiments in mice may be relevant for individuals with night eating syndrome, a disorder in which people consume an overabundance of calories at night and develop obesity or metabolic syndrome, or both. Perhaps this condition arises in part from a defect in regulating the circadian timing of hunger, an asynchrony that could predispose patients to weight gain and the misregulation of their metabolic processes.

Recently a study of dieters led by Marta Garaulet of the University of Murcia in Spain and Frank Scheer of Harvard found an association between the timing of lunch and success with weight loss. Individuals who had an earlier lunch tended to lose more weight while dieting than those who ate later. More clinical research must be done on whether eating times influence the development of obesity, diabetes and related conditions, but such findings raise the possibility that circadian feeding strategies might one day serve as entirely new, nonpharmacological complements to standard treatment regimens.

CIRCADIAN MEDICINE

OTHER WORK with humans suggests that detailed investigation of people's circadian rhythms may one day produce greater insight into their metabolic disorders, leading to more appropriate treatments. For example, Till Roenneberg and his colleagues at the Ludwig Maximilian University of Munich have studied the sleeping patterns of thousands of people around the world and described a common form of chronic circadian disruption they refer to as "social jet lag." Representing the time difference between habitual sleep cycles during the work (or school) week and free time on the weekends, this measurement provides a quantification of the weekly disruption of the internal clock, which may be equivalent to traveling across three to four time zones twice a week for someone who wakes at 6 A.M. on weekdays and sleeps until 9 or 10 A.M. on weekends. The researchers have discovered a positive association between the magnitude of social jet lag and body mass index, suggesting that the disruption of circadian cycles contributes to weight gain.

In addition to delving further into understanding the mechanisms underlying the connection between clock genes and metabolic disorders, researchers have recently produced provocative results linking circadian rhythms with many other conditions. Ties have been found between circadian disruption and ailments of the heart and stomach, as well as various cancers, neurological and neurodegenerative diseases, and psychiatric illnesses—among others. Indeed, a handful of small studies suggest that, in some cases, disrupted sleep cycles may be a contributing cause—and not just an effect—of severe depression in people who are already prone to the illness. Similarly, experiments in mice and hamsters over the past five years have shown that conditions resembling chronic jet lag impair learning and memory and disrupt neuronal structures in certain regions of the brain.

Deeper understanding of the role that our internal clocks play in our body has the potential to revolutionize medicine. Taking into account knowledge of optimal clock function—such as when glucose production is best turned on and off in the course of 24 hours—could lead to the development of what we refer to as "circadian medicine." Physicians who are able to incorporate information about circadian rhythms and sleep-wake cycles most effectively into their diagnosis and treatment of disease will be better positioned, we believe, to improve health, prevent disease and maximize the benefits of the therapies that their patients require. SA

MORE TO EXPLORE

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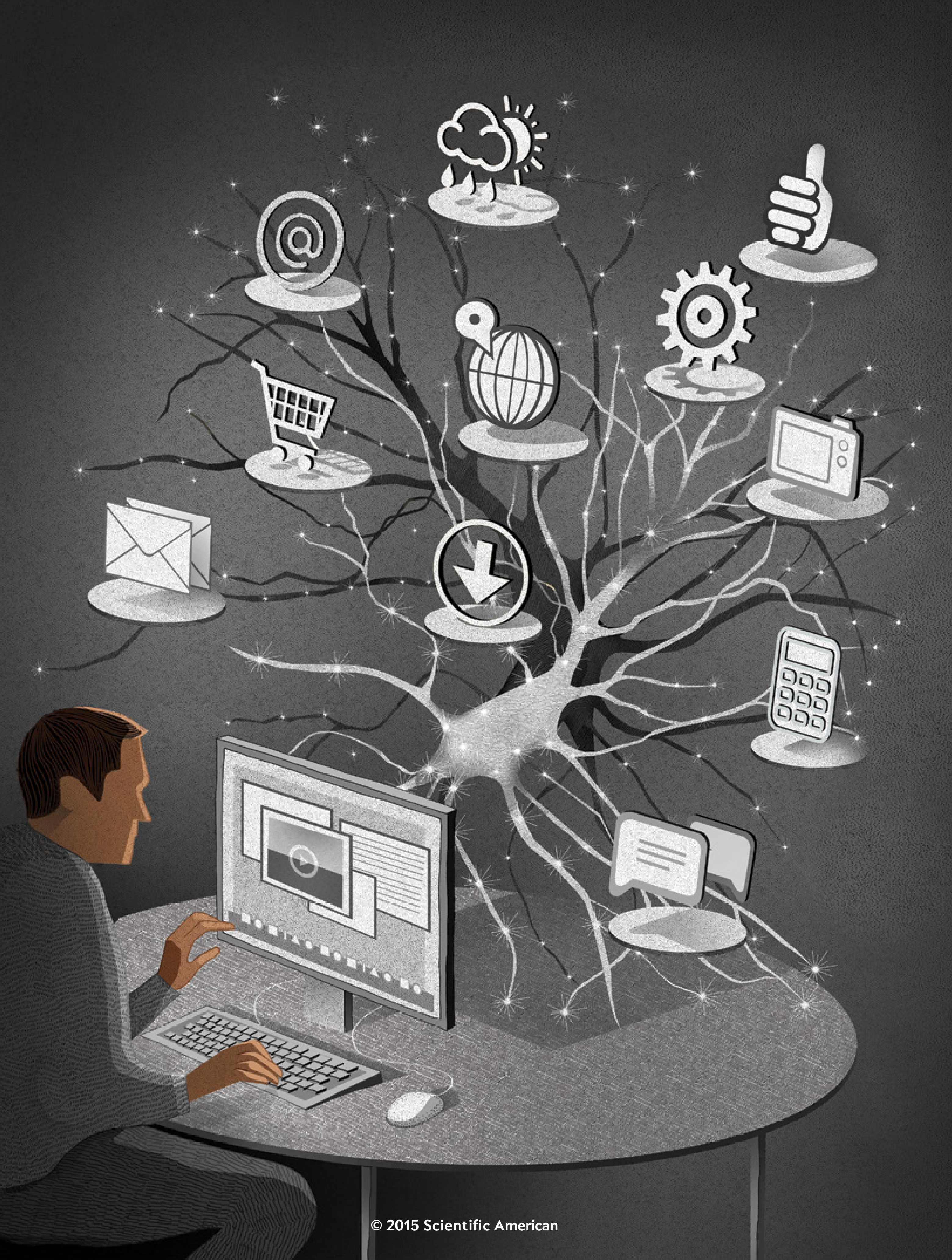


COMPUTER SCIENCE

just add memory

New types of electronic components, closer to neurons than to transistors, are leading to tremendously efficient and faster "memcomputing"

By Massimiliano Di Ventra and Yuriy V. Pershin

IN BRIEF

Modern computers all use a unit that does calculations and a separate memory unit that holds programs and data. Shuttling information back and forth takes lots of energy and time.

A new idea, memcomputing works in a way that is similar to the neurons in the human brain, which form computing and memory storage units that are physically the same.

This could mean a giant leap in computer speed and efficiency, as well as new computing architectures, so scientists are trying to learn the best ways to use different memcomputing components.

Illustration by Adam Simpson

Massimiliano Di Ventra is a professor in the department of physics at the University of California, San Diego.

Yuriy V. Pershin is an associate professor in the department of physics and astronomy at the University of South Carolina.

WHEN WE WROTE THE WORDS YOU ARE NOW READING, WE WERE TYPING on the best computers that technology now offers: machines that are terribly wasteful of energy and slow when tackling important scientific calculations. And they are typical of every computer that exists today, from the smartphone in your hand to the multimillion-dollar supercomputers humming along in the world's most advanced computing facilities.

We were writing in Word, a perfectly fine program that you probably use as well. To write "When we wrote the words you are now reading," our computer had to move a collection of 0's and 1's—the machine representation of a Word document—from a temporary memory area and send it to another physical location, the central processing unit (CPU), via a bunch of wires. The processing unit transformed the data into the letters that we saw on the screen. To keep that particular sentence from vanishing once we turned our computer off, the data representing it had to travel back along that bunch of wires to a more stable memory area such as a hard drive.

This two-step shuffle happens because, at the moment, computer memory cannot do processing, and processors cannot store memory. It is a standard division of labor, and it happens even in fancy computers that do the fastest kind of calculating, called parallel processing, with multiple processors. The trouble is that each of these processors is still hobbled by this limitation.

Scientists have been developing a way to combine the previously uncombinable: to create circuits that juggle numbers and store memories at the same time. This means replacing standard computer circuit elements such as transistors, capacitors and inductors with new components called memristors, memcapacitors and meminductors. These components exist right now, in experimental forms, and could soon be combined into a new type of machine called a memcomputer.

Memcomputers could have unmatched speed because of their dual abilities. Each part of a memcomputer can help compute the answer to a problem, in a new, more efficient version of today's parallel computing. And because difficult problems are solved by the computer's memory and stored directly into that memory, they will also save all the energy that is currently required to transfer data back and forth within the machine. This brand-new type of computing architecture would change the way computers of all types operate, from the tiny chips in your phone to vast supercomputers. It is, in fact, a design that is close to the way the human brain works, holding memories and processing information in the same neurons.

These new memcomputing machines should be much swifter—taking mere seconds to do calculations that would take current machines decades—and smaller and use much less electricity. Complete memcomputers have not yet been built, but our experiments with the components indicate that they could have a huge impact on computer design, global sustainability, power use and our ability to answer vital scientific questions.

AN ELECTRONIC, ENERGY-EFFICIENT BRAIN

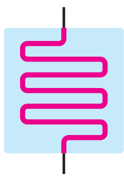
IT TAKES A TINY BIT OF ELECTRICITY and a fraction of a second to shuffle data like our Word sentence within a machine. But if you think about what happens when the energy for this back and forth is multiplied across worldwide computing use, it is an enormous operation.

Between 2011 and 2012 power requirements for computer data centers around the globe grew by a staggering 58 percent. It is not just supercomputers. Add in every gadget in every house, from ovens to laptops to televisions, that now has some computing ability. Combined, the information and communication sectors now account for approximately 15 percent of global electricity consumption. By 2030 the global electricity use by consumer electronics will equal the current total residential electricity consumption of the U.S. and Japan *combined* and will cost $200 bil-

COMPONENTS

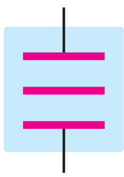
Three Memcomputer Building Blocks

Modern electrical circuits use three components that respond to electrical inputs. Resistors impede electric current that flows through them, capacitors store electrical charges and inductors convert current into a magnetic field. (In a computer, transistors are typically used instead of resistors.) When power is cut off, the components return to their original states. Memcomputing versions of these components, however, retain their changed state, and this "memory" permits complex calculations to occur quickly. (The red lines in the symbols represent the different effects on electricity.)



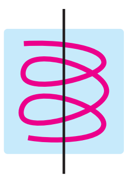
Memristor

This device changes resistance depending on the amount of current flowing through it, and it retains that change. Thus, it can both process information and hold on to it, like a memory.



Memcapacitor

Not only does this device store electrical charges, but it changes its state, or capacitance, depending on the history of voltages applied to it. Again, that gives it memory and processing ability. Any unused energy can be recycled for other computing operations, saving power.



Meminductor

Like a memristor, this device lets current flow through, but it also stores energy like a memcapacitor. The combination of flow and storage lets meminductors process information and store it as a computer memory component.

lion in electricity annually. This power hogging is not sustainable.

We cannot fix it by shrinking transistors—the fundamental element of digital electronics—to smaller and smaller sizes. The International Technology Roadmap for Semiconductors has forecasted that the transistor industry most likely will hit a technological wall by 2016 because available component materials cannot go down any further in size and maintain their capabilities.

Scientific research on some urgent problems will also hit a wall. Important questions that can only be tackled by heavy-duty computation, such as the prediction of global weather patterns or forecasting the occurrence of diseases in various populations by exploring large genome databases, will require larger and larger amounts of computational power. Memcomputers, by avoiding the expensive, power-hungry and time-consuming process of constantly transferring data between a CPU and memory, should save a significant amount of energy.

They are not, of course, the first information-processing devices to handle calculations and storage in one place. The human brain does this very thing, and memcomputing takes its inspiration from this fast, efficient organ sitting on top of our shoulders.

The average human brain, according to many estimates, can perform about 10 million billion operations per second and uses only 10 to 25 watts to do so. A supercomputer would require more than 10 million times that power to do the same amount of work. And a computer does not even come close to performing such complicated tasks as pattern recognition—like separating the sound of a dog barking from a car passing in the street—that we do in the noisy and unpredictable environment we live in. Unlike our present supercomputers, calculations in the brain are not performed in two places but are done by the same neurons and synapses. Less shuffling means less energy spent and less time lost moving information around. A computer can do calculations, one at a time, faster than humans can, but it takes all that brute-force transistor power to carry them out.

Traditionally computers have relied on their separation of powers to keep programs and the data they use from interfering with one another during processing. Physical changes in a circuit caused by new data—say, the letters we typed in Word—would change and corrupt the program or the data. This could be avoided if circuit elements in a processor could "remember" the last thing they did, even after the electricity is turned off. Data would still be intact.

THREE PARTS OF A NEW MACHINE

MEMCOMPUTING COMPONENTS can do exactly that: process information and store it after the electricity stops. One of these new devices is a memristor. To understand it, imagine a pipe that changes its diameter depending on the direction of water flow. When water is flowing right to left, the pipe gets wider, enabling more water to flow through it. When water is flowing left to right, the pipe gets narrower, and less water goes through it. If the water is turned off, the pipe maintains its most recent diameter—it remembers the amount of water that flowed through it.

Now replace the water with electric current and replace the pipe with a memristor. It changes its state depending on the amount of current flowing, as the water pipe changes diameter—a wider pipe has less electrical resistance, and a narrower pipe has more. If you think of resistance as a number and the change in resistance as a process of calculation, a memristor is a circuit element that can process information and then hold it after the current is turned off. Memristors can combine the work of the processing unit and of the memory in one place.

