ENGINEERING
Machines That Change Shape

MEDICINE
An Off Switch for Cancer

NEUROSCIENCE
How to Reach "Vegetative" Patients

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MAY 2014

A CRISIS IN PHYSICS?

IF SUPERSYMMETRY DOESN'T PAN OUT, SCIENTISTS NEED A NEW WAY TO EXPLAIN THE UNIVERSE

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Brain Science

Speaker: Larry Cahill, Ph.D.

Brains "R" Us

How do we work? What makes us tick? For much (but not all) of human history people looked to the gooey, grey organ between your ears for answers. Learn how how our perception of the brain has evolved and how some of our most "modern" ideas about the brain aren't very modern at all.

Sex on the Brain

Overwhelmingly, brain science has ignored gender differences with findings in males assumed to apply equally to females. But it turns out that "sex matters" down to the level of single neurons, even to parts of neurons. Find out why there are entrenched biases against sex difference research in brain science, and why they are, finally, crumbling.

Emotional Memory

What makes the brain a brain (and not a spleen or a pancreas or a lung) is memory, and emotion is arguably the primary sculptor of memory. Studies of emotional memory consequently lie at the heart of brain science. Explore the most dominant theories of emotional memory, and discover how sex matters (yet again) to these theories.

When Brains Fail

The brain is the single most complicated system in the known universe. When human brains fail, they can fail spectacularly, sometimes failing in fascinating ways that challenge some of our most elementary assumptions about who we are. What have we learned about the human brain from studying brain disease? Find out with Dr. Cahill.

Planets

Speaker: David Stevenson, Ph.D.

Planetary Diversity

The Kepler spacecraft has found hundreds of planets and thousands of additional candidates. Exploration of our solar system leads to a view of planets that emphasizes diversity rather than similarity. With so many planets out there, yes, some must be like Earth, but are the most exciting prospects for planets and life forms very different from our home? Absorb the possibilities.

Origin of Earth & Moon

Four and a half billion years ago our own solar system developed from a disk of gas and dust. Get our current understanding of this process and how Earth emerged with the Moon, an atmosphere, oceans, a magnetic field, and conditions for life. Explore how the nature of Earth is inextricably linked to the existence of our satellite companion.

For more info please email Concierge@InsightCruises.com or visit ScientificAmerican.com/travel

Ice Worlds

There is more ice and liquid than rock in our solar system, including some exotic stuff: hot, dense soups of protons and oxygen ions deep under planetary surfaces; rivers and lakes of liquid hydrocarbons, and ice geysers. Find out the details as we explore the structure and dynamics of the large satellites and Pluto.

Jupiter!

Our solar system's largest planet, Jupiter, likely influenced Earth's formation and so is a key to understanding Earth. Delve into Jupiter's internal properties and interior structure, and family of satellites. Get an insider's scoop on the billion dollar Juno mission arriving at Jupiter in July 2016 and learn about Dr. Stevenson's Juno role studying Jupiter's gravity and magnetic fields.

Weather

Speaker: Robert G. Fovell, Ph.D.

How and Why Clouds Form

Clouds are key in the planetary energy balance and water cycle. Historically, they have signaled atmospheric processes to observers. Learn about clouds' characteristics, formation, and function, with details on precipitation, ice, and lightning. We'll look at clouds from all sides, identifying the many ways clouds are essential to Earth and the atmosphere.

How and Why the Winds Blow

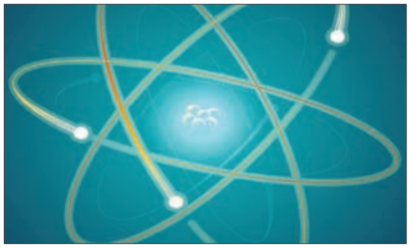
Delve into the role, causes and features of this invisible phenomenon. We'll look at the basics of atmospheric circulation and the complex interactions within the atmosphere that create wind. Learn about local winds (sea breezes), large-scale ones (fronts and cyclones) and legendary severe winds associated with mountains. Hone your knowledge of wind and its impacts.

Severe Storms

Storms impact our wellbeing, homes, cities, and economies. Learn about the causes, formation, and lifecycle of severe storms. Look at supercell thunderstorms and tornadoes, and the role of moisture and vertical wind shear in storms. From squall-lines, bow echoes, and flash flooding to hurricanes, get the latest need-to-know information on these forces of nature.

Understanding Extreme Weather

Synthesizing our knowledge from the three previous sessions, we'll apply these concepts to examples of extreme weather events from the recent past: 2013's devastating Colorado floods. The 2013 Oklahoma tornadoes. 2012's Hurricane Sandy. 1993's epic East Coast Snowstorm. 1991's "Perfect Storm."



Particle Physics

Speaker: James Gillies, Ph.D.

Hunting the Higgs Boson

Particle physics is the study of the smallest indivisible pieces of matter and the forces that act between them. Learn about the particle accelerators, detectors and computing that make this research possible at the Large Hadron Collider, and how hundreds of physicists teamed to hunt the long-sought Higgs boson.

Life after Higgs: What's Next?

Physicists at the Large Hadron Collider announced in 2012 they'd found *a* Higgs boson. But not *the* Higgs boson. What's the difference? Learn what the particular properties of the recently discovered particle could tell us about the nature of the universe, and why physicists don't know yet which Higgs boson they've found.

60 Years of Science for Peace

Sixty years ago, the idea of CERN, the European particle physics laboratory, was born. Hear the interwoven scientific and political stories of CERN's development and how particle physics has evolved from a regional to a global field, with the Large Hadron Collider as its frontier research tool.

Celebrating 25 years of the World Wide Web

"Vague, but exciting," were the words scrawled on Tim Berners-Lee's 1989 proposal for what became the World Wide Web. Hear the story of the Web's birth based on archival material and interviews with the major players, and learn how developments in physics and computing paralleled the development of the Web itself.

Astrobiology

Speaker: Peter Smith, Ph.D.

NASA's OSIRIS-Rex Mission

Learn about NASA's planned OSIRIS-REx mission to rendezvous with an asteroid and chip away samples to return home. Its target, the carbon-rich asteroid Bennu, should offer a peak at the types of organic materials and primitive minerals that existed on Earth when life was first forming.

The Earliest Life on Earth

Delve into the field of astrobiology, which investigates the origin of life on Earth and elsewhere. We'll probe the big questions: Was Earth seeded with life from space? Why is the backbone structure of DNA rarely found in nature? And what did the first microbes eat?

Life on Mars: What Do We Know?

Since the Viking missions of 1976, scientists have searched Mars for signs of life. From evidence of past water to questions of volcanism and methane gas, learn about the many signals that could tell us whether the Red Planet does, or ever did, host life.

Could Life Exist on Europa, Enceladus or Titan?

Some of the most intriguing potential sites for life in our solar system exist not on planets, but on moons with buried liquid oceans and lakes of methane and ethane full of organic materials. Learn why scientists are so interested in Saturn's moons Enceladus and Titan and Jupiter's moon Europa.

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Pre-Cruise Full-Day Tour, August 23rd.

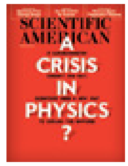
If you love vapor trails in the wild blue yonder and the thrill of takeoff, indulge in a day at the Future of Flight Aviation Center & Boeing Tour in Everett, Washington *and* the Museum of Flight at legendary Boeing Field, Seattle.

Take a 90-minute tour of Boeing's plant, getting a bird's-eye view of the new 787 Dreamliner being assembled. Get the big picture of aviation in the the Museum of Flight, from biplanes to jets. Please join us!

SCIENTIFIC AMERICAN

May 2014 Volume 310, Number 5

ON THE COVER



The Higgs boson was just the beginning. Scientists at CERN's Large Hadron Collider also desperately want to find evidence of supersymmetry, a theory of matter that posits the existence of a brand-new world of fundamental particles. To the surprise of many, no signs have yet been found. When the LHC starts up early next year, the stakes will be high: find supersymmetry, or face a crisis in physics.

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FEATURES

Photograph by Greg Ruffing


We create chemistry that helps thirst love the sea.
By 2025 it is estimated that half of the world's population will lack access to safe drinking water. A sorry state of affairs considering that two thirds of our planet is covered by water. Which is where chemistry steps in. We have developed Sokalan® antiscalant which acts as a scale control dispersant. This means that the equipment that desalts the water can desalt longer, to ensure there is the maximum output of fresh water. When salt water can satisfy our thirst, it's because at BASF, we create chemistry.
To share our vision visit wecreatechemistry.com/water
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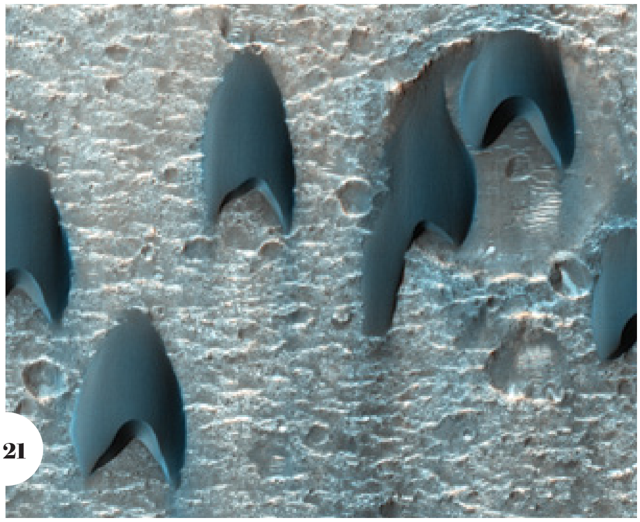

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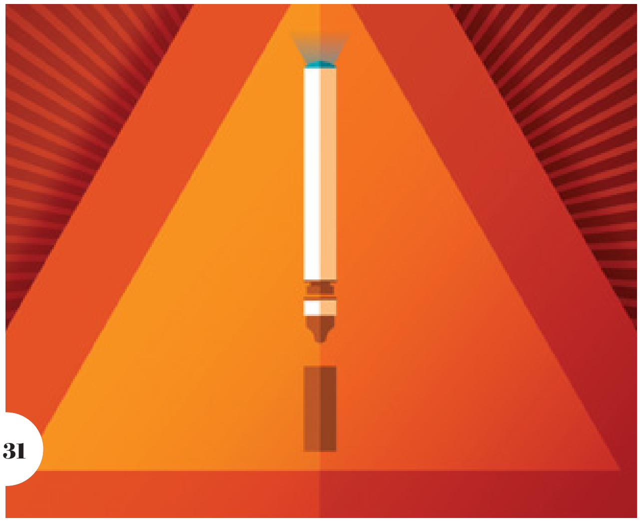

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DEPARTMENTS

ON THE WEB

The Future of the Internet
This year marks the 25th anniversary of the invention of the World Wide Web. Where will the Internet go from here, especially considering the challenges to net neutrality?
Go to www.ScientificAmerican.com/may2014/internet

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INGO ARNDT *Abrams (termite towers)*

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

Does Physics Have a Problem?

IT WAS 2012, AND PHYSICISTS HAD JUST ANNOUNCED THE BIG NEWS: CERN's Large Hadron Collider had delivered what looked like (and was later confirmed to be) a Higgs particle, the capstone of a decades-long search to complete the so-called Standard Model of particle physics—a discovery that would lead the following year to a Nobel Prize. Naturally, many scientists immediately eyed the next piece of the puzzle that they anticipate the LHC will uncover. "I'm still hanging tough, hoping for supersymmetry," said John Ellis of King's College London at the time, referring to the theory of matter that many physicists thought would supplant the Standard Model.

Since then, however, the search for "superpartner" particles that would help describe why particles have the masses they do and would solve the mystery of dark matter has led to disappointments. So far, as Joseph Lykken and Maria Spiropulu relate in their cover story, "Supersymmetry and the Crisis in Physics," the "results from the first run of the LHC have ruled out almost all the best-studied versions" of the theory. A higher-power run is due in 2015, but there is no guarantee it will yield the answers. Then what? Turn to page 34.

While we wait for the foundational picture of how the universe works to take better shape, we can watch machines develop the ability to take different forms here on Earth. In "Shape-Shifting Things to Come," starting on page 58, Sridhar Kota chronicles efforts to employ elastic, or compliant, design in our man-made contraptions. Instead of using many rigid parts in complex and often inefficient systems, as is done today, such designs can distribute loads across flexible devices made of fewer parts. The materials could enable such applications as bendable aircraft wings and snake robots, and their use would improve efficiency and durability in our engineered creations. They may not solve some of our profound questions about the universe, but they could make things easier here in the meantime. SA

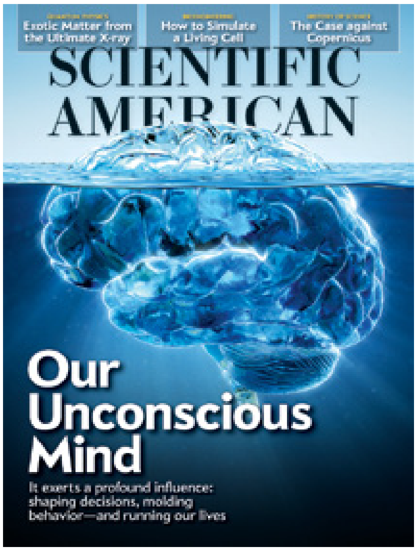
CITIZEN SCIENCE

Last Chance to Enter

Entries close on May 12 for the Google Science Fair, which includes a chance to win the $50,000 *Scientific American* Science in Action Award. The international competition is open to students ages 13 to 18. Science in Action honors a project that can make a practical difference by tackling an environmental, health or resources challenge; the prize includes a year of mentoring to continue to advance the winning work. Details can be found at **ScientificAmerican.com/education/science-in-action** —*M.D.*

Illustration by Nick Higgins

editors@sciam.com



January 2014

“The biggest advantage of open source software is that people all over the world can review it to see that it does what it says it does—and only that.”