The notion of memristors came from Leon O. Chua, an electrical engineer at the University of California, Berkeley, in the 1970s. At the time, his theory did not appear to be very practical. Materials used to make circuits did not retain memory of their last state like the imaginary water pipe, so the idea seemed far-fetched. But over the decades engineers and materials scientists were able to exert more and more control over the circuit materials they fabricated, imbuing them with new properties. In 2008 Hewlett-Packard engineer Stanley Williams and his colleagues produced memory elements that could shift resistance and hold their shifted state. They shaped titanium dioxide into an electrical component just tens of nanometers (billionths of a meter) wide. In a paper in *Nature,* the scientists showed that the component retained a state that was determined by the history of current flowing through it. The imaginary pipe was real. (*Scientific American* is part of Nature Publishing Group.)

It turns out that these devices can be fabricated with a large variety of materials and can be made just a few nanometers across. Smaller dimensions mean that more of them can be packed into a given area, so they can be crammed into almost any kind of gadget. Many of these components can be made in the same semiconductor facilities we now employ to make computer components and therefore can be fabricated on an industrial scale.

Another key component that could be used in memcomputing is a memcapacitor. Regular capacitors are devices that store electrical charges, but they do not change their state, or capacitance, no matter how many charges are deposited in them. In today's computers they are mainly used in a particular kind of memory, called dynamic random-access memory (DRAM), which stores computer programs in a state of readiness so they can be uploaded quickly to the processor when it calls for them. A memcapacitor, however, not only stores charges but changes its capacitance depending on past voltages applied to it. That gives it both memory and processing ability. Further, because memcapacitors store charges—energy—that power could be recycled during computation, helping to minimize energy consumption by the overall machine. (Memristors, in contrast, use all the energy put into them.)

Some types of memcapacitors, made of relatively costly ferroelectric materials, are already available on the market and are used as devices for data storage. But research laboratories are developing versions made of inexpensive silicon, keeping the manufacturing price low enough to use them throughout a computer.

The meminductor is the third element of memcomputing. It has two terminals, and it stores energy like a memcapacitor while letting current flow through it like a memristor. Meminductors, too, exist right now. But they are quite large because they rely on big wire magnetic coils, so they would be hard to use in small computers. Advances in materials could change that in the near future, however, as it did for memristors just a few years ago.

In 2010 we started trying to show that memcomputing could handle calculations better than current computer architecture. One problem we focused on was finding a way out of a maze. Devising programs for maze running has long been a way to test the efficiency of computer hardware. Conventional algorithms for solving mazes explore the maze in small consecutive steps. For instance, one of the best-known algorithms is the so-called wall follower. The program traces the wall of the maze through all its twists and turns, avoiding empty spaces where the wall ends, and moves, calculation after painstaking calculation, from the entrance to the exit. This step-by-step approach is slow.

Memcomputing, we have shown in simulations, will solve the maze problem extremely fast. Consider a network of mem-

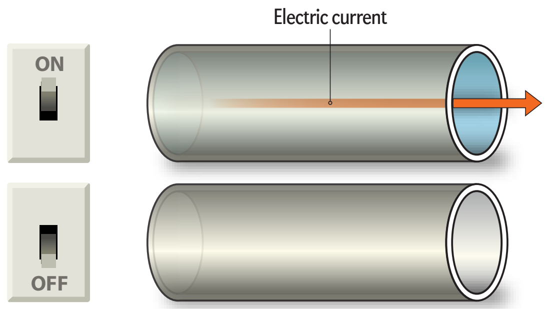
HOW MEMRISTORS WORK

The Power of Memory

One of the new memcomputing components, the memristor, responds in different ways to different levels of electric current. Three such changes are shown here. When the changes are retained, they form the basis for memory.

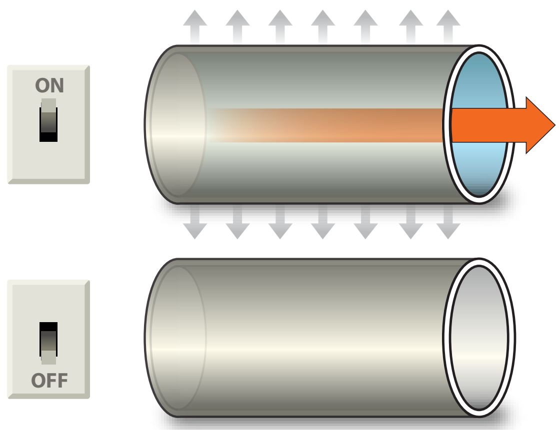
Typical Resistance

When a weak electric current passes through a memristor, the device has a specific resistance level to the current. That level is shown here by the width of the tube. Resistance, in a computer, can be interpreted as a number, which leads to calculation. When the power is cut off, the tube stays the same width.



Low Resistance

When a strong current passes through the memristor, the device lowers its resistance, shown by a wider tube. That change, interpreted as a different number than in the original configuration, permits information processing. When the power is off, the memristor retains this state, which allows it to function like memory. A traditional computer component would revert to its original state.



High Resistance (Current Reversal)

Memristors can also increase resistance if the current through them is reversed, shown by a narrower tube. Again the tube does not revert to its original state when power is off, adding memory to its processing function.

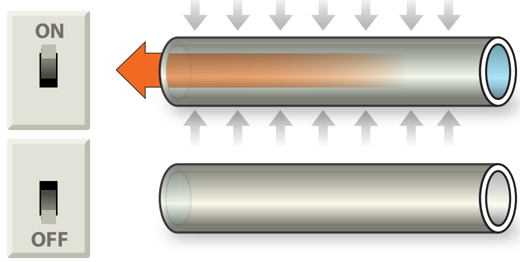


Illustration by Jen Christiansen

SCIENTIFIC AMERICAN ONLINE Di Ventra explains memcomputing in a video at ScientificAmerican.com/feb2015/memcomputing ristors, one at each turn of the maze, all in a state of high resistance. If we apply a single voltage pulse across the entrance and exit points, the current will flow only along the solution path—it will be blocked by dead ends in other paths. As the current flows, it changes the resistances of the corresponding memristors. After the pulse disappears, the maze solution will be stored in the resistances of only those devices that have changed their state. We have computed *and* stored the solution in only one shot. All the memristors compute the solution in parallel, at the same time.

This kind of parallel processing is completely different from current versions of parallel computing. In a typical parallel machine today, a large number of processors compute different parts of a program and then communicate with one another to come up with the final answer. This still requires a lot of energy and time to transfer information between all these processors and their associated—but physically distinct—memory units. In our memcomputing scheme, it simply is not necessary.

Memcomputing really shows advantages when applied to one of the most difficult types of problems we know of in computer science: calculating all the properties of a large series of integers. This is the kind of challenge a computer faces when trying to decipher complex codes. For instance, give the computer 100 integers and then ask it to find at least one subset that adds up to zero. The computer would have to check all possible subsets and then sum all numbers in each subset. It would plow through each possible combination, one by one, which is an exponentially huge increase in processing time. If checking 10 integers took one second, 100 integers would take 10^{27} seconds—millions of trillions of years.

As with the maze problem, a memcomputer can calculate all subsets and sums in just one step, in true parallel fashion, because it does not have to shuttle them back and forth to a processor (or several processors) in a series of sequential steps. The single-step approach would take just a single second.

Despite these advantages and despite the fact that components have already been made in labs, memcomputing chips are not yet commercially available. At the moment, early versions are being tested in academic facilities and by a few manufacturers to see if these untried designs are robust enough, over repeated use, to replace current memory chips made of standard transistors and capacitors. These chips are the kind you find in USB drives and solid-state memory drives. The tests can take a long time because the components need to last years without failure.

We think some memcomputing designs could be ready for use in the very near future. For instance, in 2013, together with two researchers at the Polytechnic University of Turin in Italy, Fabio Lorenzo Traversa and Fabrizio Bonani, we suggested a concept called dynamic computing random-access memory (DCRAM). The goal is to replace the standard type of memory that, as we have discussed, is used to hold programs and data just before a processor calls for them. In this conventional memory, each bit of information that makes up the program is represented by a charge stored on a single capacitor. That calls for a large number of capacitors to represent one program.

If we replace them with memcapacitors, however, all the different logic operations required by the program can be represented by a much smaller number of memcapacitors in this memory area. Memcapacitors can shift from one logic operation to another almost instantly when we apply different voltages to them. Computing instructions such as "do x AND y," "do x OR y" and "ELSE do z" can be handled by two memcapacitors instead of a large number of fixed regular capacitors and transistors. We do not have to change the basic physical architecture to carry out different functions. In computer terminology, this is called polymorphism, the ability of one element to perform different operations depending on the type of input signal. Our brain possesses this type of polymorphism—we do not need to change its architecture to carry out different tasks—but our current machines do not have it, because the circuits in their processors are fixed. And with memcomputing, of course, because this computation is occurring within a memory area, the time- and power-consuming shuffle back and forth to a separate processor is eliminated, and the result of the program's calculations can be stored in the same place.

These systems can be built with present fabrication facilities. They do not require a major leap in technology. What may hold them up is the need to design new software to control them. We do not yet know the most efficient kinds of operating systems to command these new machines. The machines have to be built, and then various controlling systems have to be tested and optimized. This is the same design process that computer scientists went through with our present crop of machines.

Scientists also would like to find the best way to integrate these new memelements into our current computers. It might be a good idea to keep present processors to handle simple tasks—like computing that sentence in Word that began this article—while using memcomputing elements in the same machine for more intricate and hitherto time-consuming operations. We will need to build, test, rebuild and retest.

It is enticing, though, to consider where this technology could lead us. After building and testing, computer users might have a small device, maybe small enough to hold in your hand, that could tackle very complex problems involving, say, pattern recognition or modeling the earth's climate at a very fine scale. Something it could do in one or a few computational steps, at very low energy and cost.

Wouldn't you stand in line to get one? ■

MORE TO EXPLORE

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scientificamerican.com/magazine/sa

ENVIRONMENT

Our future rides on our ability to integrate

ENERGY

+

WATER

+

FOOD

A Puzzle for the Planet

By Michael E. Webber

Photograph by Dan Saelinger

Michael E. Webber is deputy director of the Energy Institute at the University of Texas at Austin. His forthcoming book *Thirst for Power,* which examines energy and water use in the modern world, will be published by Yale University Press. Follow him on Twitter @MichaelEWebber

IN JULY 2012 THREE OF INDIA'S REGIONAL electric grids failed, triggering the largest blackout on earth. More than 620 million people—9 percent of the world's population—were left powerless. The cause: the strain of food production from a lack of water. Because of major drought, farmers plugged in more and more electric pumps to draw water from deeper and deeper belowground for irrigation. Those pumps, working furiously under the hot sun, increased the demand on power plants. At the same time, low water levels meant hydroelectric dams were generating less electricity than normal.

Making matters worse, runoff from those irrigated farms during floods earlier in the year left piles of silt right behind the dams, reducing the water capacity in the dam reservoirs. Suddenly, a population larger than all of Europe and twice as large as that of the U.S. was plunged into darkness.

California is facing a surprisingly similar confluence of energy, water and food troubles. Reduced snowpack, record-low rainfall and ongoing development in the Colorado River basin have reduced the river water in central California by a third. The state produces half of the country's fruits, nuts and vegetables and almost a quarter of its milk, and farmers are pumping groundwater like mad; last summer some areas pumped twice as much water for irrigation as they did the previous year. The 400-mile-long Central Valley is literally sinking as groundwater is pulled up from below. Just when more power is needed, Southern California Edison shut down two big nuclear reactors for a lack of cooling water. San Diego's plan to build a desalination plant along the coast was challenged by activists who opposed the facility on the grounds that it would consume too much energy.

Energy, water and food are the world's three most critical resources. Although this fact is widely acknowledged in policy circles, the interdependence of these resources on one another is significantly underappreciated. Strains on any one can cripple the others. This situation has made our society more fragile than we imagine, and we are not prepared for the potential disaster that is waiting for us.

Yet we are making once-in-a-generation decisions about power plants, water infrastructure and farmland that will last for many decades, locking us into a vulnerable system. Meeting the world's energy needs alone will require $48 trillion in investment between now and 2035, according to a 2014 International Energy Agency report, and the agency's executive director said there is a real risk "that investments are misdirected" because impacts are not being properly assessed.

IN BRIEF

The world is trying to improve energy, water and food supplies individually, but the challenges need to be solved in one integrated manner. That approach will also benefit the environment, poverty, population growth and disease.

Reducing wasted food can conserve energy and water. Indoor farms can use city wastewater to grow crops and power the buildings in which they are housed. Algae production next to power plants can turn wastewater and carbon emissions into food or biofuel. Wind turbines in the desert can convert brackish water into freshwater. A smart grid for water delivery can save water and energy.

Energy, water and food planners and policy makers have to stop working in isolation and devise integrated policy and infrastructure solutions.

PAGE 62: PROP STYLING BY DOMINIQUE BAYNES; THIS PAGE: ETHAN MILLER *Getty Images*

LAKE MEAD in Arizona and Nevada hit a record low in July 2014, threatening to limit drinking water for Las Vegas, irrigation for farms and power from the Hoover Dam.

An integrated approach to solving these enormous issues is urgently needed rather than an attempt to solve each problem apart from the others. A vast number of the planet's population centers are hit with drought, energy systems are bumping up against environmental constraints and rising costs, and the food system is struggling to keep up with rapidly growing demand. And the nexus of food, water and energy is a backdrop to much of the most troubled parts of the world. Riots and revolutions in Libya and Syria were provoked by drought or high food prices, toppling governments. We need to solve the interconnected conundrum to create a more integrated and resilient society, but where do we start?

CASCADING RISKS OR REWARDS

THE LATE NOBEL LAUREATE Richard E. Smalley of Rice University gave a hint at where to begin in his 2003 lecture highlighting the "Top Ten Problems of Humanity for the Next 50 Years." His list was organized in descending order of importance: energy, water, food, environment, poverty, terrorism and war, disease, education, democracy and population. Energy, water and food were at the top because solving them would combat problems lower down, in cascading fashion. Developing plentiful sources of clean, reliable, affordable energy, for example, enables an abundance of clean water. Having an abundance of clean water and energy (to make fertilizer and to power tractors) enables food production. And so on.

As brilliant as Smalley's list was, it missed two important nuances. First, energy, water and food are interconnected. And second, although an abundance of one enables an abundance of the others, a shortage of one can create a shortage of the others.