RIVER ATT *MANCHESTER, ENGLAND*

DISTRUSTED DEVICES

David Pogue asks how we can know if privacy switches on the iPhone actually do anything in “In Tech We Don’t Trust” [TechnoFiles]. We could know this if the software were not closed source but open to inspection. By far the biggest advantage of open source software is that people all over the world can review it to see that it does what it says it does—and only that.

River Att
Manchester, England

SIMULATED CELLS

In “Simulating a Living Cell,” Markus W. Covert describes the remarkable achievement of the first complete computer model of an entire single-celled organism, the bacterium *Mycoplasma genitalium*. Would it be feasible now to sequentially disable as many as possible of the bacterium’s 525 genes while still allowing the model cell to divide, as a means of investigating how an even simpler organism might have existed in the past and point the way to a possible route back to the origin of life?

Gordon Lee
via e-mail

COVERT REPLIES: I and others are in fact considering how to go about deleting genes to find viable strains that have fewer genes than M. genitalium. *It’s an interesting problem for a few reasons: First, there are many potential solutions. Second, the order matters—every gene that you knock out has consequences; in some cases, one gene has to be taken out before another one can be, or else the cell dies. We are hoping that we can use our models to generate insight into the best approach and possibly come up with a design for a cell based on that insight.*

One of our toughest problems is simply that each simulation (a cell dividing one time) takes about 10 hours, so generating the number of simulations that we would need is computationally daunting. With luck, we will have an answer in a few years.

RENEWABLE LETHARGY

Vaclav Smil’s otherwise excellent article on the factors that make a transition to renewable energy slow and gradual, and on the policies that might hasten it [“The Long Slow Rise of Solar and Wind”], does not mention the huge global subsidies enjoyed by fossil fuels (some half a trillion dollars annually). This makes it difficult for renewable energy to compete. Understanding of the urgency of switching to renewable energy sources and improving efficiency is greatly impeded by this distortion of the economy.

Peter Elliston
Clontarf, Australia

Among the evidence that we will be slow to move to renewables, Smil cites the 50 to 60 years it took to transition from wood to coal and from coal to oil. I am reminded of a caveat that comes with strategic-planning statements from investment advisers when quoting fund performance: past performance is no guarantee of future performance.

Those periods of transition took place in circumstances significantly different from the transition to natural gas, beginning in 1930. And the circumstances since then are drastically different. One difference is the explosive growth in population in the 20th century. Another is the growth in demand/expectation of domestic consumerism. But the main difference is the knowledge of the consequences of human activity vis-à-vis carbon fuels. This knowledge would indicate that if humanity indulged in the luxury of letting the unregulated capitalist market proceed at its own rate, we might well be doomed to an unlivable planet before we complete the coming transition.

There are enormous obstacles to undertaking a transition plan. Those who hold legal title to carbon-based, climate-changing fuels are unwilling to relinquish the profits from their reserves even if the well-being of the biosphere requires that they do so. And humans have a tendency to think that what they observe in their lifetime is normal and can be reasonably expected to continue even when it is clearly a historical anomaly.

Richard Fahlman
Texada Island, B.C.

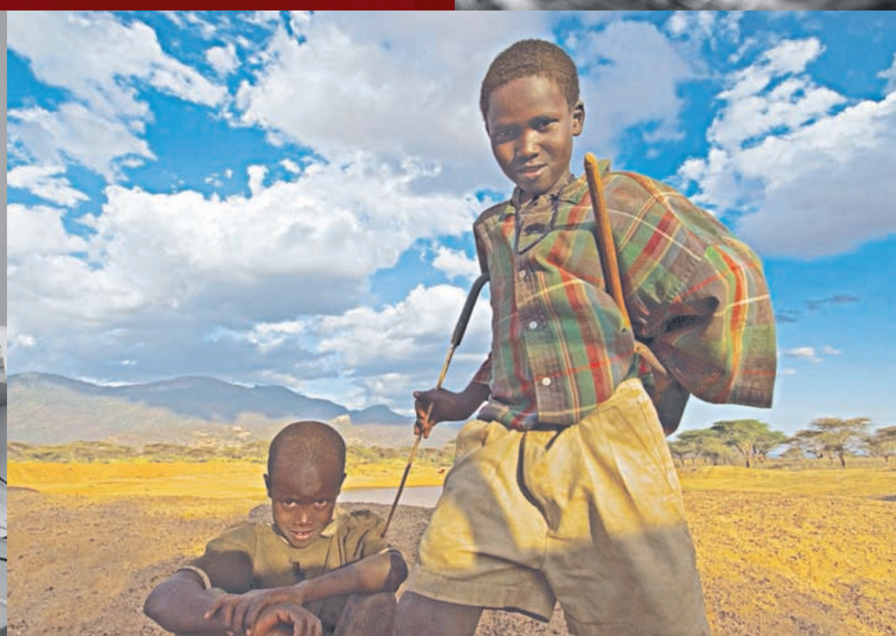
HELIOCENTRIC HOSTILITY

The scientific evidence cited in arguments against Copernican heliocentric cosmology in the 16th and 17th centuries, as described in “The Case against Copernicus,” by Dennis Danielson and Christopher M. Graney, ought not lead us to ignore the enormous—and tragic—social consequences of religious opposition to this revolutionary idea. Christianity long ago allied itself with a geocentric cosmology, with Man at the apex of a special Creation, possessed of an immortal soul and capable by perfect free will of choosing good or evil.

The Copernican, Darwinian and Freudian revolutions have laid waste this comforting ideology. The rejection of evolution, of climate change, of even the possibility of benefits from genetically modified organisms reflects a self-destructive distrust of science that stems largely from





bruised religious sensibilities. This wound to modern society will not yield to scientific education alone.

Jeff Freeman
Rahway, N.J.

THE HIDDEN MIND

While it was insightful, "Our Unconscious Mind," John A. Bargh's article on how unconscious processes affect our decision making, left me a little unsatisfied. He ends one paragraph by stating that "to make our way in the world, we need to learn to come to terms with our unconscious self," but he neglects to offer suggestions. I believe meditation has helped me a lot.

Joe Christie
via e-mail

Bargh describes a study asking participants to judge fitness for public office based on fleeting glimpses of photographs of the candidates. I was disappointed that many interesting follow-up questions were not pursued. For instance: Is there a predictable IQ level above which a person would merely laugh when asked to participate in such an idiotic task? Is the level of the participants characteristic of the voting population as a whole?

Steve Munden
via e-mail

DIMINISHED DISEASE

In the 50, 100 & 150 Years Ago column, compiled by Daniel C. Schlenoff, the item called "Battling Trachoma," excerpted from a January 1964 article, refers to nearly 500 million people then being infected with that disease.

Your readers might like to know that since that time, the number of people infected has dropped to 21.4 million. Whereas some of the reduction is from general improvement in hygiene and living conditions, much of it is the result of a global initiative to eliminate blinding trachoma sponsored by the World Health Organization, which builds on the SAFE strategy: *s*urgery for trichiasis (inward-turning eyelashes), *a*ntibiotics, *f*acial cleanliness and *e*nvironmental improvement.

Hugh Taylor
Melbourne School of Population and Global Health, Australia

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/may2014

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The Myth of the Compassionate Execution

The use of drugs to carry out capital punishment is putting bona fide medical patients at risk

In January the state of Ohio executed the convicted rapist and murderer Dennis McGuire. As in the other 31 U.S. states with the death penalty, Ohio used an intravenously injected drug cocktail to end the inmate's life. Yet Ohio had a problem. The state had run out of its stockpile of sodium thiopental, a once common general anesthetic and one of the key drugs in the executioner's lethal brew. Three years ago the only U.S. supplier of sodium thiopental stopped manufacturing the drug. A few labs in the European Union still make it, but the E.U. prohibits the export of any drugs if they are to be used in an execution.

Ohio's stockpile of pentobarbital, its backup drug, expired in 2009, and so the state turned to an experimental cocktail containing the sedative midazolam and the painkiller hydromorphone. But the executioner was flying blind. Execution drugs are not tested before use, and this experiment went badly. The priest who gave McGuire his last rites reported that McGuire struggled and gasped for air for 11 minutes, his strained breaths fading into small puffs that made him appear "like a fish lying along the shore puffing for that one gasp of air." He was pronounced dead 26 minutes after the injection.

There is a simple reason why the drug cocktail was not tested before it was used: executions are not medical procedures. Indeed, the idea of testing how to most effectively kill a healthy person runs contrary to the spirit and practice of medicine. Doctors and nurses are taught to first "do no harm"; physicians are banned by professional ethics codes from participating in executions. Scientific protocols for executions cannot be established, because killing animal subjects for no reason other than to see what kills them best would clearly be unethical. Although lethal injections appear to be medical procedures, the similarities are just so much theater.

Yet even if executions are not medical, they can affect medicine. Supplies of propofol, a widely used anesthetic, came close to being choked off as a result of Missouri's plan to use the drug for executions. The state corrections department placed an order for propofol from the U.S. distributor of a German drug manufacturer. The distributor sent 20 vials of the drug in violation of its agreement with the manufacturer, a mistake that the distributor quickly caught. As the company tried in vain to get the state to return the drug, the manufacturer suspended new orders. The manufacturer feared that if the drug was used for lethal injection, E.U. regulators would ban all exports of propofol to the U.S. "Please, Please, Please HELP," wrote a vice president at the distributor to the director of the Missouri corrections department. "This system failure—a mistake—1 carton of 20 vials—is going to affect thousands of Americans."

This was a vast underestimate. Propofol is the most popular anesthetic in the U.S. It is used in some 50 million cases a year—everything from colonoscopies to cesareans to open-heart surgeries—and nearly 90 percent of the propofol used in the U.S. comes from the E.U. After 11 months, Missouri relented and agreed to return the drug.

Such incidents illustrate how the death penalty can harm ordinary citizens. Supporters of the death penalty counter that its potential to discourage violent crime confers a net social good. Yet no sound science supports that position. In 2012 the National Academies' research council concluded that research into any deterrent effect that the death penalty might provide is inherently flawed. Valid studies would need to compare homicide rates in the same states at the same time, but both with and without capital punishment—an impossible experiment. And it is clear that the penal system does not always get it right when meting out justice. Since 1973 the U.S. has released 144 prisoners from death row because they were found to be innocent of their crimes.

Concerns about drug shortages for executions have led some states to propose reinstituting the electric chair or the gas chamber—methods previously dismissed by the courts as cruel and unusual. In one sense, these desperate states are on to something. Strip off its clinical facade, and death by intravenous injection is no less barbarous. SA

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Illustration by Logan Faerber

Veronique Kiermer is director of Author and Reviewer Services at Nature Publishing Group.

Eureka Once, Eureka Twice

Biology is making it harder for scientists to reproduce one another's experiments

Science works by iteration. Scientists repeat their peers' work and build on their findings. The literature of peer-reviewed scientific papers is the record of this step-by-step process. In recent years, however, prominent reports have suggested that many scientists are not able to replicate others' published results. Is scientific progress going wrong on an unprecedented scale? Before we jump to that conclusion, it would help to consider the changing nature of science itself—particularly biology.

Basic biomedical research and its translation into therapeutic interventions to cure diseases are at the center of this issue. In an ideal world, academic scientists identify targets for drugs—typically proteins involved in disease—and industry scientists look for agents that interfere with those targets' function. In reality, more often than not, industry scientists find that they cannot replicate the effects seen by academics in a sufficiently robust way to justify drug development. Worse, many promising drug candidates fail in phase II clinical trials when their efficacy is put to the test.

The world seemed simpler in the 1970s, when molecular biology brought us concepts such as "gene A leads to protein B, which leads to function C." Thinking this way, scientists uncovered amazing mechanistic insights and, sometimes, designed effective drugs—the cancer drug Gleevec is the poster child of that reductionist approach. Wouldn't it be nice if drug discovery always went this way?

Those first drugs, however, were low-hanging fruit. Biology is much more complicated than simple schematics. Biological processes do not work in linear ways independently of one another but in tightly interconnected networks. In each branch of these networks, layers of regulatory controls constantly change the nature and abundance of the molecular players. We know little about the inner workings of human cells.