With infinite energy, we have all the water we need because we can desalt the oceans, dig very deep wells and move water across continents. With infinite water, we have all the energy we need because we can build widespread hydroelectric plants or irrigate unlimited energy crops. With infinite energy and water we can make the deserts bloom and build highly productive indoor farms that produce food year-round.

We do not live in a world with infinite resources, of course. We live in a world of constraints. The likelihood that these constraints will lead to cascading failures grows as pressure rises from population growth, longer life spans and increasing consumption.

For example, Lake Mead outside Las Vegas, fed by the Colorado River, is now at its lowest level in history. The city draws drinking water from what amounts to two big straws that dip into the lake. If the level keeps dropping, it may sink lower than those straws: large farming communities downstream could be left dry, and the huge hydroelectric turbines inside the Hoover Dam on the lake would provide less power or might stop altogether. Las Vegas's solution is to spend nearly $1 billion on a third straw that will come up into the lake from underneath. It might not do much good. Scientists at the Scripps Institution of Oceanography in La Jolla, Calif., have found that Lake Mead could dry up by 2021 if the climate changes as expected and cities and farms that depend on the Colorado River do not curtail their withdrawals.

In Uruguay, politicians must confront tough decisions about how to use the water in their reservoirs. In 2008 the Uruguay River behind the Salto Grande Dam dropped to very low levels. The dam has almost the same electricity-generating capacity as the Hoover Dam, but only three of the 14 turbines were spinning because local people wanted to store the water for farming or municipal use. The citizens along the river and their political leaders were forced to choose whether they wanted electricity, food or drinking water. Constraints in one sector triggered constraints in the others. Although that threat might have temporarily eased for Uruguay, it repeats itself in other parts of the world. In like manner, certain communities in drought-stricken Texas and New Mexico have recently prohibited or restricted water for use in fracking for oil and gas, saving it for farming.

About 80 percent of the water we consume is for agriculture—our food. Nearly 13 percent of energy production is used to fetch, clean, deliver, heat, chill and dispose of our water. Fertilizers made from natural gas, pesticides made from petroleum, and diesel fuel to run tractors and harvesters drive up the amount of energy it takes to produce food. Food factories requiring power-hungry refrigeration produce goods wrapped in plastic made from petrochemicals, and it takes still more energy to get groceries from the store and cook them at home. The nexus is a big mess, and the entire system is vulnerable to a perturbation in any part.

PASSENGERS in Kolkata, India, were stranded after a huge 2012 blackout, triggered by too many pumps straining to water farms during drought.

BIKAS DAS *AP Photo*

TECHNICAL SOLUTIONS

IT WOULD BE FOLLY to build more power plants and water delivery and treatment facilities with the same old designs, to grow crops using the same outdated methods, and to extract more oil and gas without realizing that these pursuits impinge on one another. Thankfully, it is possible to integrate all three activities in ways that are sustainable.

The most obvious measure is to reduce waste. In the U.S., 25 percent or more of our food goes into the dump. Because we pour so much energy and water into producing food, reducing the proportion of waste can spare several resources at once. That might mean something as simple as serving smaller portions and eating less meat, which is four times more energy-intensive than grains. We can also put discarded food and agricultural waste such as manure into anaerobic digesters that turn it into natural gas. These metal spheres look like shiny bubbles. Microbes inside break down the organic matter, producing methane in the process. If we implement this technology widely—at homes, grocery stores and central locations such as farms—that would create new energy and revenue streams while reducing the energy and water that are needed to process the refuse.

Wastewater is another by-product we could turn into a resource. In California, San Diego and Santa Clara are using treated wastewater to irrigate land. The water is even clean enough to drink, which could bolster municipal water supplies if state regulators would allow it.

Urban farm proponents such as Dickson Despommier of Columbia University have designed "vertical farms" that would be housed inside glass skyscrapers. People in New York City, for example, produce a billion gallons of wastewater a day, and the city spends enormous sums to clean it enough to dump into the Hudson River. This cleansed water could instead irrigate crops inside a vertical farm, generating food while reducing the farm's demand for freshwater. Solids extracted from liquid waste are typically burned, but instead they could be incinerated to produce electricity for the big building, reducing its energy demand. And because fresh food would be grown right where many consumers live and work, less transportation would be needed to truck food in, potentially saving energy and carbon dioxide emissions.

Start-up companies are trying to use wastewater and CO_2 from power plants to grow algae right next door. The algae eat the gas and water, and workers harvest the plants for animal feed and biofuel, all while tackling the fourth priority on Smalley's list—improving the environment—by removing compounds from the water and CO_2 from the atmosphere.

We could harness the same carbon dioxide to create energy. My colleagues at the University of Texas at Austin have designed a system in which waste CO_2 from power plants is in-

SCIENTIFIC AMERICAN ONLINE Video about resource-efficient aquaculture can be seen at ScientificAmerican.com/feb2015/webber

jected into large brine deposits deep belowground. The CO_2 stays submerged, eliminating it from the atmosphere, and pushes out hot methane, which comes to the surface, where it can be sold for energy. The heat can also be tapped by industry.

Smart conservation is another way to spare different resources simultaneously. We use more water through our light switches and electrical outlets than our faucets and showerheads because so much water is needed to cool power plants that are out of sight and out of mind. We also use more energy to heat, treat and pump our water than we use for lighting. Turning off the lights and appliances saves vast amounts of water, and turning off the water saves large amounts of energy.

We can also rethink how to better use energy and water to grow food in unlikely places. In parts of the desert Southwest, brackish groundwater is abundant at shallow depths. Wind and solar energy are also plentiful. These energy sources present challenges to utilities because the sun does not shine at night and the wind blows intermittently. But that schedule is fine for desalting water because clean water is easy to store for use later. Desalination of seawater is energy-intensive, but brackish groundwater is not nearly as salty. Our research at U.T. Austin indicates that intermittent wind power is more economically valuable when it is used to make clean water from brackish groundwater than when it is used to make electricity. And of course, the treated water can then irrigate crops. This is the nexus working in our favor.

The same thinking can improve hydraulic fracturing for oil and gas. One unfortunate side effect is that waste gas, mostly methane, coming up the well is flared—burned off into the air. The flaring is so voluminous that it can be seen at night from space. The wells also produce a lot of dirty water—millions of gallons of freshwater injected into wells for fracking come back out laden with salts and chemicals. If operators are smart, they can use the methane to power distillers or other heat-based machines to clean the water, making it reusable on-site, which spares freshwater while avoiding the wasted energy and emissions of a flare.

We can also be smarter about how we deliver water to homes and businesses. Sensors embedded in smart grids help to make electricity distribution more efficient. But our water system is a lot dumber than our electricity system. Outdated, century-old meters often fail to accurately record water use, and experts say that antiquated pipes leak 10 to 40 percent of the treated water that flows through them. Embedding wireless data sensors in the water delivery system would give utilities more tools to reduce the leaks—and lost revenues. Smart water would also help consumers manage their consumption.

We can do smart food, too. One reason so much food is wasted is because grocery stores, restaurants and consumers rely on expiration dates, a crude estimate of whether food has spoiled. Food is not sold or consumed past the expiration date even though it may still be fine if its temperature and condition have been well managed. Using sensors to assess food directly would be smarter. For example, we could use special inks on food packaging that change color if they are exposed to the wrong temperature or if undesirable microbes begin to grow in the food, indicating spoilage. We can install sensors along the supply chain to measure trace gases that are released by rotting fruits and vegetables. Those same sensors can lead to tighter refrigeration controls that minimize losses.

NEW POLICY THINKING

ALTHOUGH MANY TECHNICAL SOLUTIONS can improve the energy-water-food nexus, we often do not exploit them because ideologically and politically, the U.S. has not fully grasped the interrelatedness of these resources. Policy makers, business owners and engineers typically work in isolated fashion on one issue or another.

Sadly, we compound the problems with policy, oversight and funding decisions made by separate agencies. Energy planners assume they will have the water they need. Water planners assume they will have the energy they need. Food planners recognize the risks of drought, but their reaction is to pump harder and drill deeper for water. The most important innovation we need is holistic thinking about all of our resources.

That kind of thinking can lead to smarter policy decisions. For example, policies can fund research into energy technologies that are water-lean, water technologies that are energy-lean, and food production, storage and monitoring techniques that prevent losses while reducing energy and water demands. Setting cross-resource efficiency standards can kill two birds with one stone. Building codes can also be a powerful tool for reducing waste and improving performance. Permitting for new energy sites should require water-footprint assessments, and vice versa. And policy makers can set up revolving loan funds, direct capital investments or tax benefits for institutions that integrate these kinds of technical solutions.

One encouraging sign was a declaration made by 300 delegates from 33 countries at the Nexus 2014: Water, Food, Climate and Energy Conference in Chapel Hill, N.C. The declaration, written not just by political representatives but also by attendees from the World Bank and the World Business Council for Sustainable Development, stated that "the world is a single complex system" and that "solutions and policy interventions should be sought that are beneficial for the system as a whole."

As Smalley pointed out, energy can be the driver. We have to think about using our energy sector to solve multiple challenges simultaneously. Policies that are monomaniacal about lowering atmospheric CO_2 levels, for example, might push us toward low-carbon electricity choices that are very water-intensive, such as nuclear power plants or coal plants with carbon capture.

Personal responsibility plays a role, too. Demand for fresh salads that land on our winter plates from 5,000 miles away creates a far-flung, energy-hungry food distribution system. In general, our personal choices for more of everything just push our resources to the edge. The energy-water-food nexus is the most vexing problem to face our planet. To quote the late George Mitchell, father of modern hydraulic fracturing and a sustainability advocate: "If we can't solve the problem for seven billion people, how will we do so for nine billion people?" SA

MORE TO EXPLORE

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NEUROSCIENCE

TREATING DEPRESSION AT THE SOURCE

Electrical stimulation deep within the brain may alleviate devastating mood disorders

By Andres M. Lozano and Helen S. Mayberg

IN BRIEF

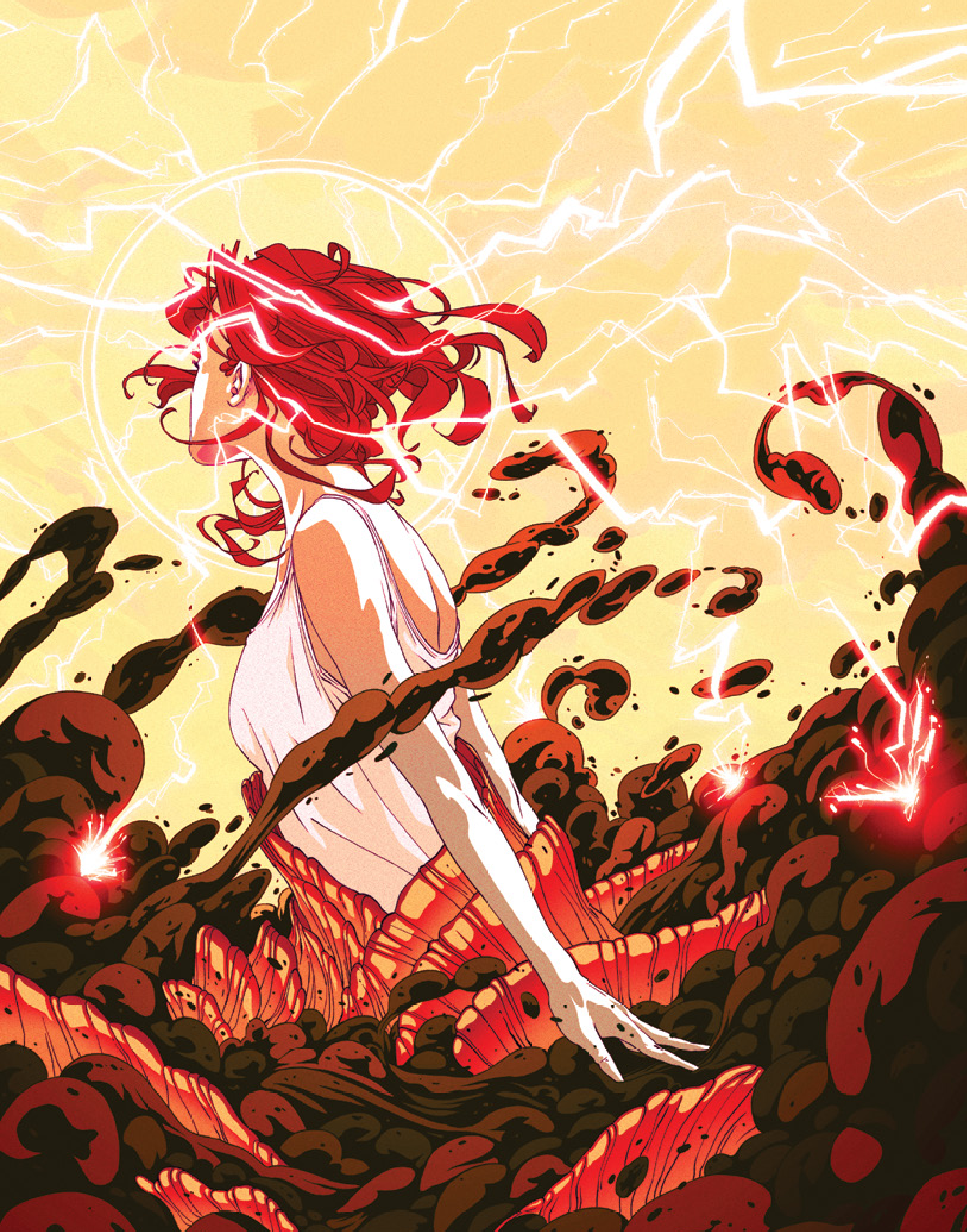
Some 17 percent of the U.S. population suffers from what psychiatrists call a "major depressive episode" at any given time.

Available treatments—ranging from medication to electroconvulsive therapy—provide little relief in up to 20 percent of sufferers.

Implanting electrodes deep in the brain, now commonly used to treat Parkinson's disease, is being studied in people for treating severe depression.

Specific brain circuits linked to depression have been identified, and knowledge of them provides guidance for where to place the electrodes.

Illustration by Goni Montes



Andres M. Lozano is a professor in the department of surgery at the University of Toronto. He specializes in treating movement disorders and in recording from the brain.

Helen S. Mayberg is a professor of psychiatry, neurology and radiology at Emory University. Much of her work focuses on tracing brain circuits involved in depression.