To illustrate how little, consider how genes are controlled. The modern study of gene regulation started in the 1950s, but researchers only started to unravel the complex array of histone modifications that fine-tune chromatin control of gene expression 20 years ago. The fact that RNA interference, another mode of gene regulation, is pervasive has only been realized in the past 10 years. What else don't we know yet?

Laboratory biologists deal with complexity on a daily basis. Mice bred with identical DNA behave differently. Two cells growing side by side in a petri dish cannot be considered identical. In the variable environment of the cell, it is difficult to distinguish a change that is meaningful to a process from one that is unrelated. Working in a modern lab also entails using sensitive apparatuses, rare technical skills and biological reagents—antibodies and enzymes, for example—which are themselves variable.

In such noisy systems, it is easy to mistake a chance observation for a robust, biologically meaningful effect. Biologists have to undertake large studies that can guarantee the statistical significance of observations, and they need self-critical analysis to avoid inadvertent biases. Scientists cannot be too careful to avoid falling prey to their own enthusiasm.

In that regard, they need the support of their institutions and the journals that publish their results. Some journals, such as *Nature,* have introduced checklists to ensure that scientists consider and report key information about experiments. (*Scientific American* is part of Nature Publishing Group.) Still, research institutions should provide more training and supervision of younger scientists. Institutions and funders should manage their incentive systems to limit undue pressures on researchers and promote best practices.

The need for replicating results is as important as ever. But it is inevitable that results obtained in one cell line might not exactly match those in another. They in turn might not be completely predictive of the observations in animal models, let alone human beings. The literature of published results is still strong. To keep it that way, the scientific community cannot afford to be complacent. It must pay attention to the professionalism of researchers and take into account the complexity of biology. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/may2014

Illustration by Sam Falconer

BLOWING ITSELF UP: A rapidly expanding universe spawns gravitational waves that stretch and compress spacetime.

COSMOLOGY

Our Inflated Universe

Traces of primordial gravitational waves could tell us how and when the early universe went through its precipitous expansion

Score one for inflation. The idea that the universe ballooned rapidly after the big bang received a boost in March, when physicists confirmed a prime prediction of inflation theory. The Background Imaging of Cosmic Extragalactic Polarization 2 (BICEP2) experiment at the South Pole found evidence for primordial gravitational waves, ripples in the fabric of space and time, that were created when the early universe swelled. The discovery is not just a major validation of inflation, physicists say, but a good way to narrow down the many possible versions of inflation that might have taken place. "This really collapses the space of plausible inflationary models by a huge amount," says Marc Kamionkowski of Johns Hopkins University, who was not involved in the discovery but who co-predicted back in 1997 how these gravitational-wave imprints could be found. "Instead of looking for a needle in a haystack, we'll be looking for a needle in a bucket of sand."

BICEP2 found a pattern called primordial B-mode polarization in the light left over from just after the big bang known as the cosmic microwave background. This pattern, basically a curling in the polarization, or orientation of the electric field, of the light, can be created only by inflation-induced gravitational waves. "We've found the smoking-gun evidence for inflation, and we've also produced the first image of gravitational waves across the sky," says Chao-Lin Kuo of Stanford University, who designed the BICEP2 detector and co-leads the collaboration.

Such a groundbreaking finding requires confirmation from other experiments to be truly believed, physicists say. Nevertheless, the result was heralded as a huge win for cosmology. "There's a chance it could be wrong, but I think it's highly probable that the results stand up," says Alan Guth of the Massachusetts Institute of Technology, who first predicted inflation in 1980.

Physicists are now parsing the finding for clues about the timing and details of inflation. The BICEP2 measurement suggests that inflation began a trillionth of a trillionth of a trillionth of a second after the big bang, a time when the universe would have been so energetic that all the fundamental forces of nature—the electromagnetic, strong and weak forces, with the exception of gravity—might have been unified into a single force. The new results could also quell any remaining doubters of inflation. "If this discovery is confirmed," says Andrei Linde of Stanford, one of the main authors of inflation, "inflationary theory does not have any real alternatives." —*Clara Moskowitz*

SLIM FILMS

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GETTY IMAGES

GLOBAL WARMING

The Little Volcanoes That Could

Many small eruptions over the past decade or so have helped restrain climate change

On Valentine's Day, Indonesia's Mount Kelud blew its top and coated villages up to 500 kilometers away with ash. At the same time, the eruption injected a small but consequential amount of sulfur dioxide 28 kilometers up into the stratosphere. Tiny droplets of sulfuric acid then reflected away incoming sunlight, helping to cool the planet. Such "small" eruptions—along with others at places like Manam, Soufrière Hills, Jebel at Tair and Eyjafjallajökull, to name a few of the 17 between 2000 and 2012—have helped slow the pace of global warming, according to work published in *Nature Geoscience.* (*Scientific American* is part of Nature Publishing Group.)

"The uptick in early 21st-century volcanism clearly was a contributing factor to the hiatus," says atmospheric scientist Benjamin Santer of Lawrence Livermore National Laboratory, lead author of the report. The volcanoes did not act alone. There was also an unusually quiescent sun, air pollution from China's coal-fired power plants and the mysterious workings of the ocean. Santer adds, "The net impact was to offset part of the human-caused greenhouse gas warming."

In the meantime, global warming continues to gather strength, hidden behind volcanoes that may shutter their tops at any moment. Based on supersized eruptions such as Mount Pinatubo in the Philippines in 1991, reflective aerosols would then fall to Earth within a few years at most, leaving the planet exposed to the full heat-trapping effects of greenhouse gases from human activities.

If the volcanoes do not do their part, a last resort may be required—bring our own aerosols. Advocates of one form of geoengineering want to step in, injecting sulfate aerosols in the stratosphere to augment or replace eruptions. Such deliberate tinkering with planetary-scale systems has been proposed as a fallback plan if climate change were to turn catastrophic, though at the cost of the stratospheric layer that helps to shield life from ultraviolet light. Sulfuric acid high in the sky has the unfortunate side effect of eliminating ozone. But given the inertia in reducing greenhouse gas pollution, the debate around geoengineering will undoubtedly linger longer than the aftermath of these small volcanic eruptions. *—David Biello*

COMMENT AT ScientificAmerican.com/may2014

DAVID PONTON Corbis

EXTINCTION COUNTDOWN
HAWAIIAN HAWK

A Symbol of Royalty Makes a Tentative Comeback

Back in 1997, the conservative National Wilderness Institute petitioned the U.S. Fish and Wildlife Service to remove the Hawaiian hawk, or *'io* (*Buteo solitarius*), from the Endangered Species Act (ESA). The FWS finally moved forward on the proposal in February, asking for public comments on the pending delisting.

The hawk joined the endangered species list in 1967, fewer than six months after passage of the original Endangered Species Preservation Act, the predecessor to the current ESA. The only modern hawk native to Hawaii, the *'io,* in 1967, was limited to just a small portion of Hawaii Island (aka the Big Island). The original causes of its decline are unknown, but today it has expanded its range across nearly 60 percent of the island.

More than 40 years of legal protection and recovery efforts seem to have helped the Hawaiian hawk. Since 1967 the species' population has grown to around 3,000—a number that seems to have been stable since 1998 despite continued urbanization on the Big Island and risks from invasive species.

But the newspaper *West Hawaii Today* found that many Hawaiians do not think the *'io* should be delisted. The owner of an animal sanctuary told the paper that people still shoot the birds—she recently rehabilitated two hawks that had been shot with a BB gun—and that their habitat continues to shrink. One Hawaiian cultural practitioner said he sees the birds less often than he did 10 or 20 years ago. The hawks are valued in Hawaiian culture as a symbol of royalty.

Even if the hawk is delisted, it will be protected under the Migratory Bird Treaty Act, a 1918 federal law. The FWS would also act as a monitor for at least five years to make sure that new threats do not emerge—oversight that is needed. Hawaii is, after all, known as the "extinction capital of the world." *—John R. Platt*

FROM "HOMININ FOOTPRINTS FROM EARLY PLEISTOCENE DEPOSITS AT HAPPISBURGH, U.K.," BY NICK ASHTON ET AL., IN *PLOS ONE*, VOL. 9, NO. 2, ARTICLE NO. E88329; FEBRUARY 7, 2014

ARCHAEOLOGY

Ancient Footprint

English mud captures an ancestral stroll

Archaeologists working on the eastern coast of England have found a series of footprints that were made by human ancestors sometime between one million and 780,000 years ago. Pressed into estuary mudflats now hard with age, these prints are the oldest ones known outside of Africa, where humanity arose.

Scientists discovered the prints in early May 2013, at a seaside site in Happisburgh. High seas had eroded the beach sand to reveal the mudflats underneath. The team had to act quickly to record the tracks before they, too, eroded. The researchers used a technique called multi-image photogrammetry and laser scanning to capture the prints in three dimensions.

In a paper published this past February in *PLOS ONE,* Nick Ashton of the British Museum and his colleagues reported that analysis of the footprints—which show impressions of the arch, ball, heel and toes of several individuals—suggests they were left by a party of five as they walked south along a large river. Based on the apparent foot lengths, they ranged in height from 0.93 to 1.73 meters, evidence that the group was composed of both adults and youngsters. The researchers estimated the body mass of the adults at 48 to 53 kilograms.

Exactly which species of early human left the trails is unknown because no human remains have turned up at the site. Yet judging from the antiquity of the prints, a likely candidate is *Homo antecessor,* a species known from the site of Atapuerca in Spain that had body dimensions similar to those reconstructed for the largest Happisburgh footprint makers.

Happisburgh is the oldest known site of human occupation in northern Europe. Previous excavations there have turned up dozens of flint tools that these ancient people may have used to butcher animals or process their skins. Where had the track makers come from, and where were they going? Perhaps continuing erosion of the coastline will reveal more clues to the lives they lived. —*Kate Wong*

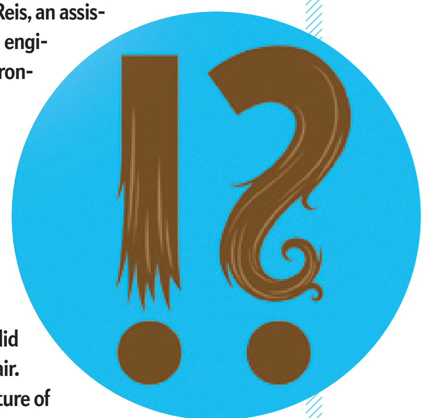
COMPUTER GRAPHICS

The Physics of Long, Loose Tresses

Simulating a single spiraling hair strand may prove a boon to computer animators

In DreamWorks Animation's *Shrek* franchise, Princess Fiona almost exclusively wears her hair pulled back. The character's preference for braids has more to do with physics than fashion. Letting a cartoon character's hair down requires calculating a string of complex equations to create a realistic effect, so computer animators often just opt for short hair and updos rather than long, loose tresses. Likewise, most animated characters turn up on the big screen with straight locks because rendering them in three dimensions is a simpler mathematical task.

Animators' tool kits may be about to expand, and a convincing rendition of curls might one day abound in features by DreamWorks and Pixar. A team of researchers recently untangled the physics of a single strand of curly hair, publishing the results in *Physical Review Letters.* "This is the first time someone described the full 3-D configuration of a single naturally curved hair," says co-author Pedro Reis, an assistant professor of mechanical engineering and of civil and environmental engineering at the Massachusetts Institute of Technology. "I would attribute that to the fact that the geometry of a curly hair is highly nonlinear—a word we often use for something complicated."



Reis and his colleagues did not set out to model curly hair. They wanted to study curvature of long, thin structures. Think of submarine cables, oil and gas pipes, and even the tiny tails on bacteria. The team first laid hollow, tubular molds out straight or wrapped them around cylindrical objects ranging in diameter from 3.2 centimeters to one meter. Then they injected the molds with a rubberlike material, which dried to produce flexible rods with different curvatures. They suspended the rods to study how gravity affected their shape. With curls hanging one beside another, they realized the rods bore a striking similarity to the single strands that combine to form coifs ranging from rail-straight to the kinks of Afro-textured hair.

The researchers carried out some 11,000 computer simulations, using the results to create a phase diagram depicting different geometric shapes a hanging strand will assume as a function of four properties: curvature, weight, length and stiffness. Eventually such a tool could be incorporated into animation software, but other groups will first have to investigate how a full head of curly hair interacts with itself and with wind and other outside forces.

The model could also calculate curvature of steel pipes or other spooled material. "We were engineers trying to solve practical, useful problems from the start," Reis says. "I'm not a professional hairstylist—I'm bald, actually." —*Rachel Nuwer*

Illustrations by Thomas Fuchs

BY THE NUMBERS

4.4 billion

Age in years of the oldest piece of Earth's crust ever discovered: an ancient zircon crystal from Australia that is only 160 million years younger than our solar system.

SOURCE: "Hadean Age for a Post-Magma-Ocean Zircon Confirmed by Atom-Probe Tomography," by John W. Valley et al., in *Nature Geoscience*, Vol. 7; March 2014

ASTRONOMY

Kepler's Afterlife

Data from the damaged spacecraft reveal new worlds

NASA's Kepler space telescope was launched in 2009 and stopped taking data last year after a mechanical failure. Yet in its relatively short lifetime, it has offered up a wealth of discovery. In February scientists announced a new harvest that brought Kepler's tally of discovered planets to nearly 1,700. "This is the biggest haul ever," says Jason Rowe of the NASA Ames Research Center, who co-led the research. The scientists studied more than 1,200 planetary systems and validated 715 planets. All the new worlds are members of multiplanet systems—stars with more than one orbiting satellite.

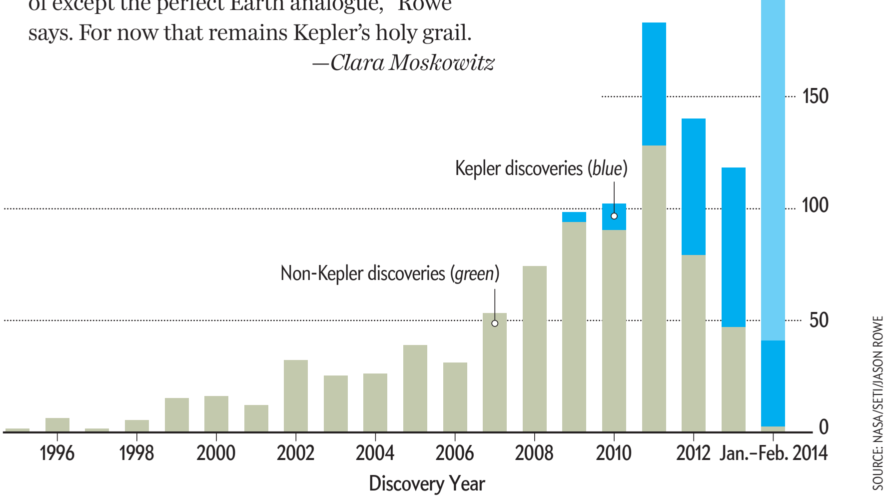
Researchers used a new method for weeding out false signals. Kepler searched for planets by measuring dips in a star's brightness, which occur when a planet passes in front of it. This technique, called the transiting method, is very accurate, but sometimes a nonplanet can fool the telescope. One of the most common reasons for a "false positive" is an eclipsing binary—a pair of orbiting stars that sometimes cross in front of each other from our perspective.

Stars with a single planet can be hard to distinguish from eclipsing binaries. But multiplanet systems are far less likely to be frauds. "It happens, but it's unlikely that you have two eclipsing binaries in the background of the same star," says Francois Fressin of the Harvard-Smithsonian Center for Astrophysics, who was not involved in the study. It is also possible, albeit extremely unlikely, to have an eclipsing binary and a star with a planet lying right on top of each other.

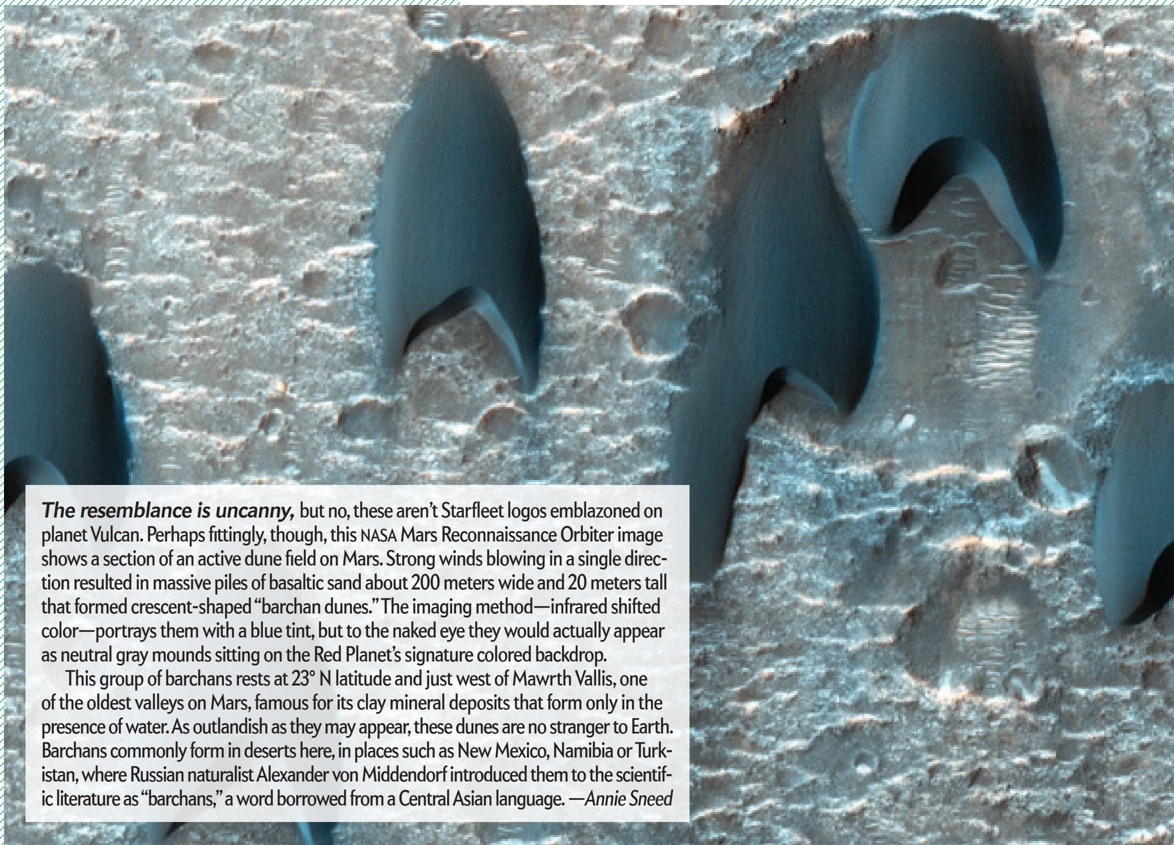
Rowe and his colleagues tried to weed out false signals by examining light from the candidate planets. They looked for a particular signature known as a moving centroid: an off-center point of light that could be created only by an eclipsing binary, not by a planet.

What remained among the trove of ample discoveries: a potentially rocky world; an odd binary star system where each star has planets of its own; and cramped systems where the multiple planets are each gravitationally tugging one another around. "Of course, we have every type of planetary system in our validated set that people can think of except the perfect Earth analogue," Rowe says. For now that remains Kepler's holy grail.

—Clara Moskowitz



Graphic by Jen Christiansen



The resemblance is uncanny, but no, these aren't Starfleet logos emblazoned on planet Vulcan. Perhaps fittingly, though, this NASA Mars Reconnaissance Orbiter image shows a section of an active dune field on Mars. Strong winds blowing in a single direction resulted in massive piles of basaltic sand about 200 meters wide and 20 meters tall that formed crescent-shaped "barchan dunes." The imaging method—infrared shifted color—portrays them with a blue tint, but to the naked eye they would actually appear as neutral gray mounds sitting on the Red Planet's signature colored backdrop.

This group of barchans rests at 23° N latitude and just west of Mawrth Vallis, one of the oldest valleys on Mars, famous for its clay mineral deposits that form only in the presence of water. As outlandish as they may appear, these dunes are no stranger to Earth. Barchans commonly form in deserts here, in places such as New Mexico, Namibia or Turkistan, where Russian naturalist Alexander von Middendorf introduced them to the scientific literature as "barchans," a word borrowed from a Central Asian language. *—Annie Sneed*

COURTESY OF NASA, JPL AND UNIVERSITY OF ARIZONA

SWARM: Some ant species build living rafts or bridges, such as this overpass constructed by *Eciton burchelli.*

ALEX WILD

ENTOMOLOGY

A Pontoon of Pupae

A species of ant escapes floods on a raft made of its babies

"In the ant's house, the dew is a flood," an old proverb tells us. Yet for floodplain-dwelling ants, a little dew is nothing. When a real flood arrives, some ant species are known to evacuate their nest and self-assemble into rafts that float to dry ground. Swarm behavior is common in ants: some species even build living bridges to let their kindred march atop.

When it comes to raft building, the behavior has been observed in fire ants, but scientists at the University of Lausanne in Switzerland have discovered a peculiar design in living rafts of another species, which builds boat bottoms with its young. Using babies as flotation devices is not as much a threat to propagating ant genes as you would think.

This species of floodplain-dwelling ant, *Formica selysi,* nests throughout the Pyrenees and the Alps. The queen ant lives for about 10 to 15 years and experiences a Noah's ark–like flood an average of two or three times in her lifetime. During a flood, the worker ants collect the brood—immobile eggs, larvae and pupae—into a pile, and then another three or four layers of workers climb atop them and hold onto the babies with their mandibles. The queen assumes her place in the protected middle of the raft.

Placing the brood on the bottom, where it is most at risk of drowning, seems like a bad idea. After all, along with the queen, offspring are the most valuable members of the colony because their survival will determine its evolutionary success. "The conventional wisdom would be that the workers would put the brood in the middle of the raft with the queen," says postdoctoral student Jessica Purcell, who led the research.

Purcell and her colleagues mimicked flood conditions in their laboratory with *F. selysi* ants they collected along the Rhône River banks in Switzerland. All ants rafted in artificial flood conditions, regardless of whether or not they had a brood; those with no babies at hand built their boat base out of worker ants instead. After the flood subsided, the raft without a brood had more unresponsive worker ants and they took more time to recover, which may explain why this species recruits its buoyant youth.

Surprisingly, the ant babies did not appear to suffer at all from their watery chores. Those that made up the raft bottom survived just as successfully as the brood control group kept on dry land. The tremendous buoyancy of ant babies, most likely the result of high fat content, prevents them from sinking when they have to carry their parents on their back. So in the ant world, offspring are not so useless: it's the mommies and daddies who are the hangers-on. *—Annie Sneed*

COMMENT AT ScientificAmerican.com/may2014

NEUROSCIENCE

It Takes a Prion to Remember

An infamous protein helps to explain how memory works

The protein family notorious for causing neurogenerative diseases such as Parkinson's—not to mention mad cow—appears to play an important role in healthy cells. "Do you think God created prions just to kill?" muses Eric R. Kandel of Columbia University. "These things have evolved initially to have a physiological function."

Kandel's work on memory helped to reveal that animals make and use prions in their nervous systems as part of an essential function: stabilizing the synapses involved with forming long-term memories. These natural prions are not infectious, but on a molecular level they chain up exactly the same way as their disease-causing brethren. (Some researchers call them "prion-like" to avoid confusion.) Now neuroscientist Kausik Si of the Stowers Institute for Medical Research in Kansas City, Mo., one of Kandel's former students, has shown that the prion's action is tightly controlled by the cell and can be turned on when a new long-term memory needs to be formed.

Once the prion's chain reaction gets started, it is self-perpetuating, and thus the synapse—where neurons connect—can be maintained after the initial trigger is gone, perhaps for a lifetime. But that still does not explain how the first prion is triggered or why it happens at only certain of the synapses, which play a crucial role in forming memories. Si's work, published February 11 in *PLOS Biology*, traces the biochemistry of this protein-preservation process in fruit flies, showing how the cell turns on the machinery responsible for the persistence of memory—and how the memory can be stabilized at just the right time and in the right place.

Si and his colleagues focused on a protein called Orb2A—its human equivalent is CPEB—that functions as a prion in the flies. A series of molecular interactions results in a phosphate becoming attached to Orb2A but only when an electrical impulse is targeted to a particular synapse among the multitude that can populate a neuron. The specificity allows the prion chain reaction to turn on at the specific time and place needed, stabilizing some synapses but not others—and perhaps explaining why some of our memories fade. *—Beth Skwarecki*

What Makes a Brain Smart?

Neuro-imaging research has identified brain features and specific areas distributed throughout the brain that are related to intelligence test scores. We'll review, in non-technical terms, how neuro-imaging works and we'll see some amazing dynamic views of intelligence at work in the brain during problem-solving, including some findings "hot off the press."

How Smart Do You Want To Be?

As we learn about the neural mechanisms of intelligence, prospects for enhancing intelligence become more likely. We'll discuss the ethical quandaries this raises. If there were an IQ pill, would you take it? What about enhancing intelligence in children? If we could enhance intelligence, do we have a moral obligation to do so?

Dinosaurs

Speaker: Darren Naish, Ph.D.

Predatory Dinosaurs and the Origins of "Birdiness"

Theropods, which included giants like Allosaurus and Tyrannosaurus, also had numerous lineages of smaller bird-like dinosaurs, and many theropods were feathered. Take a tour through theropod diversity, and examine the many controversial ideas of how they lived, how they hunted, and what they looked like when they were alive.