"I SUDDENLY FEEL CALM."

Our patient, a middle-aged woman who suffered from severe depression, uttered these beautiful words in the operating room just a few seconds after one of us (Lozano) applied electrical stimulation to a selected area deep in her brain. The operation, which took place in 2003 at Toronto Western Hospital, relied on only local anesthesia so that the woman could remain conscious and talk to us.

Then, as the current's strength was increased, we asked her if she noticed anything different. To our surprise, she described the room as going from "black-and-white to color"—as if a light switch had been flicked that instantly elevated her mood.

This test was the first of many studies that have led to the development of a potentially new way to treat depression: deep-brain stimulation, a technique that is already in use for some other disorders, such as Parkinson's disease. Novel treatment options for depression would meet an acute need. Over a lifetime, some 17 percent of the U.S population suffers one or more bouts of what psychiatrists call a "major depressive episode"; at any given time, an estimated 8 percent of women and 5 percent of men are afflicted. These are not mere episodes of sadness. Major depressive disorder, which occurs intermittently, is marked by a period of sustained sorrowful mood, feelings of guilt, a sense of worthlessness and a loss of interest in everyday activities. It can impair thinking, sleep, appetite and libido and can be experienced as physical aching. Winston Churchill, who battled the condition, called it his "black dog."

Depression can be lethal. An estimated 15 percent of patients with major depression die by committing suicide. It can also exacerbate such medical problems as heart disease and diabetes, reducing the life expectancy of people with those conditions.

Available treatments—graduating from psychotherapy to medication to electroconvulsive therapy—are generally effective in most patients. But in an estimated 10 to 20 percent of depressed patients, these treatments provide little or no relief. This subset of patients may become candidates for deep-brain stimulation as the technique becomes established.

The technology has not yet been approved for routine use in hospitals but has been tested in about 200 people worldwide. It requires doctors to drill holes in the skull and to implant electrodes permanently within the brain, and so it will never be anyone's first choice for therapy. If further testing pans out, however, it should offer a lifeline to people who might otherwise be doomed to endless despair.

IT'S ALL IN THE CIRCUITS

THE 2003 TEST grew out of research conducted by one of us (Mayberg) to pinpoint the brain regions involved in depression. Neuroscientists recognized by then that the symptoms of depression and various other brain disorders arise from disturbances in the functioning of specific neuronal circuits. The tremor or rigidity of Parkinson's occurs because of misfiring in circuits that control movement. Circuitry involved in forming new memories or retrieving old ones goes awry in Alzheimer's disease. Similarly, considerable evidence in the early 2000s pointed to disturbances in circuits mediating mood as being at the core of depression.

The circuits themselves are formed by connections among subsets of the brain's 86 billion neurons. Each cell links up with thousands of others, some to the next neuron, some reaching out great distances through the central nervous system. Whether a link extends to one cell or another depends on genetics, early life experiences and stress. The malfunctioning of the circuits involved in depression probably involves many brain regions. But pinpointing the location of this web of connections remains an ongoing challenge for neuroscientists.

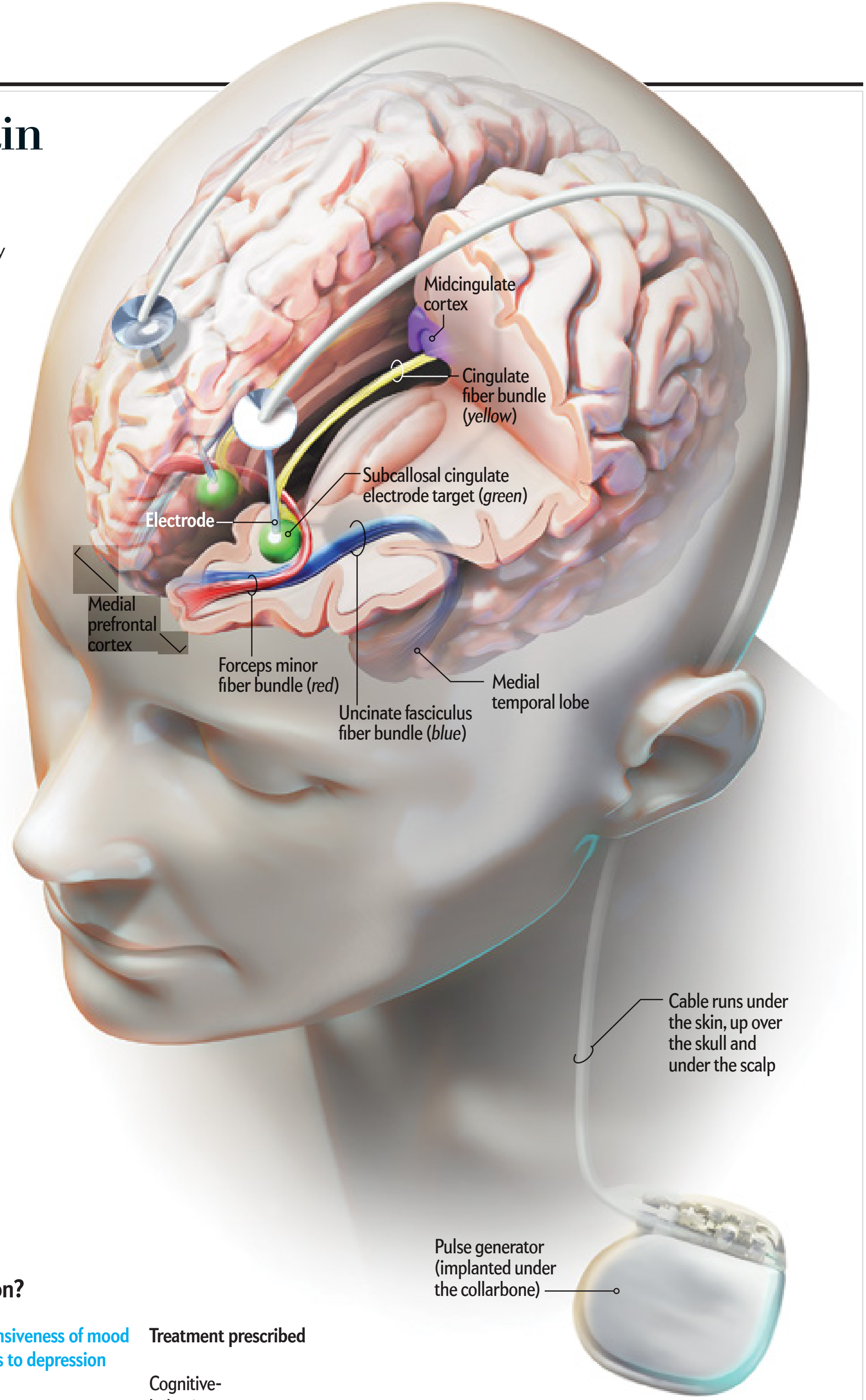
Starting in the mid-1990s, Mayberg designed a series of experiments to identify brain areas involved in the regulation of mood in both healthy subjects and patients with depression. In an early experiment, healthy volunteers had to go through a mental exercise of reliving a sad experience in their life.

A type of brain scan known as positron-emission tomography (PET) mapped out areas that had a marked change in activity when the patient was feeling despondent. One type of PET imaging found that depressed patients had increased blood flow, a measure of brain cell activity, in a particular area in the middle of the brain when compared with healthy individuals. In contrast, areas of the brain involved in motivation, drive and executive functions showed diminished activity.

The spot on the scan that exhibited the most activity was a small region in the middle of the brain called the subcallosal cingulate area—also known as Brodmann area 25, a surname bor-

Giving the Brain a Reboot

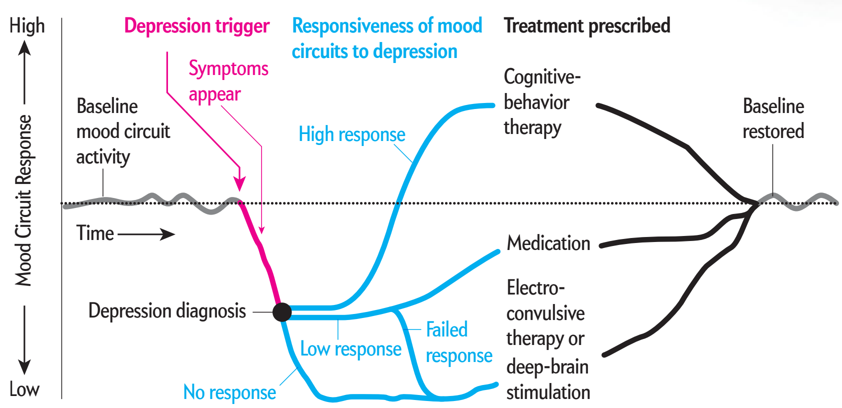
Deep-brain stimulation uses surgically placed electrodes to send an electric current through neural circuits (nerve fiber bundles that connect brain regions). These circuits do not function properly in people suffering from major depression. The therapy, which has yet to be approved for routine clinical use, can sometimes correct signaling impairments and thereby rapidly dissipate feelings of hopelessness and lack of pleasure.



The Target

The electrodes are positioned to affect several interconnected brain areas. They are put close to the subcallosal cingulate (*green*), a hub region from where circuits involved with decision making, emotional responses and memory branch out to other parts of the brain. Some of the branches (*red* and *blue*) connect to the medial prefrontal cortex and the medial temporal lobe (*blue*). And another (*yellow*) links to the midcingulate cortex. All become dysfunctional in a depressive episode.

Who Benefits from Brain Stimulation?



Depression upsets the ordinary functioning of neural circuits. But brain scans may point to therapies that enhance circuits' own natural tendency to respond to and correct this imbalance. A scan might show whether cognitive-behavior therapy or medication could assist in restoring equilibrium. Other therapies, such as deep-brain stimulation, would be used if the circuits had lost this self-corrective responsiveness.

SOURCES: "DEFINING CRITICAL WHITE MATTER PATHWAYS MEDIATING SUCCESSFUL SUBCALLOSAL CINGULATE DEEP BRAIN STIMULATION FOR TREATMENT-RESISTANT DEPRESSION," BY PATRICIO RIVA-POSSE ET AL., IN *BIOLOGICAL PSYCHIATRY*, VOL. 76, NO. 12; DECEMBER 15, 2014 (*brain*); "TARGETED ELECTRODE-BASED MODULATION OF NEURAL CIRCUITS FOR DEPRESSION," BY HELEN S. MAYBERG, IN *JOURNAL OF CLINICAL INVESTIGATION*, VOL. 119, NO. 4; APRIL 1, 2009 (*chart*)

Illustration by David Killpack, Graphic by Jen Christiansen rowed from the German neuroanatomist who created a map of the brain in 1909 using numerical designations based on the way cells were arranged at a particular location. Mayberg also found that the frontal cortex ratcheted down activity in proportion to the degree of sadness experienced.

In a second set of experiments by Mayberg, depressed patients received antidepressant medication for several weeks. Afterward, PET imaging showed that when patients' symptoms resolved, improvement was accompanied by a decrease in activity in Brodmann area 25, along with an increase in activity in the frontal cortex. Although brain changes also occurred in other areas, the striking differences in the subcallosal cingulate area pointed to that region as playing a critical role in modulating negative moods.

Brodmann area 25 sends out and receives connections to many other major brain sites, including the orbital and medial sections of the frontal lobes, the hypothalamus, the nucleus accumbens, the amygdala and the hippocampus, the periaqueductal area and the dorsal raphe. These areas govern the way the brain regulates basic attributes of human behavior, including the sleep-wake cycle, motivation, responses to perceived threats and novel stimuli, feelings of reward and reinforcement, short-term memory, and the ability to use past experience to guide thinking about future events. Such critical brain processes all go awry in depression. Hence, Mayberg reasoned, perhaps stimulating this hub of neural activity with an electric current could help depressed individuals.

BRAIN SURGERY FOR DEPRESSION

BY 2002 DEEP-BRAIN STIMULATION of other brain regions had been approved for Parkinson's and a condition called essential tremor, so we knew it could feasibly be used in humans. Today more than 100,000 patients worldwide have received it to ease the symptoms of Parkinson's. The basic surgical procedure for depression is identical. Patients are selected for study who meet criteria similar to those required of our first patient at Toronto Western. They must have been ill for a minimum of a year without any improvement on at least four different types of medications. In addition, they must have failed to improve after electroconvulsive therapy or refused its administration.

Deep-brain stimulation is not just another form of electroconvulsive therapy—which induces a controlled but generalized seizure while the patient is anesthetized and is delivered in short sessions that are repeated over several weeks. The new technology applies small electric pulses in a specific brain region that has connections to many other brain areas implicated in depression. Patients must undergo major surgery to implant the electrodes that will deliver ongoing stimulation, but they do not suffer memory loss, as can happen in electroconvulsive therapy.

On the day of surgery for our first depression patient at Toronto Western, the surgical team affixed a frame to the patient's head to keep it stable. Magnetic resonance imaging identified the particular place in the subcallosal cingulate area where the electrode was to be placed. In the operating room, under local anesthesia and without sedation, the surgical team drilled two holes in the skull through which the electrodes could be inserted.

With the aid of William D. Hutchison and Jonathan O. Dostrovsky, both expert neurophysiologists at Toronto Western, we recorded from the neurons in the subcallosal cingulate region, for the first time, to chart the activity of the neurons there to learn about their function. Based on imaging experiments conducted previously, we suspected that these areas would be involved in processing emotions related to sadness. Using a microelectrode with a tip finer than a human hair, we obtained direct measures of cellular activity of neurons that populated this brain region.

While recording from the neurons, we presented the patient with various photographs depicting a range of emotional scenes, both positive and negative. We discovered from the recordings that these neurons became most active when the patient looked at sad and disturbing photographs and that they did not react at all to happy, exhilarating or neutral scenes.

We then inserted stimulation electrodes into Brodmann area 25 on both the right and left sides of the brain. Within seconds of turning on the current, our patient reported a marked reduction in mental pain and emotional heaviness. A burdensome weight somehow lifted, a sensation that we have found occurs in most but not all patients. The effects became most pronounced when the stimulation was first applied. When repeated subsequent times, the effects occurred again but were less robust. We now know that if the treatment is continued over days or weeks in this same spot, a patient generally receives long-lasting benefits.