Sauropod Dinosaurs and the "Necks For Sex" Debate

Sauropod dinosaurs had immensely long necks, sometimes more than four times longer than their bodies. Some have suggested this evolved as a sexual signal, its length driven by sexual selection pressure. I'll discuss my work testing this hypothesis, and why the neck might actually have evolved for feeding and foraging.

Pterosaurs: Flying Reptiles of the Mesozoic

Ancient reptiles called pterosaurs flew on membranous wings supported by enormous fourth fingers. They had furry bodies, air-filled bones and many species possessed crested skulls. Little is known about pterosaur behavior and social life, but we can make some educated guesses. Learn about the diversity, anatomy and biology of this amazing group.

The Remarkable Azhdarchoid Pterosaurs

Among the most unusual of pterosaurs are the azhdarchoids—animals with huge wingspans that stood over 4 meters tall. They have been imagined as mud-probers, vulture-like scavengers, skim-feeders and heron-like waders. We'll discuss the newest data that has changed our view of these fascinating animals.

Eclectic Astronomy

Speaker: Donald Kurtz, Ph.D.

Planets and Pulsations: The New Keplerian Revolution

The Kepler space telescope has discovered more than 3,500 candidate exoplanets, and is closing in on finding another Earth—a rocky planet in the "Goldilocks zone" where life might exist. Kepler has also allowed us to see stars as never before. Learn how this mission is revolutionizing our knowledge of the galactic zoo we inhabit.

It's About Time!

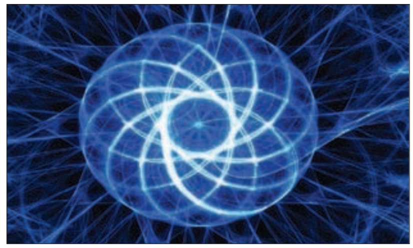
Days, weeks, months, years and more: Hear about Roman emperors, Zulu wars, Rider Haggard, Thomas Hardy, the English time riots, and how the days of the week got their names in an amusing and informative tour of the Western calendar.

The Stars are Ours!

"What good is astronomy?" Through colorful historical anecdotes and science, we'll answer that question. Hear stories of wealth and poverty, castles and dungeons, kings and princes, sailors and maidens, sea battles and Shakespeare, as we look back at the improbable, unpredictable path that gave us the Power of the Stars.

The Sun-Earth Connection

Learn how magnetic activity on the Sun affects Earth, from our planet's magnetosphere to the aurora lights. We'll see why the Sun is not the source of global warming, and we'll discuss weather on other stars. I'll also introduce you to a group of peculiar magnetic stars that I discovered.



Particle Physics

Speaker: Don Lincoln, Ph.D.

The Higgs Boson

Hear the saga of the Higgs boson particle, from its initial prediction in 1964 through its discovery to the 2013 Nobel Prize. As a member of one of the teams that discovered it, I will give an insider's perspective, including answering the very important question, "What's next?"

Accelerators and Particle Detectors

The Higgs boson, the top quark, dark matter—none of these particles are part of our everyday experiences. So how do scientists study these elusive particles? Learn about the complex technology we use to glimpse them, from 14,000-ton experiments with over a hundred million elements to particle observatories under the Antarctic ice.

History of Particle Physics

The search for the ultimate building blocks of matter has a long history. Hear the story, from the 1987 discovery of the electron to finding protons, neutrons and eventually particles that have no role in ordinary matter. Learn how we arrived at our current picture of quarks, leptons and a handful of force-carrying particles.

The Dark Side of the Universe

We understand the nature of the ordinary matter that makes up you and me, but ordinary matter is only 5% of the universe. Learn about the data that led us to conclude that a bizarre dark world must exist, and hear about current experimental efforts aimed at finding it.

SCIENTIFIC AMERICAN Travel HIGHLIGHTS

ROQUE DE LOS MUCHACHOS OBSERVATORY

Friday, December 5th, 1pm – 5:30pm

Join an optional field trip to one of the most renowned groups of telescopes in the world, La Palma's Roque de los Muchachos Observatory in the Canaries.

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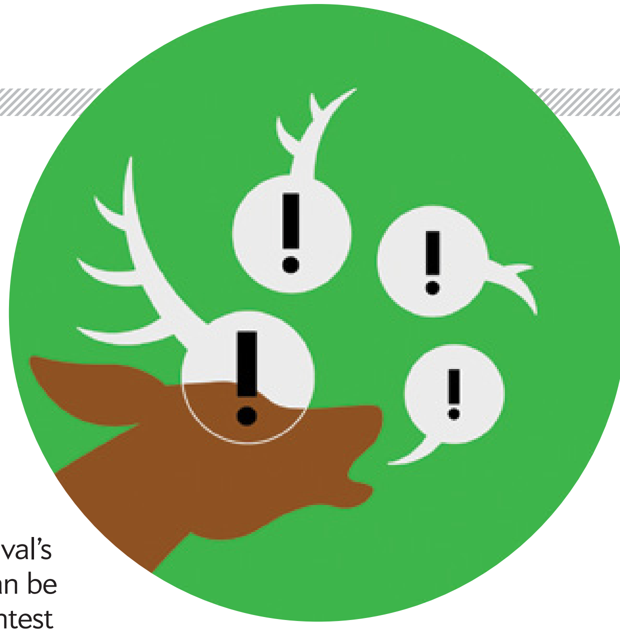


ANIMAL BIOLOGY

He Who Hollers Fastest Gets the Girl

A fallow buck judges a rival's call to tell whether he can be trounced in a mating contest

When a male fallow deer wants to mate, he isn't shy about letting everyone around him know. The males, also called fallow bucks, can produce their mating calls as many as 3,000 times each hour during the mating season. Those calls serve two functions: to attract females and to deter rival males. Yet there is more hidden in the groans of fallow bucks than first meets the ear, according to a new study in *Behavioral Ecology*.

Every October around 25 bucks gather in Petworth Park in England's county of West Sussex, where each stakes out a territory, hoping to entice a female at a feral conclave of romance, combat and deer calling, an event known as a lek. "Leks are really rare in mammals, and they're really rare in ungulates. Fallow deer are the only species of deer that we know that lek," says Alan McElligott of Queen Mary, University of London, who oversaw the study.

Mating calls reveal information about the caller, such as body size or dominance rank, which is useful both to interested females and to rival males—and every conceivable type of fallow deer utterance turns up at the lek. In one study, McElligott found that the quality of groans decreased over time. "The mature bucks stop eating for a couple of weeks," over the course of the lek, McElligott explains, so "they are really worn out."

That fatigue is reflected in their calls, but do other males notice? Because the lek is such a spectacle, the deer in Petworth Park are accustomed to human interlopers, which allowed Queen Mary postdoctoral scholar Benjamin J. Pitcher to cart a sound system around without interrupting the festivities.

Broadcasting prerecorded calls, he discovered that deer can distinguish those made early in mating season, when males are still healthy, from those made later, once they are fatigued. If a rival male sounds exhausted, it might be worth trying to displace him from his territory. If a subordinate male is to challenge a dominant one, it is best to be sure that he can actually win.

—Jason G. Goldman

BY THE NUMBERS

57

Percentage of U.S. adults who used Facebook in 2013, nearing the 10th anniversary of the social media site going live.

SOURCE: "6 New Facts about Facebook," by Aaron Smith. Pew Research Center, February 3, 2014

COMMENT AT ScientificAmerican.com/may2014

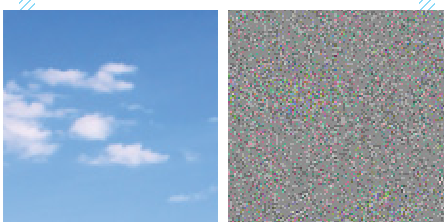
IMAGE PROCESSING

Cameraprints

A unique camera "signature" to identify online criminals

New developments in tracing particular photographs to the cameras that snapped them might provide the basis for a forensic method of catching pedophiles who distribute child pornography anonymously on the Internet. It could also help law-enforcement agencies identify smartphone thieves who take pictures with the stolen gadgets and then post the images online.

It has been known since 2006 that tiny variations in the silicon chip–based camera sensors create differences in response to light that leave a signature "noise" pattern (*below right*) on every photo that can be matched to a specific camera and cannot be removed. "It is not currently possible to perfectly separate the image from the noise, modify the noise and then add it back to the image," says Riccardo Satta, a scientific officer at the



European Commission Joint Research Center's Institute for the Protection and Security of the Citizen. At a recent privacy conference in Brussels, Satta presented work showing that sensor-pattern noise persists when photos are modified and uploaded to social media.

Investigators have long known of other identifiers that digital cameras insert into images as they convert a stream of light into digital bits. But none are as reliable for tracing the source of an image as sensor-pattern noise.

In a preliminary study of 2,896 images taken from 15 different social networks or blog accounts, Satta and his colleague Pasquale Stirparo found that a photograph could be linked half the time to a specific camera as a most probable match. They also discovered that a set of images could be accurately grouped according to the originating camera 90 percent of the time, with a false positive rate of 2 percent.

These statistics are not good enough to use at a trial. But the technique could help select targets for investigation, especially when presented along with other information found on social networks, such as location and friend lists. —*Wendy M. Grossman*

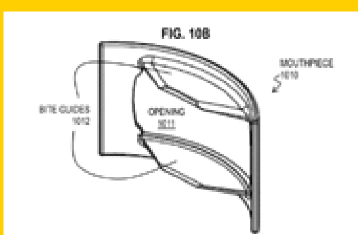
COURTESY OF RICCARDO SATTA

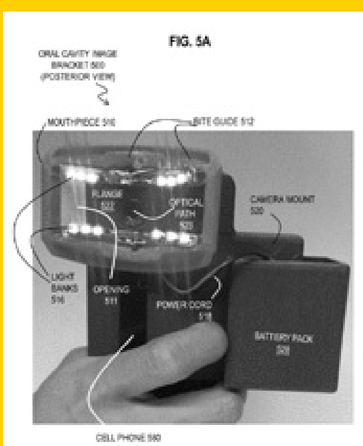
PATENT WATCH

Using a Smartphone to Detect Cancer

Oral cancer is straightforward for dentists to detect early on. They can easily identify lesions in the mouth that are precancerous. But for people living in parts of the world with few dentists, these lesions can go undiagnosed until it is too late for effective treatment. Now a patent application has been filed for a device that aims to tackle that problem, designed by Manu Prakash of Stanford University and his colleagues.

Called OScan, the device has bite guides to hold open a patient's mouth and a mount that allows a smartphone or digital camera to attach to the front. In this way, health workers in the field can easily photograph the inside of a person's mouth and send those images wirelessly to an off-site dentist or medical expert who can evaluate them for signs of malignancy. In countries such as India, where there can be as few as one dentist per quarter of a million residents in rural areas and where oral cancer accounts for more than 40 percent of all cancer-related deaths, OScan has the potential to save many lives. *—Geoffrey Giller*





Q&A

"Millions of People Are Suffering"

A prominent Italian heart surgeon talks about his plan to build free, state-of-the-art hospitals in Africa

Building on the success of your Salam Center for Cardiac Surgery in Sudan, you plan to open 10 free hospitals throughout Africa. Funding will come from Emergency, the NGO you founded in 1994. Can you talk about your approach?

If I look at the health indicators in Africa, I see something that is very, very similar to what the situation was in Europe 200 years ago. In other words, medicine has not developed. Millions of people are suffering and dying, and so we have to ask, How do we reverse this trend?

How will you do things differently?

Most health facilities in Africa are completely filthy. There's no hygiene whatsoever. The staff doesn't go to work; patients are attended by family. Nothing's free of charge; nothing's available.

If you start with a completely different approach to building medicine from top to bottom by establishing high-standard facilities, there is a possibility you can start training qualified personnel and helping other centers not at the same level.

The Salam Center treats patients whose hearts have been damaged by rheumatic fever. Can you talk about the epidemiology of that illness in Africa?

Rheumatic fever is becoming the leading cause of death in Africa. The link to poverty is quite clear. The World Health Organization estimates that around 20 million people have rheumatic fever in Africa. They require two million hospitalizations every year. One million need heart surgery because of that. Two thirds of those affected are children, and there are 300,000 deaths every year. Would there be more of a public health benefit if you spent this money on vaccines and antibiotics instead of on more sophisticated care?

If you're comparing the cost of treatment of patients with heart disease with treatment of patients with malaria, tuberculosis or hepatitis, the cost of cardiac treatment is much higher for sure. But this way of thinking makes sense if we've established that the main factor determining what we do for health is money. The problem is not to put one against the other: malaria versus rheumatic fever. The problem is to understand we have to solve both problems.

PROFILE

NAME
Gino Strada

AGE
65

TITLE
Surgeon; Founder of Emergency (an Italian NGO)

LOCATION
Khartoum, Sudan

How will you get started with the 10 centers of excellence you are building?

We're hoping to construct a center of excellence in pediatric surgery in Uganda. In most cases, it will correct congenital defects. Care will be free of charge, and it won't matter where the patients come from. Uganda will pay 20 percent of the overall cost of the program. If we get the resources, we will start in a very few months. The hospital has already been designed by one of the greatest architects in the world, Renzo Piano, who is a friend of Emergency. *—Gary Stix*

COURTESY OF U.S. PATENT AND TRADEMARK OFFICE (*camera patent*); COURTESY OF EMERGENCY (*Strada*)

COMMENT AT ScientificAmerican.com/may2014

PHARMACOLOGY

Pot Ingredient for Epilepsy

A new marijuana-derived drug may treat epileptic children, without the high

A rising number of epileptic patients are using an alternative medicine to reduce their seizures. The herb in question is *Cannabis sativa*. Among the users are some of the almost 100,000 American children who have "intractable epilepsy," which does not respond to standard antiseizure medications. Some parents report that marijuana helps to control their child's seizures when other standard drugs do not.

There is no pharmaceutical preparation of cannabis as a drug. Instead parents must personally buy pot at a medical marijuana dispensary—or perhaps illegally—to help their child.

The isolation of a chemical in marijuana that may be involved with tamping down seizures could soon change all that. Cannabidiol is a purified compound derived from cannabis that shows promise in treating epilepsy in both adults and children. The chemical, which also is responsible for some of the other health benefits associated with medical marijuana, is the main active ingredient in a new drug under investigation, called Epidiolex, manufactured by GW Pharmaceuticals. Epidiolex contains several other cannabinoid compounds but is formulated without tetrahydrocannabinol, the compound that makes people feel high.

As with some approved seizure medications, researchers do not understand exactly how cannabidiol functions as an anticonvulsant. Whatever its physiological underpinnings, cannabidiol seems to work. Animal studies and preliminary investigations with human adults suggest it significantly reduces seizures and is well tolerated and safe.

Now researchers are making formal efforts to test cannabidiol in children with intractable epilepsy. A year-long clinical trial will test whether it diminishes epileptic activity in 150 children who have not been helped by standard seizure medications. If Epidiolex proves itself, it will supply additional evidence that marijuana may serve as a potential cornucopia of medical leads to be used for future drug development. *—Annie Sneed*

Are E-Cigarettes Safe?

Even without tobacco, the poorly regulated devices may pose unique dangers

Television advertisements for cigarettes have been banned in the U.S. since 1971, but in the past few years supposedly healthier, battery-powered alternatives have landed numerous prime-time appearances. Electronic cigarettes, or e-cigs, as they are known, soaked up the spotlight in recent Super Bowl commercials, on late-night talk shows and in a comedy sketch during the 2014 Golden Globe Awards. Indeed, a recent survey shows that nearly 60 percent of Americans are now familiar with the sleek, smokeless devices.

The concept behind e-cigs is clever: they allegedly offer all the fun of typical cigarettes without any of the dangers. E-cigs use a small, heated coil to vaporize a nicotine-laced solution into an aerosol mist. By inhaling the mist, users enjoy the same satisfaction they would get from an ordinary cigarette but do not expose themselves to tobacco, which turns into cancer-causing tar when it is burned. Such products free smokers from huddling in the cold or rain and, in many places, from ordinances that forbid smoking in public places.

But are e-cigs truly safe? No one knows for sure. Yet there is no question that the nicotine they contain is addictive—which is one reason many public health experts have grown alarmed by their rapidly increasing popularity. Among their concerns: e-cigs might lure former smokers back to conventional cigarettes, expose users and bystanders alike to unidentified dangers, or become a gateway for teens who might subsequently experiment with tobacco products and other drugs.

The U.S. Food and Drug Administration and the European Union are grappling with these issues as they decide how to regulate the products. Unfortunately, they must act before all the facts are available. Unfettered access could leave people vulnerable to unknown health hazards, but there is also the chance that greater restrictions might hurt folks who are trying to forgo conventional—and more dangerous—tobacco products.

FIRST PUFFS

THE CURRENT ITERATION of e-cigarettes was invented and popularized by Chinese pharmacist Hon Lik in 2003 and entered the U.S. market some seven years ago. (Earlier attempts at a "smokeless, non-tobacco cigarette," patented in 1965, never caught on.) Initially the FDA tried to regulate them as drug-delivery devices, defined under federal law as items "intended to affect the structure or any function of the body." E-cigarette company NJOY sued the agency, however, arguing that nicotine-containing devices were similar to tobacco products—which the FDA had also previously tried and failed to have declared drug-delivery systems. A federal appeals court ruled in December 2010 that the agency lacked authority over e-cigs because they offer only the recreational benefits of a regular cigarette. That legal decision allowed sales of e-cigarettes to proceed but left many questions about their safety unaddressed.

In lieu of carcinogenic tobacco, e-cigarettes typically contain three main ingredients: nicotine, a flavoring of some kind and propylene glycol—a syrupy synthetic liquid added to food, cosmetics, and certain medicines to absorb water and help them stay moist. The primary established danger of nicotine is that the stimulant is highly addictive, although emerging science also links it to an impaired immune system. Propylene glycol has been "generally recognized as safe," or GRAS (an official FDA designation), since 1997. Yet more needs to be understood before e-cigarettes can be a given a clean bill of health.

Propylene glycol, for example, is usually eaten (in cupcakes, soft drinks and salad dressings) or slathered onto the body (in soaps, shampoos and antiperspirants)—not breathed into the lungs. Many things that can be safely eaten—such as flour—can damage the lungs when inhaled. No one knows whether propyl-

Illustration by Tom Whalen

ene glycol falls into that category. "We have little information about what happens to propylene glycol in the air," the federal Agency for Toxic Substances and Disease Registry says on its Web site. An assessment from the agency, issued in 2008, references only a couple of studies that cover inhalation exposures—all with laboratory animals rather than people.

Beyond the three main ingredients, some researchers worry about by-products from heating electronic cigarettes and the solution inside them. Various studies suggest the vapors from e-cigarettes contain several cancer-causing substances, as well as incredibly tiny particles of tin, chromium, nickel and other heavy metals, which, in large enough concentrations, can damage the lungs. These particles likely fleck off the solder joints or metal coil in the devices when heated. Because they are so small, the tiniest bits of metal, known as nanoparticles, can travel deep into the lungs. There they could exacerbate asthma, bronchitis—an inflammation of the tubes that carry air to and from the lungs—and emphysema—a disease in which the lungs' many air sacs are destroyed, leaving patients short of breath. So far there are not enough data to say with certainty whether e-cigs worsen these disorders.

Vapors from electronic cigarettes contain several cancer-causing substances, as well as tiny particles of tin, chromium and nickel.

Craig Weiss, president and CEO of NJOY, went on NPR during the summer and espoused the safety of e-cigarettes, pointing to "clinical trial" data he said would soon be published in peer-reviewed literature. When Scientific American requested that study, it received a draft of a small study looking at the use of e-cigs for short-term smoking reduction, not the kind of large, long-term, rigorously conducted trial that has become the gold standard in medicine. "It is not a study that would lead to drug approval," admits Joshua Rabinowitz, NJOY's chief scientist, but a clinical trial "is defined as a test of biological response in a human in a clinical setting, and that is exactly what was done."

The few scientists actively trying to fill the gap in the research literature are running into obstacles. When studying tobacco cigarettes, researchers rely on smoking machines that simulate how frequently a typical smoker takes a puff and how much smoke is inhaled with each breath. No one has yet determined how much e-cig vapor the typical user breathes in, so different studies assume different amounts of vapor as their standard, making it difficult to compare their results. Tracing what happens to that vapor once it is inhaled is equally problematic. When the human body breaks down a foreign substance, one can typically find chemical by-products in hair or urine that provide clues about how it has interacted with cells. This is true for nicotine, but in the case of propylene glycol, no one has established what the relevant by-product is or how to best detect it.

WILD WEST

As scientists struggle to test the safety of e-cigarettes, the devices are becoming more and more popular among teens and preteens. E-cigarette use among U.S. high school students more than doubled from 4.7 percent in 2011 to 10 percent in 2012, according to recent data from the Centers for Disease Control and Prevention's National Youth Tobacco Survey. At least 160,000 students who had never tried conventional cigarettes puffed on e-cigs. Yet another analysis linked e-cig use with greater odds of trying tobacco. They come in kid-friendly flavors, including chocolate, bubble gum and gummy bear. Sold online and in the mall, e-cigarettes are also easy for minors to acquire.

Federal legislative milestones that protect youngsters from conventional cigarettes—such as blocking sales to minors and preventing commercials targeted at adolescents—do not exist for e-cigarettes. In an attempt to remedy the situation, 40 state attorneys general signed a letter last September urging the FDA to assume "immediate regulatory oversight of e-cigarettes, an increasingly widespread, addictive product."

Yet there has been hardly any definitive legislation regarding the sale and consumption of e-cigs in the U.S. Meanwhile Canada has made it illegal to sell e-cigarettes preloaded with nicotine in stores, but the regulation is not well enforced, and customers can buy vials of nicotine online. Things are slightly better across the pond. At press time, the European Parliament had approved a ban on e-cigarette advertising starting in mid-2016, and the ban seemed likely to get approval from the E.U.'s member states.

Without regulations, it is the "Wild West" for e-cigarette companies, says Stanton Glantz, director of the Center for Tobacco Control Research and Education at the University of California, San Francisco, and a self-described e-cigarette pessimist. He argues that given the paucity of health data, current indoor smoking bans should apply to e-cigs as well. "One of the real problems [with] these things is that because of the low quality control, you never quite know what you are getting," he says. Those who support minimal regulation contend that limiting the use of e-cigarettes would encourage more people to smoke conventional cigarettes.

As the debate blazes, deep-pocketed big tobacco investors are buying up e-cig companies, injecting millions of dollars into the market and banking on a bright future for the devices. More than 100 e-cigarette companies are now jockeying for the business of smokers and nonsmokers alike. The success of all these enterprises hinges on the claim that e-cigarettes are healthier than traditional cigarettes. Companies like to paint a black-and-white picture of a new era of safe smoking. "Cigarettes, you've met your match," NJOY proudly proclaims in its Super Bowl ads. Whether e-cigs are genuinely safe is far hazier. SA

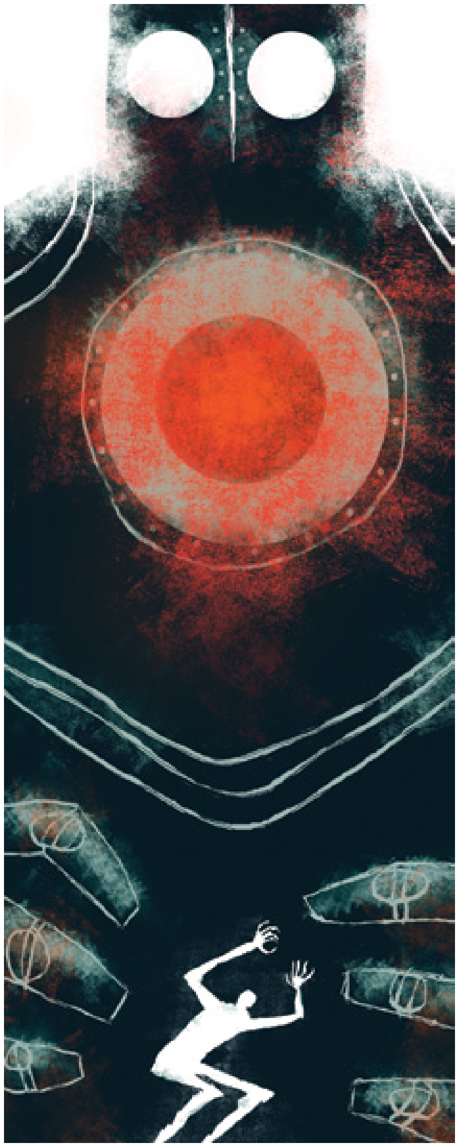
Dina Fine Maron is an associate editor at Scientific American.

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/may2014

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

Fear the Worst

A little outrage over new technology can be a good thing



It's human to fear new technology. We instinctively worry about almost anything that is unknown, probably for sound evolutionary reasons. And in the Fear of the Unknown Department, technologies probably top the list.

It's nothing new. In the 1970s microwave ovens were said to leak radiation and cause birth defects. In the 1950s TV was supposed to rot our brains. In the 1930s people worried that radio would be too stimulating for children's excitable minds, harming their school performance. In the 1800s the tractor, on its first appearance in farmers' fields, was thought to be the devil's work.

New technologies now arrive (and depart) faster than ever. We scarcely have the time to adjust to one status quo before it changes again.

No wonder, then, that our fears for the future are also blooming like crazy.

Today we fear the effect of electronics on our children, their brains and their ability to socialize. We know that big companies and the government are collecting our data, and we are afraid for our privacy. We fret that cell phones give us brain cancer. We worry that the country's 82,000 fracking wells, which push natural gas out of underground shale, may create environmental catastrophe.