A few moments after the electrodes activated, our patient experienced a lightening of mental pain and emotional heaviness.

We learned from this surgery and others we have performed about the need for precise placement of the electric contacts that deliver a constant level of stimulation. In that first surgery, relief came when one or two of the four electric contacts delivered a constant current to the patient.

From continuing observations, Patricio Riva-Posse and Ki Sueng Choi, both in Mayberg's laboratory at Emory University, have developed a new imaging approach to more precisely pinpoint the bundles of nerve wiring, or white matter, that intersect at Brodmann area 25 and that seem to produce both immediate relief and long-term antidepressant effects when stimulated.

Once the electrodes are in place and fixed to the skull, a surgeon implants a pulse generator, which is similar to a cardiac pacemaker, under the skin below the collarbone—a battery-powered pacemaker that stimulates the target area continuously with 130 pulses per second. We chose the stimulation parameters, in part, based on our experience in treating Parkinson's patients, and so far it appears that this high-frequency pulsing provides the best benefit for the patient.

Once the settings are made, the operation is complete. Afterward, physicians use a handheld, wireless remote to fine-tune the stimulation each patient receives. In our experience, once an effec-

SCIENTIFIC AMERICAN ONLINE Watch Mayberg speak on deep-brain stimulation and depression at ScientificAmerican.com/feb2015/dbs

tive setting is established, no additional adjustments are necessary. Further work will determine if different settings might be required for those who do not respond to the standard adjustments or if different ones might speed up antidepressant effects. Batteries need replacement every three years or so when they become depleted, and rechargeable units are now available.

WHY DOES A BRAIN PACEMAKER HELP?

SOME PATIENTS have seen their symptoms completely disappear, but responses have varied, and not everyone has been helped. The proportion of patients who show a clinical response—a 50 percent or more reduction on scales that measure depression—can differ among hospitals and has ranged from 40 to 70 percent within a six-month period. The variability of the findings may relate to the continuing challenge of using symptoms and brain scans to identify the best patients for deep-brain stimulation.

One study that has received some attention has shown poor results. This industry-sponsored investigation, conducted by St. Jude Medical, headquartered in St. Paul, Minn., decided in 2013 to suspend taking on new patients, although patients who have already begun the trial are continuing with the therapy. No major safety concerns arose, but an analysis required by the U.S. Food and Drug Administration at the experiment's halfway point showed that patients with stimulator implants did not receive sufficiently greater symptom relief compared with a group in which the electrodes had remained off for six months. Researchers are reviewing the study's methodology to determine whether the therapy might improve with a different design.

We do not fully understand the reason for the disparities among different studies that have examined deep-brain stimulation. Explanations may relate to differences in criteria for patient selection. Some patients may have had depression combined with other psychiatric symptoms. Varying surgical techniques—where the electrodes are placed or the way stimulation is delivered—may also be critical. A potential confounding factor is that some patients who improve may do so simply because they believe in the power of surgery (the placebo effect, in other words) or because they benefit psychologically from the sometimes intense interactions they have with the treatment team. Some of these concerns may diminish over time because a few more recent studies suggest that the therapy has a genuine effect: patients deteriorate when the battery is low or stimulation is turned off. They recover again when stimulation resumes, making the placebo effect a less likely explanation.

Several experimental clinical research studies are under way in Atlanta, Hanover, N.H., and Toronto that will provide important new information as to what the technique can really achieve. All the while, researchers continue to refine surgical techniques to implant the electrodes. They also want to develop an understanding of how to optimize the precise amount of stimulation for a given patient while also learning about short- and long-term effects of deep-brain stimulation on depression.

Some new avenues of investigation are exploring different sites for stimulating brain circuits because the subcallosal cingulate area may not prove ideal for every patient. Volker Coenen and Thomas Schläpfer, both then at the University of Bonn in Germany, have achieved rapid improvement in a small number of patients in a region called the medial forebrain bundle. Other regions deep within the brain are also potential targets—the ventral striatum, the anterior limb of the internal capsule, the inferior thalamic peduncle and the habenula.

Testing different brain locations that may be involved with depression may allow for the selection of targets based on specific symptoms, as is done in Parkinson's. Patients with depression have varying combinations of symptoms that are reflected in a different pattern of brain scans. Looking at these patterns of aberrant brain activity already shows promise for making decisions about whether drug or cognitive-behavior therapy is the best option—and it may eventually do so as well for deep-brain stimulation.

Attempts to refine these techniques must be supplemented by more basic research to understand how the technology changes brain functioning. After a prolonged period of stimulation, antidepressant effects can persist for days or weeks even when the stimulation is turned off. The brain may undergo long-lasting alterations—a process known as neuroplasticity—as brain circuits change as a consequence of stimulation. Indeed, rodent studies point to evidence that deep-brain stimulation alters the activity of large networks of brain circuits and that it may also induce the birth of new neurons in the hippocampus, a process that other work has shown is important both for forming new memories and for easing depression. If the therapy is discontinued for an extended period, however, symptoms return, suggesting that the brain does not permanently heal itself through this therapy.

The ability to control electric circuits with deep-brain stimulation has generated interest in using the technique for other psychiatric maladies, including bipolar disorder, obsessive-compulsive disorder, Tourette's syndrome, and alcohol and drug addiction. Deep-brain stimulation has potential for treating patients who have failed other options and whose disorder has been linked to abnormally functioning circuits.

Lozano's group has recently applied deep-brain stimulation to the same subcallosal target used in depression to treat severe chronic anorexia nervosa. In some patients who have lived with the eating disorder for 10 years or more, deep-brain stimulation eased symptoms of depression, anxiety and obsessiveness. Subjects became less anxious about eating and gaining weight and were able to participate in therapeutic programs. In about half of the 18 cases, the change in patients' moods enabled them to return to normal weight a year later.

The results so far point in new directions. Growing understanding of the functioning of brain circuits is helping to explain abnormal brain activity. With this knowledge, neurosurgeons should be able to place electrodes in strategic locations deep in the brain to give needed relief to depressed patients who fail to respond to drugs and talk therapy, as well as to people grappling with a range of other disorders, from anorexia to Alzheimer's. SA

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NUCLEAR FALLOUT

The Swallows of Fukushima

We know surprisingly little about what low-dose radiation does to organisms and ecosystems. Four years after the disaster in Fukushima, scientists are beginning to get some answers

By Steven Featherstone

Photographs by Steven Featherstone

BARN SWALLOWS in the zone around Japan's Fukushima Daiichi nuclear power plant are good subjects for studying the effects of radioactive contamination on living things.

DESERTED business district in the town of Okuma (*opposite page*).

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UNTIL A REACTOR AT THE CHERNOBYL NUCLEAR POWER PLANT EXPLODED ON APRIL 26, 1986, spreading the equivalent of 400 Hiroshima bombs of fallout across the entire Northern Hemisphere, scientists knew next to nothing about the effects of radiation on vegetation and wild animals. The catastrophe created a living laboratory, particularly in the 1,100 square miles around the site, known as the exclusion zone.

In 1994 Ronald Chesser and Robert Baker, both professors of biology at Texas Tech University, were among the first American scientists allowed full access to the zone. "It was a screaming place—really radioactive," Baker recalls. "We caught a bunch of voles, and they looked as healthy as weeds. We became fascinated with that." When Baker and Chesser sequenced the voles' DNA, they did not find abnormal mutation rates. They also noticed wolves, lynx and other once rare species roaming around the zone as if it were an atomic wildlife refuge. The Chernobyl Forum, founded in 2003 by a group of United Nations agencies, issued a report on the disaster's 20th anniversary that confirmed this view, stating that "environmental conditions have had a positive impact on the biota" in the zone, transforming it into "a unique sanctuary for biodiversity."

Five years after Baker and Chesser combed the zone for voles, Timothy A. Mousseau visited Chernobyl to count birds and found contradicting evidence. Mousseau, a professor of biology at the University of South Carolina, and his collaborator Anders Pape Møller, now research director at the Laboratory of Ecology, Systematics and Evolution at Paris-Sud University, looked in particular at *Hirundo rustica,* the common barn swallow. They found far fewer barn swallows in the zone, and those that remained suffered from reduced life spans, diminished fertility (in males), smaller brains, tumors, partial albinism—a genetic mutation—and a higher incidence of cataracts. In more than 60 papers published over the past 13 years, Mousseau and Møller have shown that exposure to low-level radiation has had a negative impact on the zone's entire biosphere, from microbes to mammals, from bugs to birds.

Mousseau and Møller have their critics, including Baker, who argued in a 2006 *American Scientist* article co-authored with Chesser that the zone "has effectively become a preserve" and that Mousseau and Møller's "incredible conclusions were supported only by circumstantial evidence." But their research and the outcome of the debate about the effects of low-grade radiation have the potential to inform everything from how we respond to nuclear disasters to nuclear energy policy in general.

Almost everything we know about the health effects of ionizing radiation comes from an ongoing study of atomic bomb survivors known as the Life Span Study, or LSS. Safety standards for radiation exposures are based on the LSS. Yet the LSS leaves big questions about the effects of low-dose radiation exposure—exactly the conditions that exist in Chernobyl—unanswered. Most scientists agree that there is no such thing as a "safe" dose of radiation, no matter how small. And the small doses are the ones we understand the least. The LSS does not tell us much about doses below 100 millisieverts (mSv), and it tells us nothing about radioactive ecosystems. For instance, how much radiation does it take to cause genetic mutations, and are these mutations heritable? What are the mechanisms and genetic biomarkers for radiation-induced diseases such as cancer?

The triple meltdown at the Fukushima Daiichi nuclear power plant in March 2011 created another living lab where Mousseau and Møller could study low doses of radiation, replicating their Chernobyl research and allowing them "much higher confidence that the impacts we're seeing are related to radiation and not some other factor," Mousseau says. Fukushima's 310-square-mile exclusion zone is smaller than Chernobyl's but identical in other ways. Both zones contain abandoned farmland, forests and urban areas where radiation levels vary by orders of magnitude over short distances. And they would almost certainly gain access to Fukushima more quickly than scientists could get into Soviet-run Chernobyl. In short, Fukushima presented an opportunity to settle a debate.

Within months of Fukushima, Mousseau and Møller were

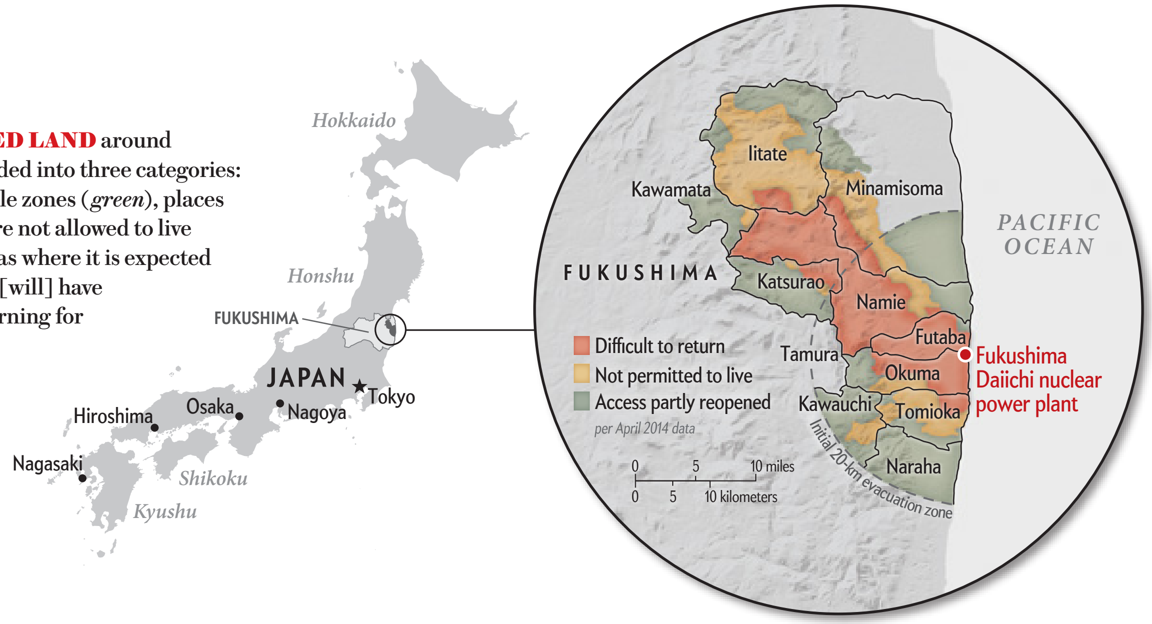
IN BRIEF

In the nearly three decades since the Chernobyl nuclear disaster, a consensus has emerged that the flora and fauna of the contaminated region have fared surprisingly well despite long-term exposure to background radiation.

Yet this consensus is based on very limited data. Our understanding of the effects of low-dose radiation on living things remains incomplete.

The meltdown at Japan's Fukushima Daiichi reactor four years ago provided another chance to study these effects. The first results suggest that fallout from Fukushima has harmed the biota in ways we are just beginning to see.

CONTAMINATED LAND around Fukushima is divided into three categories: relatively accessible zones (*green*), places where residents are not allowed to live (*yellow*), and "areas where it is expected that the residents [will] have difficulties in returning for a long time."



SOURCE: SAFECAST http://blog.safecast.org

counting birds in the contaminated mountain forests west of the smoldering nuclear plant, but they could not get into the zone itself to see what was happening to the barn swallows. Finally, in June 2013, Mousseau was among the first scientists allowed full access to Fukushima's exclusion zone.

Sensitivity to radiation varies greatly in living things and among individuals of the same species, which is one reason it is important not to extrapolate from butterflies to barn swallows or from voles to humans. Butterflies are particularly radiosensitive, Mousseau says. In August 2012 the online journal Scientific Reports published a paper examining the effects of Fukushima's fallout on the pale grass blue butterfly. (*Scientific American* and Scientific Reports are Nature Publishing Group affiliates.) Joji Otaki, a biology professor at the University of the Ryukyus in Okinawa, revealed that butterflies collected near Fukushima two months after the disaster had malformed wings, legs and eyes. Mousseau and Møller's surveys of insects in Chernobyl and Fukushima show drop-offs in butterflies as a group. But Otaki's paper adds an important new wrinkle. When he bred mutant Fukushima butterflies with healthy lab specimens, the rate of genetic abnormalities increased with each new generation. Otaki is the first scientist to rigorously demonstrate the accumulation of genetic mutations over multiple generations of a creature living in Fukushima.