It's true that our fears often turn out to be needless (tractors were fairly benign instruments of agriculture). Some modern fears may be misplaced, and some may be genuine causes for alarm; we just don't know yet. These topics are controversial precisely because all the research isn't in. Besides, every now and then, the public's fear of an unfamiliar technology is well founded. Thalidomide, a treatment for morning sickness, really *did* cause birth defects. Cell phone–addled drivers really *do* kill thousands of people a year. The National Security Agency really *was* snooping on Americans.

Should we think about giving up, then? Should we call a five-year moratorium on progress while we assess what we're doing? Should we abandon technology for a simpler life?

Well, that's one option. But the surprising thing about reasonable fear is that it can be healthy—when it's channeled into outrage. And just as we have a long tradition of fearing new technologies, we have another long, proud tradition: course correction.

Give us enough time, and we guide ourselves back onto the tracks almost every time.

Sometimes the transgressions are minor: Facebook overreached in a new privacy statement, Verizon began charging customers $2 a month for making online payments, Netflix announced it would spin off its DVD company, the Federal Aviation Administration banned perfectly harmless gadgets like e-book readers. In each case, public outrage forced the transgressors to retreat.

Sometimes the issues that come up are more serious. Once the science is in, we usually manage to phase out what's killing us (thalidomide, trans fats). Eventually we also get around to phasing out what's killing our planet (sulfur emissions, chlorofluorocarbons).

Many people believe that the NSA scandal was a blight on our government's reputation. I agree. But the resulting outrage has been fantastic. We don't know yet what kind of limits will be put on the NSA's actions, although you can bet that its days of entirely unsupervised freedom are over.

Meanwhile the national conversation about privacy triggered a ripple effect. As a result of the NSA revelations, the big tech companies (Google, Yahoo, Facebook, and so on) now encrypt all their data to and from your computer. The public is demanding to know exactly what those companies do with our data—and now know to keep a better eye on them to make sure they tell the truth.

Technology will always change us, and it will always frighten us, but we will push back when necessary. Okay, not every time and not always promptly. In general, though, we can count on the beneficial results of outrage, course corrections—and fear. SA

SCIENTIFIC AMERICAN ONLINE
A brief history of outrage: ScientificAmerican.com/may2014/pogue

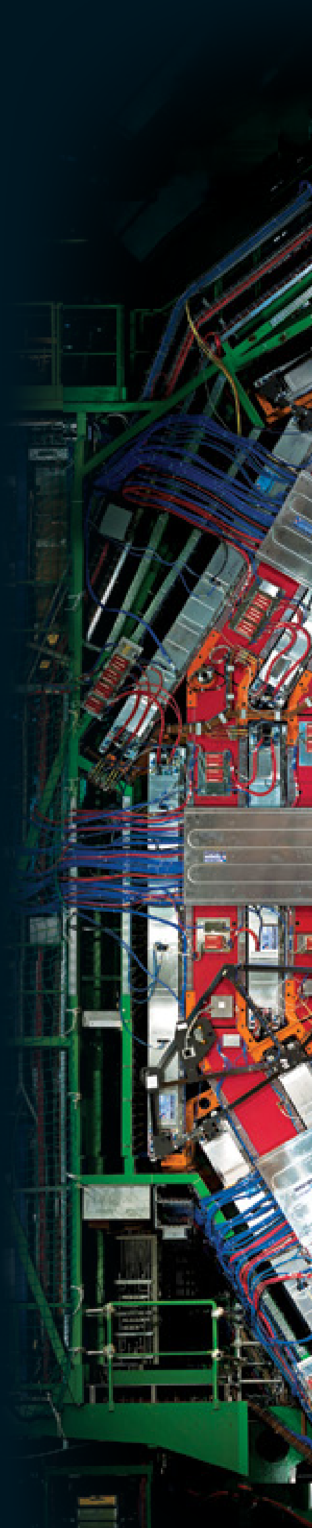
Illustration by Jeffrey Alan Love

For decades physicists have been working on a beautiful theory that has promised to lead to a deeper understanding of the quantum world. **Now they stand at a crossroads:** prove it right in the next year or confront an epochal paradigm shift

By Joseph Lykken and Maria Spiropulu

PARTICLE PHYSICS

Supersymmetry and the Crisis in Physics

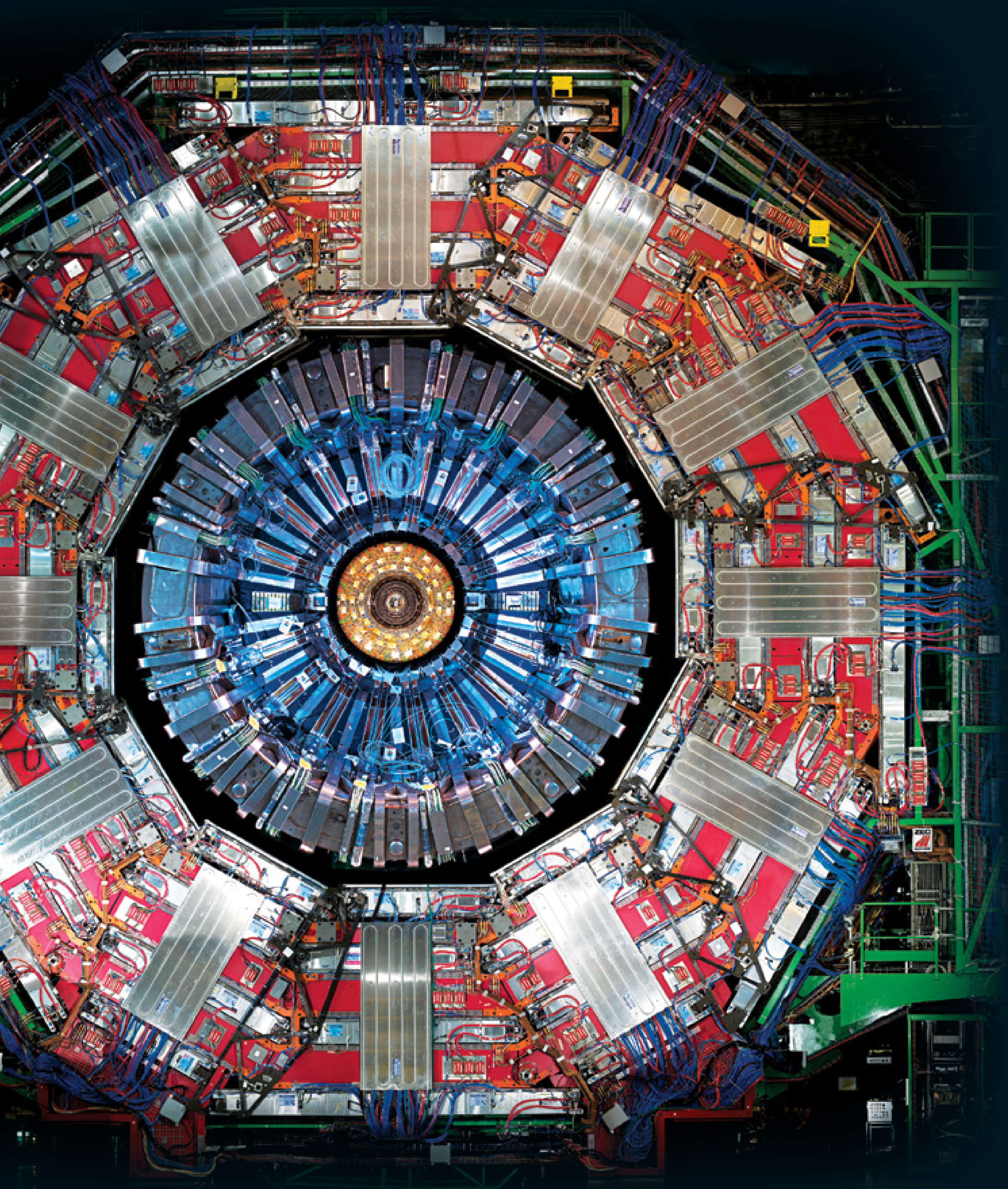


IN BRIEF

Supersymmetry postulates that every known particle has a hidden superpartner. Physicists love supersymmetry because it solves a number of problems that crop up when they try to extend our understanding of quantum mechanics. It would also potentially solve the mystery of the universe's missing dark matter.

Physicists hoped to find evidence of supersymmetry in experiments at the Large Hadron Collider (LHC). To date, they have not. If no evidence arises in the next run of the LHC, supersymmetry will be in trouble.

The failure to find superpartners is brewing a crisis in physics, forcing researchers to question assumptions from which they have been working for decades.



CMS DETECTOR at the Large Hadron Collider will start its final search for evidence of supersymmetry when the LHC starts back up in early 2015.

Joseph Lykken is a theoretical physicist based at the Fermi National Accelerator Laboratory in Batavia, Ill.

Maria Spiropulu is an experimental particle physicist based at the California Institute of Technology. She searches for supersymmetry with the CMS experiment at CERN's Large Hadron Collider after spending many years at Fermilab's Tevatron.

At dawn on a summer morning in 2012, we were on our third round of espresso when the video link connected our office at the California Institute of Technology to the CERN laboratory near Geneva. On the monitor we saw our colleagues on the Razor team, one of many groups of physicists analyzing data from the CMS experiment at CERN's Large Hadron Collider (LHC). Razor was created to search for exotic collisions that would provide the first evidence of supersymmetry, a 45-year-old theory of matter that would supplant the standard understanding of particle physics, solving deep problems in physics and explaining the nature of the universe's mysterious dark matter. After decades of searching, no experimental evidence for supersymmetry has been found.

At CERN, Maurizio Pierini, the Razor team's leader, flashed a plot of new data, and from nine time zones away we could see the raised eyebrows around the room: there was an anomaly. "Somebody should look at this event," Pierini said matter-of-factly. By "event" he meant a particular proton-proton collision, one of trillions produced at the LHC. Within minutes the two of us had pulled up the full record for this collision on a laptop.

Supersymmetry is an amazingly beautiful solution to the deep troubles that have been nagging at physicists for more than four decades. It provides answers to a series of important "why" questions: Why do particles have the masses they do? Why do forces have the strengths they do? In short: Why does the universe look the way it does? In addition, supersymmetry predicts that the universe is filled with heretofore hidden "superpartner" particles that would solve the mystery of dark matter. It is not an exaggeration to say that most of the world's particle physicists believe that supersymmetry *must* be true—the theory is that compelling. These physicists' long-term hope has been that the LHC would finally discover these superpartners, providing hard evidence that supersymmetry is a real description of the universe.

As we pulled up the interesting collision, we immediately saw that it appeared to be a smoking-gun signal of supersymmetry. Two clusters of very energetic particles were observed moving one way, recoiling against something unseen—perhaps a superpartner? Yet soon enough we noticed a big red spike on the readout. Could this be a fake signal from a detector malfunction? And so it turned out—another disappointment in the seemingly unending quest to find supersymmetry.

Indeed, results from the first run of the LHC have ruled out almost all the best-studied versions of supersymmetry. The negative results are beginning to produce if not a full-blown crisis in particle physics, then at least a widespread panic. The LHC will be starting its next run in early 2015, at the highest energies it was designed for, allowing researchers at the ATLAS and CMS experiments to uncover (or rule out) even more massive superpartners. If at the end of that run nothing new shows up, fundamental physics will face a crossroads: either abandon the work of a generation for want of evidence that nature plays by our rules, or press on and hope that an even larger collider will someday, somewhere, find evidence that we were right all along.

Of course, the story of science has many examples of long quests succeeding triumphantly—witness the discovery of the long-sought Higgs boson at the LHC. But for now most particle theorists are biting their nails, as LHC data are about to test the foundations of the mighty cathedral of theoretical physics that they have built up over the past half-century.

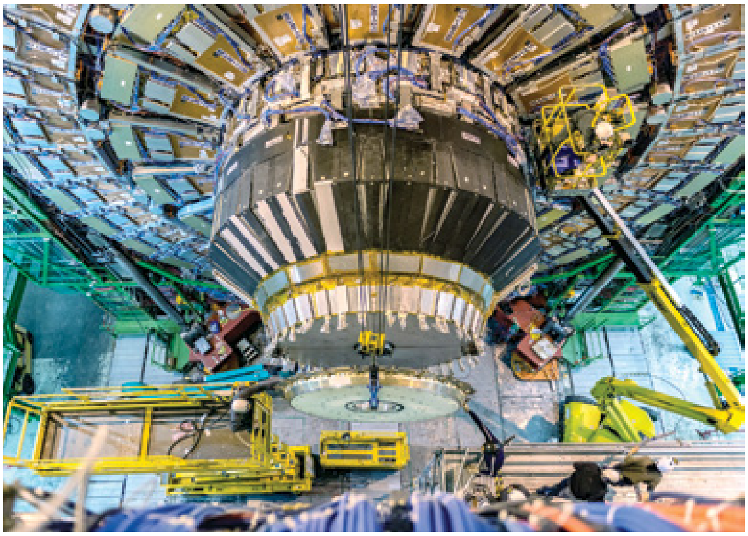
THE NEED FOR SUPERSYMMETRY

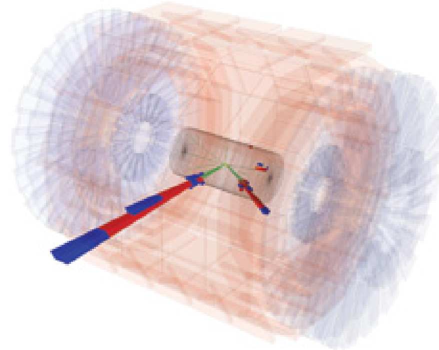
SUPERSYMMETRY IS PART of a broader attempt to understand the big mysteries of quantum weirdness. We have a fantastically successful and predictive theory of subatomic physics, prosaically known as the Standard Model, which combines quantum mechanics with Einstein's special theory of relativity to describe particles and forces. Matter is made of one variety of particles called fermions (after Enrico Fermi) and held together by forces related to another type of particle called bosons (after Satyendra Bose).