Mousseau believes that this phenomenon, the accumulation of genetic mutations, is a hidden undercurrent eroding the health of radioactive ecosystems, occasionally revealing itself in the offspring of mutant butterflies or barn swallows with partial albinism. Even Baker agrees with Mousseau on Otaki's conclusions: "Clearly, there's something going on with the butterflies that's radiation-induced. Multigenerational exposure does result in an altered genome."

Before he booked his flight to Tokyo, Mousseau tried to locate a Japanese supplier of lead bricks that he needed for a new set of experiments. He could not find enough in Japan, however, so he flew to Tokyo with 600 pounds of lead bricks crammed into eight suitcases. I met him and his postdoctoral fellow, an Italian named Andrea Bonisoli Alquati, at the airport and helped them load the bricks into the back of a rental car. Then we drove to our hotel in Minamisoma, north of the Fukushima power plant.

The car rattled over earthquake-heaved roads as we passed through one deserted town after the next, meandering north toward the nuclear plant. Mousseau scanned shuttered storefronts and empty houses for barn swallow nests as he drove. Barn swallows are ideal scientific subjects because they are philopatric, meaning the birds tend to return to breed in the same locations over a lifetime. Much is already known about them under normal conditions, and they share similar genetic, developmental and physiological characteristics with other warm-blooded vertebrates. The barn swallow is the proverbial canary in the coal mine, except the coal mine in question is radioactive. Mousseau counted about a dozen old nest "scars," crescent-shaped blots of mud plastered under eaves, but not one new nest.

"They were showing such negative effects the first year," he said. "I figured it'd be very difficult to find them this year."

A few miles west of the nuclear plant, we hit the border of the exclusion zone: a barricade manned by two surprised police officers, who waved their arms and shouted "U-turn!" at us through their face masks. Mousseau's permits were not yet valid, so he turned around.

"I just can't believe there aren't any active barn swallow nests," he said on the way back to the detour point. He glanced up at a lone wagtail perched on a telephone wire. "I don't see any butterflies flying. Don't see any dragonflies flying. It's really a dead zone."

Fukushima offers a vanishingly rare glimpse of an ecosystem's early response to radioactive contamination. Little is known about generations of Chernobyl's voles and barn swallows, not to mention other critters. Anecdotal reports point to massive die-offs of plants and animals, but no details exist about their recovery. Did some species evolve a heightened ability to repair DNA damaged by radiation? Studying Fukushima's ecosystem, right now, is critical to developing predictive models that could explain how adaptations to low-level radiation exposure, as well as the accumulation of genetic damage, progress over time.

Map by XNR Productions

Mousseau regretted that he could not get access to the zone immediately after the accident. "We'd have much more rigorous data on how many swallows were there, how many disappeared," he said after we arrived at the hotel. "Are the ones that are coming back the resistant genotypes, or are they just lucky in some way?"

The next day, with Mousseau's permits validated, a line of officers waved our car through the barricades and into the exclusion zone. Then Mousseau drove straight to the gates of the Fukushima Daiichi power plant. He planned to work his way along the coastal plain, from ground zero to the abandoned towns of Futaba, Okuma and Namie, counting every barn swallow, plotting the location of every nest and capturing as many of the birds as possible. "Every data point we get here is absolutely invaluable," he said to Bonisoli Alquati.

A mile from the nuclear plant Bonisoli Alquati spotted a barn swallow perched on a wire near a house. A nest made with fresh mud sat on a ledge inside the garage. Radiation levels peaked at 330 microsieverts per hour, more than 3,000 times above normal background radiation and the highest level Mousseau has ever recorded in the field.

"In 10 hours, you'll get your annual dose," said Bonisoli Alquati, referring to the amount of background radiation the average person in the U.S. receives in an entire year. He and Wataru Kitamura, a faculty member in the environmental studies department at Tokyo City University, strung up mist nets, which resembled oversized volleyball nets made of nylon mesh, over the garage's entrance. Then they waited—and waited—for the swallow to fly into them. Mousseau did not want to waste time trying to catch one bird, even if it was living next to a hotspot. So they packed up the mist nets and drove into Futaba.

Futaba is a ghost town, off-limits to all except former residents, who are allowed to return for only a few hours every month to check on homes and businesses. A sign over the town's commercial center reads, "Nuclear Power: Bright Future of Energy." Radiation levels on the main street were no worse than many contaminated areas outside the zone. But contamination is only one of Futaba's problems. The magnitude 9.0 earthquake left few structures unscathed. Many buildings tilted on their foundations. Some had completely collapsed. We rolled down the street, crunching over ceramic roof tiles and broken glass. Rats and ravens poked around piles of trash and food rotting on store shelves. Peering through binoculars, Kitamura counted six swallows circling near a smashed sporting goods shop.

"Set up the nets and poles!" he shouted.

Kitamura and Bonisoli Alquati crouched outside the store, a mist net bunched loosely between them. Swallows swooped and chattered overhead. Suddenly, a pair darted into the shop. The men leaped to their feet, stretching the net over the entrance and trapping the birds inside. Bird by bird, it took two hours to catch and sample all six swallows. Before releasing the birds, Mousseau fitted them with tiny thermoluminescent dosimeters (TLDs) to track their radiation dose. Down by the Futaba train station, where radiation levels were 10 times higher, they captured two more swallows.

Later that night the team ate dinner together in Minamisoma. Everybody was exhausted. I asked Kitamura what it was like to see the zone firsthand. "I feel a kind of sadness," he said, "because nothing has happened after the accident." Troubled by what he saw in Futaba, he had no interest in going back.

The Japanese government initially vowed to clean up 11 of the most severely contaminated municipalities in Fukushima Prefecture by March 2014. Their goal was to reduce annual dose rates to 1 mSv, the limit for the general public, according to the recommendations of the International Commission on Radiological Protection. But the bulk of the cleanup effort has so far been

POLICE OFFICER inspects permits and passports for entry into the Fukushima restricted zone (*1*). Bicycles lie abandoned on a damaged street in Futaba (*2*). Women in Futaba wait while family members inspect what remains of their seafood shop (*3*). A tsunami-damaged diner in the restricted zone (*4*).

focused on stabilizing the damaged reactors at the nuclear plant, which continue to leak radiation into the Pacific. Japanese authorities no longer have a specific time frame for decontamination. Instead they have set 1 mSv per year as a long-term goal and are now encouraging some of the 83,000 evacuees to return to places with annual dose rates of up to 20 mSv, equivalent to the commission's dose limit for nuclear workers. The ruling party in Japan recently issued a report acknowledging that many contaminated areas will not be habitable for at least a generation.

This goalpost moving underscores the gap between our knowledge of the effects of low-dose radiation and public policy governing—among other things—nuclear cleanup protocols. Although scientists have not determined a "safe" dose of radiation, Japanese administrators need a target number to craft decontamination and resettlement policies, so they rely on advisory bodies such as the International Commission on Radiological Protection and imperfect studies such as the LSS.

"You have to ultimately set some arbitrary limits," says David Brenner, director of the Center for Radiological Research at Columbia University. "Arbitrary because we don't know what the risks are. More arbitrary because it's probably not a yes/no, safe/not safe thing anyway." Brenner's research shows evidence for increased rates of cancer associated with annual doses as low as 5 mSv. Below this arbitrary threshold, there is no firm evidence for or against direct health risks in humans, although Mousseau and Møller have observed negative effects in plant and animal populations. Of the Fukushima residents exposed to radiation in the four months after the disaster, 97 percent received a dose of less than 5 mSv. "Once you get down to these sorts of doses, you have to rely on best understandings of mechanisms," Brenner says, "and that's pretty limited."

In a residential neighborhood on the outskirts of Namie, Bonisoli Alquati spotted a barn swallow nest wedged in a narrow alley between two houses. It was the first active nest he had seen after a disappointing day of cruising the deserted districts around Futaba and Namie, counting dozens of empty nests and scars. Counting nests before the rain washes them all away is crucial to establishing a baseline for what swallow populations were before the accident, but Mousseau also needed samples from live birds for his lab work. The nest in the alley contained three chicks, the first he found in the zone, and three undeveloped eggs. "This is an important nest," Mousseau said. A recorded voice crackled over the public address system, echoing eerily across the misty hills and fallow rice paddies: the zone would close in one hour.

Bonisoli Alquati sat in the front seat of the car. He scooped a chick out of a plastic container and measured it with various

BIOLOGIST Andrea Bonisoli Alquati scrapes samples of swallow droppings from a garage floor near Futaba (*1*). Bonisoli Alquati takes a blood sample from a swallow to be examined for evidence of genetic damage and oxidative stress (*2*). Timothy A. Mousseau holds a swallow captured in Okuma (*3*). Mousseau releases a barn swallow in Futaba (*4*).

tools. Puffing on the downy underside of the chick's wing, he exposed a patch of skin and lanced it with a needle. Some of the blood went into a capillary tube; some got smeared on a glass slide. Then he cinched the chick in a canvas sack and lowered it into the "oven," a stack of lead bricks strapped together with duct tape. The bricks formed a shielded chamber, allowing Mousseau to measure the whole-body burden of individual birds without background radiation muddying the result.

"Our objective is to be able to look at individual birds from one year to the next and to determine whether the probability of survival is related to the dose they receive," he said. "If we really want to get at mechanisms of genetic variation and radiosensitivity and how they impact individuals, then it's necessary to do this finer-scale dosimetry."

But radiation levels in this spot were too hot for accurate measurements. Mousseau moved the car down the street and reset the gamma spectrometer. After a few minutes, it displayed a distinct signal for cesium 137 contamination, the main isotope in Fukushima's fallout. The chick, perhaps a week old, was radioactive.

Police stopped Mousseau's car every day to scrutinize his permits. The only thing I understood during these tense exchanges was *tsubame,* the Japanese word for "barn swallow." The utterance of *tsubame* was usually followed by puzzled smiles. Barn swallows are omens of good fortune in Japan. Many people nail little wooden platforms over the doors of their houses to attract the birds. In the zone, the platforms, like the houses, were all empty.

Each day after the zone closed, Mousseau and Bonisoli Alquati

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worked well into the night, capturing barn swallows in clean areas north of Fukushima to establish a control group. Clean is a relative term. Background radiation in Minamisoma, which was evacuated during the disaster, is still twice that of normal. Still, after we spent all day in the zone, Minamisoma's tidy neighborhoods, identical to those of Namie, Futaba and Okuma, felt like a parallel universe. It was strange to find barn swallow nests overflowing with fat, peeping chicks. Curious neighbors often came out to watch Mousseau and Bonisoli Alquati net the birds. Invariably, they offered us tea and cakes and politely asked about radiation.

"Last year one of the striking things going from house to house was that people were asking us, 'Is it safe or not? Should we live here?'" Bonisoli Alquati recalled. "That's for the politicians to say. I tell them we're there for the birds."

On Mousseau's last day in Japan, he spotted an active barn swallow nest on a gritty side street in Kashima. It was plastered to a light fixture in the portico of an empty home. Mousseau received permission from a neighbor to net the birds. A member of the local river society, he said he was glad somebody was investigating the radioactive contamination because the government was not. "Always secret, the government," he said, complaining about fallout washing into the river. Koi fish caught there registered 240,000 becquerels of cesium per kilogram, he said. People do not eat these fish, which is fortunate, because the radiation limit for fish consumption in Japan is 100 becquerels per kilogram.

Other neighborhood residents asked Mousseau to survey the street with his dosimeter. He obliged, scribbling figures—all well above normal background radiation levels—on a scrap of paper, which the man from the river society accepted with a solemn nod. As we packed the nets in preparation to leave, an old woman held out a package of mandarin oranges. She said something to me that translated as "safe to eat."

"I'm sorry," I said. "I can't help you."

The old woman proffered the oranges again, and I realized that she was not asking a question; she was trying to reassure me that her gift was not contaminated by Fukushima.

"Safe," she said, smiling. "From Nagasaki."

Forty percent of us will one day be diagnosed with some form of cancer. If there is a signal hidden in the noise of this sobering statistic, one that might point to low-dose radiation-induced cancers, it is too faint for epidemiologists to hear. The big questions about low-dose radiation will eventually be answered by researchers studying "radiation-induced chromosome damage, or radiation-induced gene expression, or genomic instability," Brenner says. This is the direction Mousseau and Møller are beginning to take with their research on barn swallows.

"Unfortunately, tumors don't tell us if they were caused by radiation or something else," Mousseau says. If he had enough funding, Mousseau would sequence the DNA of every swallow that he fitted with a TLD in the field. By comparing the results with individual dose estimates, he might be able to locate genetic biomarkers for radiation-induced diseases.

Last November, Mousseau made his 12th trip to Fukushima, 18 months after I accompanied him to the zone. Mousseau and Møller have published three papers demonstrating steep declines in Fukushima's bird populations. Mousseau says that the latest census data, which they are preparing to publish in the *Journal of Ornithology,* provide "pretty striking" evidence for continued declines, "with no evidence of a threshold effect." But for some reason, radiation appears to be killing off birds in Fukushima at twice the rate it is in Chernobyl. "Perhaps there is a lack of resistance, or there is an increased radiosensitivity in Fukushima's native populations," Mousseau says. "Perhaps Chernobyl birds have evolved resistance to some degree, or the ones that are susceptible have been weeded out over the past 26 years. We don't really know the answer to that, but we're hoping to get to it." The answer might be found in the blood of the barn swallows that Mousseau and Bonisoli Alquati collected on our trip. A preliminary analysis of those samples does not reveal any evidence for a significant increase in genetic damage, although it is still too early to tell. Mousseau needs many more samples from barn swallows in the most contaminated areas, where populations are crashing.

Although Mousseau and Møller's initial findings afford a compelling glimpse of a troubled ecosystem in Fukushima, the 2014 report by the U.N. Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) echoes its earlier assessment of the Chernobyl disaster, declaring that radiation effects on "non-human biota" in highly contaminated areas are "unclear" and are "insignificant" in less contaminated ones.

"We're doing basic science, not toxicology, but UNSCEAR hasn't gone to the trouble of either asking us about our work or finding someone to interpret our findings," Mousseau says. "They set the standard for human health, and they're ignoring a large portion of potentially relevant information."

He says the evidence being ignored is substantial. "In my years of experience at Chernobyl and now Fukushima, we've found signals of the effects of increased mutation rates in almost every species and every network of ecological processing that we've looked at," Mousseau says. "It's all there, just waiting to be observed, described and published."

Baker has no plans to conduct research in Fukushima, but he recently sequenced DNA from a different genus of vole from Chernobyl. The new data appear to support Mousseau's and Otaki's conclusions that elevated mutation rates are linked to radiation exposure. The consequences of multigenerational exposure, whether or not it diminishes an animal's fitness or reproductive capabilities or causes birth defects or cancers in future generations, are still unclear. "We need to keep doing the genomic research," Baker says, "because that's where the real story is." SA

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FROM OUR ARCHIVES

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scientificamerican.com/magazine/sa

MORE TO EXPLORE
For more recommendations and an interview with author Jim Bell, go to ScientificAmerican.com/feb2015/recommended

Melting Away: A Ten-Year Journey through Our Endangered Polar Regions

by Camille Seaman.
Princeton Architectural Press, 2014 ($55)


ROSS SEA, Antarctica, in 2006

CAMILLE SEAMAN

The steady disappearance of Earth's polar ice is illustrated beautifully, but devastatingly, in this large-format book. Seaman's photographs, shot over a period of roughly a decade, document the architectural wonder of icebergs, many of which are visibly diminishing in response to warming temperatures. Playful penguins, majestic polar bears and other arctic creatures also appear here, but, as Seaman shows, their habitats are shrinking rapidly. She accompanies her pictures with essays tracing the changes she has witnessed.

The Interstellar Age: Inside the Forty-Year Voyager Mission

by Jim Bell. Dutton, 2015 ($27.95)

The twin Voyager space probes, launched by NASA in 1977, have traveled farther into the cosmos than any other human-made machine. Now about 19.5 billion kilometers from home, Voyager 1 became the first spacecraft to exit the solar system in 2013. Voyager 2 should follow this year. Their mission was not just to visit outer planets that people had never seen up close but to be emissaries to the universe for Earth's citizens. Both craft carried "golden records" loaded with pictures and sounds—from whale songs to Bach to Chuck Berry—to represent our planet to any extraterrestrial beings who might encounter them. Planetary scientist Bell, who worked on the mission from the time he was an undergraduate, chronicles the two probes' journeys, their revelations about our solar system, and the many people who have dedicated their careers to the mission.

The Powerhouse: Inside the Invention of a Battery to Save the World

by Steve LeVine. Viking, 2015 ($28.95)

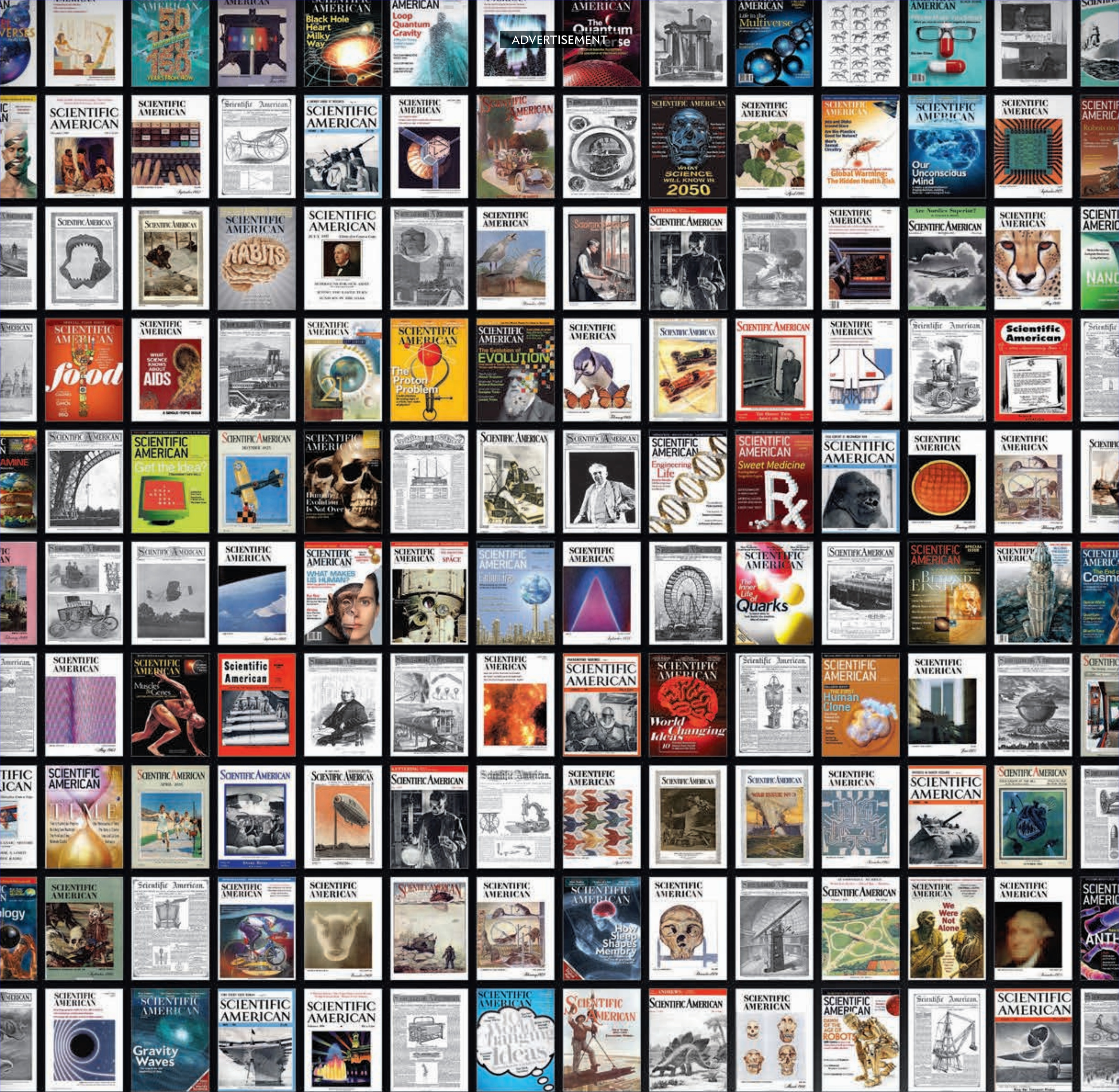
Why didn't electric cars win the race for vehicular dominance at the beginning of the 20th century? After all, they were cleaner and easier to use than cars burning gasoline. The answer, in a word, is batteries. Now, in the early years of the 21st century, the electric car is making a comeback of sorts, but the challenge remains the same—how to get more juice out of battery chemistry. Journalist LeVine examines the race to develop a better battery at Argonne National Laboratory and provides a history of battery design in recent decades. With the pace, if not quite the payoff, of a thriller, he also reveals how the very human foibles of scientists and entrepreneurs, as well as fundamental physics and chemistry, stand in the way of such efforts, which, if successful, could result in a new global industry and attendant jobs.

—*David Biello*

Island on Fire: The Extraordinary Story of a Forgotten Volcano That Changed the World

by Alexandra Witze and Jeff Kanipe.
Pegasus Books, 2015 ($26.95)

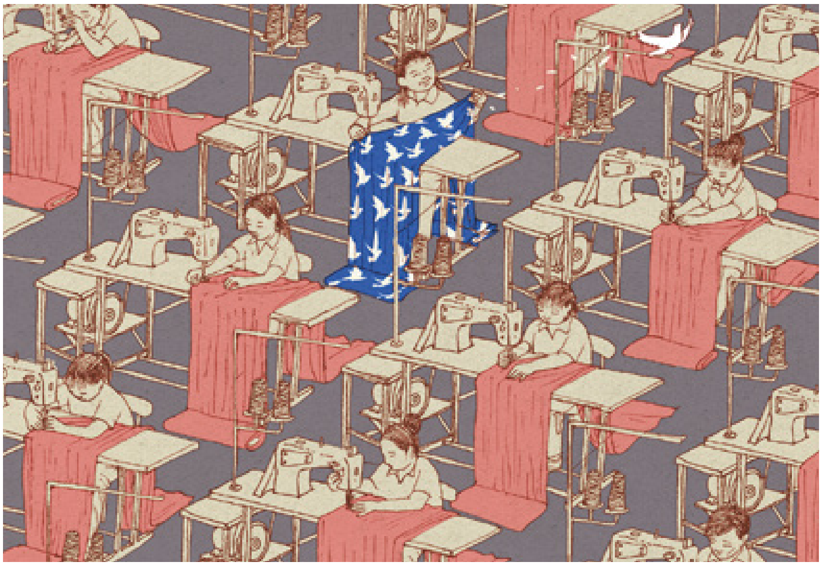
In 1783 the Icelandic volcano Laki erupted, with catastrophic consequences. The ash it pumped into the atmosphere blanketed most of the Northern Hemisphere in a sun-blocking fog, causing one of the most severe winters for hundreds of years. Many across Europe froze to death, and crops withered, leading to mass famine. In Africa, the monsoons failed to come, and the Nile did not flood as usual, causing one sixth of Egypt's population to starve or leave the country. The official death tally in Iceland from Laki was around 9,000, but some experts suggest the global toll was much higher. Journalists Witze and Kanipe tell the scientific and human story of Laki and predict that because a Laki-scale eruption happens on average every 200 to 500 years in Iceland, a similar event is not unlikely.




SCIENTIFIC AMERICAN
The Proton Problem

Viewing the world with a rational eye

Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com). His new book, *The Moral Arc*, is out now (Henry Holt, 2015). Follow him on Twitter @michaelshermer



A Moral Starting Point

How science can inform ethics

Why is it wrong to enslave or torture other humans, or take their property, or discriminate against them? That these actions are wrong, almost no one disputes. But why are they wrong?

For an answer, most people turn to religion (because God says so), or to philosophy (because rights theory says so), or to political theory (because the social contract says so). In *The Moral Arc,* published in January, I show how science may also contribute an answer. My moral starting point is *the survival and flourishing of sentient beings.* By survival, I mean the instinct to live, and by flourishing, I mean having adequate sustenance, safety, shelter, and social relations for physical and mental health. By sentient, I mean emotive, perceptive, sensitive, responsive, conscious, and, especially, having the capacity to feel and to suffer. Instead of using criteria such as tool use, language, reasoning or intelligence, I go deeper into our evolved brains, toward these more basic emotive capacities. There is sound science behind this proposition.

According to the Cambridge Declaration on Consciousness—a statement issued in 2012 by an international group of prominent cognitive and computational neuroscientists, neuropharmacologists and neuroanatomists—there is a continuity between humans and nonhuman animals, and sentience is the most important common characteristic. The neural pathways of emotions, for example, are not confined to higher-level cortical structures in the brain but are found in evolutionarily older subcortical regions. Artificially stimulating the same regions in human and nonhuman animal brains produces the same emotional reactions in both. Attentiveness, decision making, and the emotional capacity to feel and suffer are found across the branches of the evolutionary tree. This is what brings all humans and many nonhuman animals into our moral sphere.

The arc of the moral universe really is bending toward progress, by which I mean *the improvement of the survival and flourishing of individual sentient beings.* I emphasize the individual because that is who survives and flourishes, or who suffers and dies, not the group, tribe, race, gender, state or any other collective. Individual beings perceive, emote, respond, love, feel and suffer—not populations, races, genders or groups. Historically, abuses have been most rampant—and body counts have run the highest—when the individual is sacrificed for the good of the group. It happens when people are judged by the color of their skin, or by their gender, or by whom they prefer to sleep with, or by which political or religious group they belong to, or by any other distinguishing trait our species has identified to differentiate among members instead of by the content of their *individual* character.

The rights revolutions of the past three centuries have focused almost entirely on the freedom and autonomy of individuals, not collectives—on the rights of persons, not groups. Individuals vote, not genders. Individuals want to be treated equally, not races. In fact, most rights protect individuals from being discriminated against as individual members of a group, such as by race, creed, color, gender, and now sexual orientation and gender preference.

The singular and separate organism is to biology and society what the atom is to physics—a fundamental unit of nature. The first principle of the survival and flourishing of sentient beings is grounded in the biological fact that it is the discrete organism that is the main target of natural selection and social evolution, not the group. We are a social species, but we are first and foremost individuals within social groups and therefore ought not to be subservient to the collective.

This drive to survive is part of our essence, and therefore the freedom to pursue the fulfillment of that essence is a natural right, by which I mean it is universal and inalienable and thus not contingent only on the laws and customs of a particular culture or government. As a natural right, the personal autonomy of the individual gives us criteria by which we can judge actions as right or wrong: Do they increase or decrease the survival and flourishing of individual sentient beings? Slavery, torture, robbery and discrimination lead to a decrease in survival and flourishing, and thus they are wrong. QED. SA

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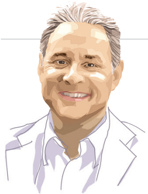
HENRY HOLT AND *SCIENTIFIC AMERICAN* ARE AFFILIATES

Illustration by Izhar Cohen



Steve Mirsky has been writing the Anti Gravity column since a typical tectonic plate was about 34 inches from its current location. He also hosts the *Scientific American* podcast Science Talk.

Insect Aside

Urban bugs pick up after all us slobs

In this space last September, I broached the culturally charged subject of eating insects. Eating them on purpose. Insects are plentiful, a great source of protein, easy to raise and much more environmentally friendly than the more familiar (to Westerners, anyway) vertebrates widely available at your deli counter: cows, chickens and pigs. Let's turn that plague into a plate of locusts.

I come not to bury bugs but to praise them further. Because arthropods can be good on both sides of the food equation: a study by North Carolina State University researchers working in New York City quantified the food waste disposal ecosystem service provided by our hungry six-legged compatriots. And the finding is not a throwaway with regard to what we throw away. The results, published online in early December in the journal *Global Change Biology,* revealed that insects—and other six-legged critters that perhaps only an entomologist would recognize as being noninsects—in a single 400-square-meter street median could be consuming annually as much as 6.5 kilograms of tossed, dropped and, if there's a bar close by, regurgitated food. (One reason the neon lights are bright on Broadway is so you have enough visual input to tiptoe your way past the piles of semidigested pizza and chicken wings near drinking establishments late on a Friday or Saturday night.) And that's assuming the insects take the winters off, which would really mess up Aesop's ants versus grasshopper auditing results.

To do their investigation, the genteel Southern scientists visited my hometown and proceeded to dump garbage in dozens of sites, within parks and in the aforementioned street medians. Their test materials, "expected to attract fat-, sugar-, and protein-feeding animals," were Ruffles Original potato chips, Nabisco Nilla Wafers and Oscar Mayer hot dogs. (Oh, I wish I was an Oscar Mayer weiner, part of this here urban garbage caper, 'cause if I was some junk food in this study, I'd get published in a scientific paper.)

Six and a half kilograms of food per street median may not sound like all that much, so the researchers extended the area to illustrate the cumulative effect: "We estimated that arthropods in the medians of Manhattan's Broadway and West St. could remove 600–975 kg (dry weight) of food waste per year—equivalent to approximately 60,000 hot dogs, 200,000 Nilla Wafers, or 600,000 Ruffles potato chips." We humans make a lot of garbage, relegating the insect waste removal total to what the scientists called "modest but notable. Without these animals, more littered food waste would accumulate in cities." Which means that insects are eating food that otherwise would be attracting and nourishing rats. A heartfelt thank-you, insects.

One reason the North Carolinians tested both park sites and street medians was their expectation that the wider array of insect species in parks would be a more efficient trash-digesting community. "Theory and data from natural systems suggest that the magnitude and resilience of this service should increase with biological diversity," they wrote. So they were surprised to find that insects in the less diverse street-median environment actually consumed up to 3.3 times more of the snacks.

Perhaps upper crusty park insects have a more discerning palate, and the study's selections couldn't compete with the plethora of culinary delights available in our emerald spaces. Items such as buried squirrel nuts, street vendor meat and New York's special blend of dog feces surely make our parks a hexapod paradise.

And yet a single organism may account for the medians' superiority at making food disappear—and it's not that quintessential urban insect, the cockroach. Because roaches, like your between-jobs brother-in-law, prefer an extended stay inside your home, not out on the mean streets. No, the key critter for street-median food removal is what is commonly known as the pavement ant.

Of said ant, the study authors explained that, much like my own immigrant ancestors, "this Palearctic species was introduced to North America more than 100 years ago, is common in urban areas, and—consistent with its occurrence in medians—prefers to nest near pavement." Seems that when Emma Lazarus wrote, "Give me your tired, your poor, your huddled masses," she inadvertently invited the ants to the party: their colonies average about 10,000 workers. That's enough ants to make an exterminator cry uncle. SA

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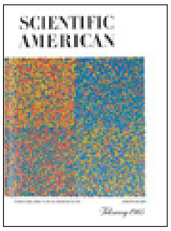
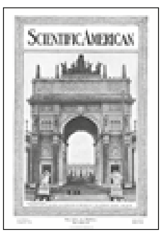


February 1965

Planetwide Tinkering

"The American Association for the Advancement of Science Committee on Science in the Promotion of Human Welfare report, entitled 'The Integrity of Science,' was specifically critical of failures to evaluate ahead of time the broad effects of scientific experiments or technological innovations. On these grounds it cited the widespread use of pesticides and detergents without preliminary tests of their effects on environmental pollution. Two major American military projects came in for similar criticism: Project Starfish, a high-altitude nuclear explosion above the Pacific Ocean, and Project West Ford, an attempt to orbit millions of tiny copper needles as a reflecting layer for military communications. 'Science has developed powers of unprecedented intensity and world scale,' the committee wrote. 'The entire planet can now serve as a scientific laboratory.'"



February 1915

Coast-to-Coast Telephone

"Thirty-nine years ago, in his bedroom in a Boston boarding house, Alexander Graham Bell picked up a crude telephone transmitter and cried: 'Mr. Watson, come here; I want you'; Thomas A. Watson, in the adjoining room, listening at the other end of the wire, heard the first sentence ever transmitted by telephone and, full of excitement, burst into the bedroom to congratulate his associate. Last week, over the same wire, and with a replica of the old instrument, Dr. Bell again called up Mr. Watson. But this time Bell was in New York, in the office of the president of the American Telephone and Telegraph Company, and a whole continent separated him from his former associate, in San Francisco."

Puzzling Sunshine

"Three different hypotheses have been advanced to explain how the sun has for ages been emitting substantially the same quantity of heat, viz.: by chemical reaction, by intra atomic energy (such as is exhibited by radium), and by the attraction of gravitation. Some precise calculations based upon recent data seem to indicate that the last theory, advanced by Helmholtz, is the one that is most tenable. The energy produced by mass falling on the surface of the sun may be calculated as four hundred times less than necessary for the maintenance of solar heat. Hence, there is but one hypothesis left—that of the generation of heat by the contraction of the sun itself; and this alone can and must account for all the heat the sun is radiating."

X-rays for War Work

"Though X-ray work has, even in normal times, become so valuable an aid to the medical practitioner that no up-to-date hospital can do without it, it is even more useful and necessary in warfare. Whenever, for instance, the shape and position of a projectile in the body of a patient are to be ascertained, Roentgen photography will quickly give all the desired information. Special transportable Roentgen outfits [*see photograph*] have been perfected for army hospitals installed at halting places, which generally remain stationary for some time. Beside the X-ray generator, these comprise a current generator, mostly a gasoline dynamo, so as to be independent of any electric installation.—By the Berlin correspondent of the *Scientific American*"

Take a tour of the latest medical technology in 1915 at www.ScientificAmerican.com/feb2015/medicine

MOBILE X-RAY UNIT for German military use in the Great War, 1915

SCIENTIFIC AMERICAN SUPPLEMENT, VOL. LXXIX, NO. 2042; FEBRUARY 20, 1915

February 1865

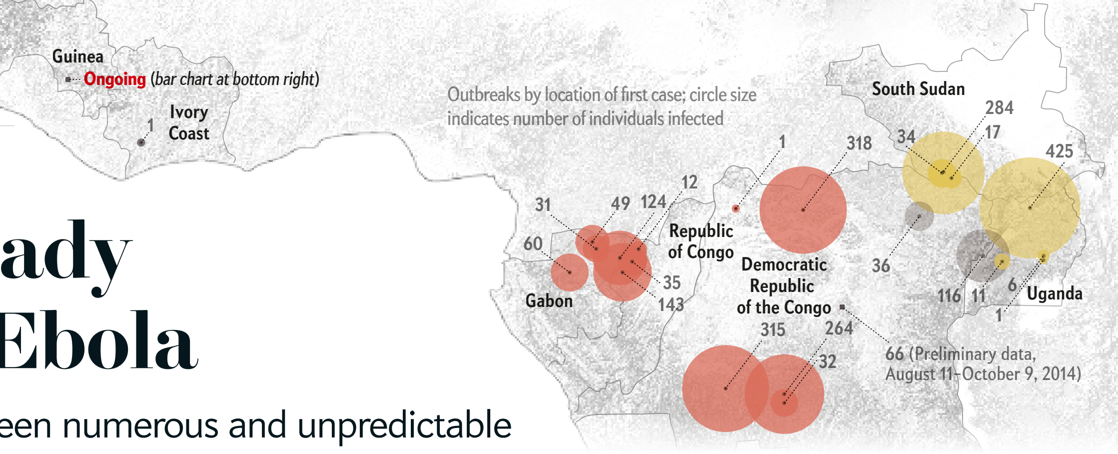
Fighting Smallpox with Cows

"At Naples they vaccinate directly from the cow. The subject has been seriously taken up in Paris, and it is estimated that a good commercial speculation can be made of it. A cow, it is said, will produce 100 pustules each, at 5 francs each, bringing in 500 francs, the cow suffering no deterioration in value. The practice is greatly recommended by the safety it ensures that no other contagion will be communicated along with the cowpox. Smallpox is rather prevalent in and around Paris, and people are becoming anxious on the subject."

Graphic Science

The Steady Rise of Ebola

Outbreaks have been numerous and unpredictable



The Ebola crisis now under way in West Africa is the biggest outbreak of the virus ever, but it is not the first—it is the 23rd since the disease arose in 1976 (*polygons below*). The scourge began in Guinea, distant from earlier cases (*map*), and is by far the largest (*bottom right corner below*). This analysis by University of Oxford researchers of previous outbreaks shows that the death rate has been greater than 33 percent and that there is often more than one cluster of infections, typically because of sick individuals seeking treatment or traveling. Experts worry that without vigorous, sweeping efforts to identify and suppress new outbreaks as soon as they emerge, the virus will become a permanent health risk, erupting unpredictably in Africa and around the world.

—Mark Fischetti

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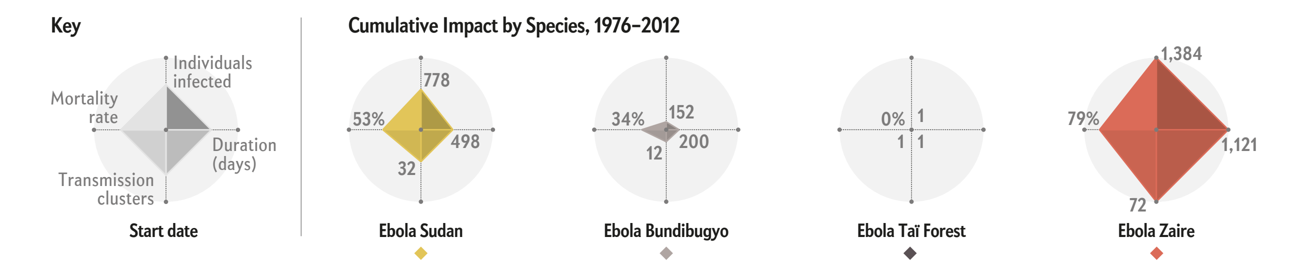
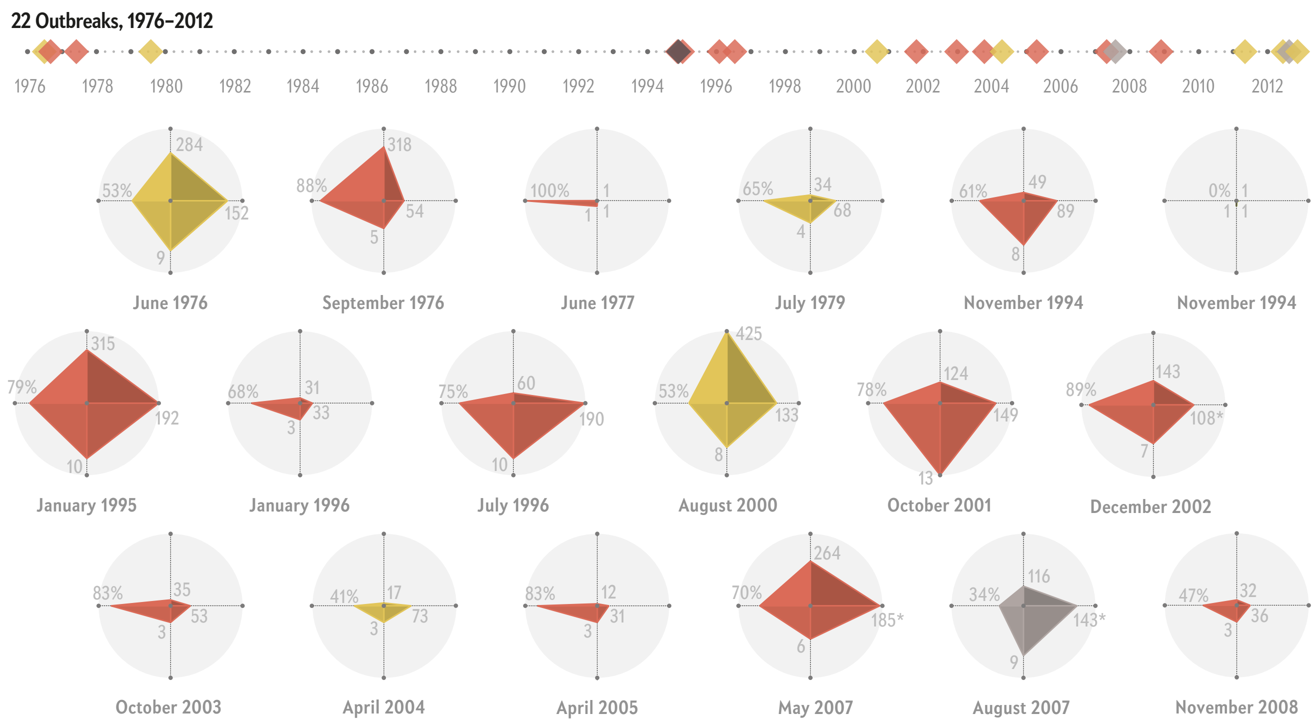
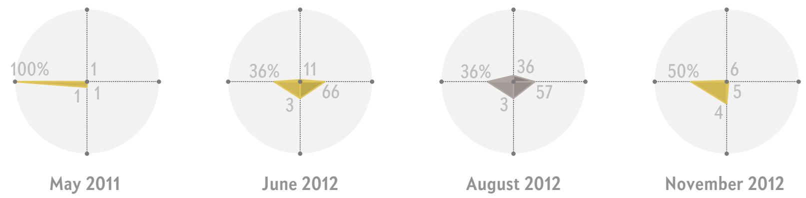
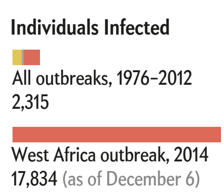
For the latest coverage, see ScientificAmerican.com/feb2015/graphic-science







The 2014 Explosion
The West Africa outbreak dwarfs all others. An unrelated eruption in the Democratic Republic of the Congo ended in October 2014 and killed 49 of 66 victims. (Both involved the Zaire species.)



*Duration not included in primary source. Calculated based on descriptions from supplementary information.

SOURCES: "A COMPREHENSIVE DATABASE OF THE GEOGRAPHIC SPREAD OF PAST HUMAN EBOLA OUTBREAKS," BY ADRIAN MYLNE ET AL., IN *SCIENTIFIC DATA*, VOL. 1, ARTICLE NO. 140042; OCTOBER 23, 2014 (*historical data*); CENTERS FOR DISEASE CONTROL AND PREVENTION (*2013–2014 data*)

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