The Standard Model provides an excellent description of what goes on in the subatomic world. But we begin to get into trouble when we ask the questions of why the Standard Model has the features that it does. For example, it holds that there are three different types of leptons (a type of fermion): the electron, muon and tau. Why three? Why not two, or four, or 15? The Standard Model does not say; we need to explore a deeper level of nature to discover the answer. Similarly, we might ask, Why does the electron have the mass that it does? Why is it lighter than, say, the Higgs boson? Again: on this, the Standard Model is silent.

Theoretical particle physicists spend a lot of time thinking about such questions. They build models that explain why the Standard Model looks the way it does. String theory, for example, is one effort to get down to a deeper level of reality. Other examples abound.

PRECEDING PAGES: COURTESY OF CERN





UPGRADES to the CMS experiment (*left*) will aid in the search for supersymmetry. A positive signal of supersymmetry would look much like this 2012 event (*above*): two high-energy jets of particles on the lower half of the detector imply that missing matter—perhaps a "dark" superpartner—is escaping above.

COURTESY OF CERN (*CMS construction*); COURTESY OF CMS COLLABORATION (*CMS event*)

All these additional theories have a problem, however. Any theory (like string theory) that involves new physics necessarily implies the existence of new hypothetical particles. These particles might have an extremely high mass, which would explain why we have not already spotted them in accelerators like the LHC, as high-mass particles are difficult to create. But even high-mass particles would still affect ordinary particles like the Higgs boson. Why? The answer lies in quantum weirdness.

In quantum mechanics, particles interact with one another via the exchange of so-called virtual particles that pop into and out of existence. For example, the repulsive electric force between two electrons is described, to first approximation, by the electrons exchanging a virtual photon. Richard Feynman derived elegant rules to describe quantum effects in terms of stable particles interacting with additional virtual particles.

In quantum theory, however, anything that is not strictly forbidden *will* in fact happen, at least occasionally. Electrons will not just interact with one another via the exchange of virtual particles, they will also interact with all other particles—including our new, hypothetical particles suggested by extensions of the Standard Model. And these interactions would create problems—unless, that is, we have something like supersymmetry.

Consider the Higgs boson, which in the Standard Model gives elementary particles mass. If you had a Higgs but also had some superheavy particles, they would talk to one another via virtual quantum interactions. The Higgs would itself become superheavy. And the instant after that, everything in the universe would transform into superheavy particles. You and I would collapse into black holes. The best explanation for why we do not is supersymmetry.

THE PROMISE OF SUPERSYMMETRY

THE BASIC IDEA of supersymmetry, generally known by the nickname "SUSY" (pronounced "Suzy"), was developed by physicists in the 1970s who were interested in the relation between symmetries and particle physics. Supersymmetry is not one particular theory but rather a framework for theories. Many individual models of the universe can be "supersymmetric" if they share certain properties.

Many ordinary symmetries are built into the physical laws for particles and forces. These laws do not care about where you are, when you do the measurement, what direction you are facing, or whether you are moving or at rest with respect to the objects that you are observing. These spacetime symmetries mathematically imply conservation laws for energy, momentum and angular momentum; from symmetries themselves, we can derive the relation between energy, momentum and mass famously exemplified by $E = mc^2$. All of this has been pretty well understood since 1905, when Albert Einstein developed special relativity.

Quantum physics seems to respect these symmetries. Scientists have even used the symmetries to predict new phenomena. For example, Paul Dirac showed in 1930 that when you combine quantum mechanics with relativity, spacetime symmetries imply that every particle has to have a related antiparticle—a particle with opposite charge. This idea seemed crazy at the time because no one had ever seen an antiparticle. But Dirac was proved right. His theoretical symmetry arguments led to the bold but correct prediction that there are about twice as many elementary particles as everyone expected.

Supersymmetry relies on an argument that is similar to Dirac's. It postulates that there exists a quantum extension of spacetime called superspace and that particles are symmetric in this superspace.

Superspace does not have ordinary spatial dimensions like left-right and up-down but rather extra fermionic dimensions. Motion in a fermionic dimension is very limited. In an ordinary spatial dimension, you can move as far as you want in any direction, with no restriction on the size or number of steps that you take. In contrast, in a fermionic dimension your steps are quantized, and once you take one step that fermionic dimension is "full." If you want to take any more steps, you must either switch to a different fermionic dimension, or you must go back one step.

If you are a boson, taking one step in a fermionic dimension turns you into a fermion; if you are a fermion, one step in a fermionic dimension turns you into a boson. Furthermore, if you take one step in a fermionic dimension and then step back again, you will find that you have also moved in ordinary space or time by some minimum amount. Thus, motion in the fermionic dimensions is tied up, in a complicated way, with ordinary motion.

Why does all of this matter? Because in a supersymmetric world, the symmetries across fermionic dimensions restrict how particles can interact. In particular, so-called natural supersymmetries greatly suppress the effects of virtual particles. Natural supersymmetries prevent Higgs bosons from interacting with high-energy particles in such a way that we all turn into black holes. (Theories that are supersymmetric but not natural require us to come up with additional mechanisms to suppress virtual particles.) Natural supersymmetry clears the way for physicists to develop new ideas to make sense of the Standard Model.

THE SEARCH FOR SUPERSYMMETRY

ALL SUPERSYMMETRIC THEORIES imply that every boson particle has a fermion partner particle, a superpartner, and vice versa. Because none of the known boson and fermion particles seem to be superpartners of one another, supersymmetry can be correct only if the universe contains a large number of superpartner particles that have eluded detection.

Therein lies the rub. In the simplest, most powerful versions of supersymmetry—natural supersymmetry—the superpartners should not be that much heavier than the Higgs boson. That means that we should be able to find them at the LHC. Indeed, if you would have asked physicists 10 years ago, most would have guessed that by now we should have already found evidence of superpartners.

And yet we have not. One of us (Spiropulu) remembers the night in 2009 that I went to work as a shift leader at the CMS detector just before midnight. The control room was crowded with physicists, each monitoring a different subsystem of the massively complex, 14,000-metric-ton detector. At 2 A.M., I got a call from the CERN Control Center on the opposite side of the 27-kilometer-long LHC ring: tonight was the night; they were going for the highest-energy proton collisions ever attempted.

I gave the signals to carefully bring up each portion of the CMS, keeping the more fragile parts of the detector for last. At 4:11 A.M., the full detector went live. A wall of monitors went wild, with ultrafast electronics flashing displays of the collisions happening 20 million times a second 100 meters below. After chasing supersymmetry for a decade at Fermilab's Tevatron collider in Batavia, Ill., my heart leapt in anticipation of recognizing certain patterns. Calm, I told myself, this is only the beginning—it is seductive to analyze collisions by visual inspection, but it is impossible to make a discovery like that.

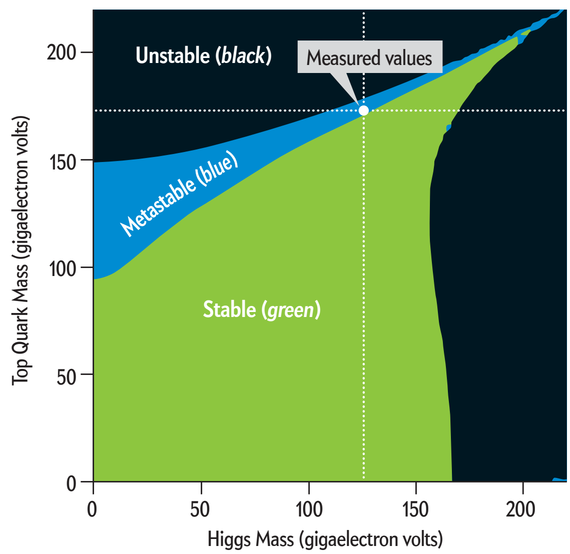
Indeed, you don't build a $10-billion collider with its giant detectors, turn it on and expect discoveries on the first night—or even during the first year. Yet our expectations were high from the very start. At CMS (and at ATLAS), we had laid out an elaborate plan to discover supersymmetry with the first LHC data. We had geared up to find dark matter particles in supersymmetry signals, not directly but as "missing energy": a telltale imbalance of visible particles recoiling from something unseen. We even went so far as to write a template for the discovery paper with a title and a date.

That paper remains unwritten. The experiments have left only a few unexplored windows in which superpartners might be hiding. They can't be too light, or we would have found them already, and they can't be too heavy, because then they wouldn't satisfy the needs of natural supersymmetry, which is the type of supersymmetry that is effective at suppressing virtual particles. If the LHC does not find them during its next run—and does not do so quickly—the crisis in physics will mount.

COSMIC CONSEQUENCES

The Edge of Doom

The Higgs boson reveals a lot about the Higgs field, an energy field that gives elementary particles mass. So far as we know, this field is constant because any sudden change would destroy the universe. Yet the recently measured mass of the Higgs boson, when combined with the top quark's mass, indicates that the Higgs field is not completely stable. Instead it is in a so-called metastable state. Quantum effects could bounce it into a lower energy state, annihilating the universe in the process. (Don't worry: it shouldn't happen for many billions of years.) Supersymmetry would help stabilize the Higgs field.



SOURCE: "HIGGS MASS AND VACUUM STABILITY IN THE STANDARD MODEL AT NNLO," BY GIUSEPPE DEGRASSI ET AL., IN *JOURNAL OF HIGH ENERGY PHYSICS*, VOL. 2012, NO. 8, ARTICLE NO. 98; AUGUST 2012

LIFE AFTER SUPERSYMMETRY

THEORISTS ARE NOT READY to give up on a more general idea of supersymmetry, though—even if it cannot do all the work that we were hoping natural supersymmetry would do. Recall that supersymmetry is a framework for making models of the world, not a model itself, so future data may vindicate the idea of supersymmetry even if all current models are excluded.

During a talk at the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara, Nima Arkani-Hamed, a physicist at the Institute for Advanced Study in Princeton, N.J., paced to and fro in front of the blackboard, addressing a packed room about the future of supersymmetry. What if supersymmetry is not found at the LHC, he asked, before answering his own question: then we will make new supersymmetry models that put the superpartners just beyond the reach of the experiments. But wouldn't that mean that we would be changing our story? That's okay; theorists don't need to be consistent—only their theories do.

This unshakable fidelity to supersymmetry is widely shared. Particle theorists do admit, however, that the idea of natural supersymmetry is already in trouble and is headed for the dustbin of history unless superpartners are discovered soon. This is the kind of conundrum that has in the past led to paradigm shifts in science. For example, more than a century ago the failure to find the "luminiferous ether" led to the invention of special relativity.

SCIENTIFIC AMERICAN ONLINE How the LHC is being rebuilt in an effort to find supersymmetry (and more)—watch a video at **ScientificAmerican.com/may2014/lhc**

If supersymmetry is not a true description of the world, what might take its place? Here are three different speculative answers. All of them imply profoundly new directions for thinking about basic physics and cosmology:

The multiverse: The strengths of the fundamental forces and the relative size of particle masses involve numbers, the origins of which are a mystery. We don't like to think that the numbers are random, because if they were slightly different, the universe would be a much different place. Atoms would have trouble forming, for example, and life would fail to evolve. In the parlance of theoretical physics, the universe appears to be "finely tuned." Supersymmetry attempts to provide an answer for why these parameters take the values they do. It carves out a doorway to a deeper level of physics. But what if that doorway doesn't exist?

In that case, we are left to consider the possibility that this fine-tuning is just a random accident—a notion that becomes more appealing if one postulates a multiverse. In the multiverse scenario, the big bang produced not just the universe that we see but also a very large number of variations on our universe that we do not see. In this case, the answer to questions such as "Why does the electron have the mass that it does?" takes an answer in the form of: "That's just the random luck of the draw—other parts of the multiverse have different electrons with different masses." The seemingly precise tunings that we puzzle over are mere accidents of cosmic history. Only the universes with parameters finely tuned to allow life to develop will have physicists in them wondering why they did not find natural supersymmetry at the LHC.

To many physicists, however, the multiverse bears an uneasy resemblance to asserting that anomalies in particle physics are caused by armies of invisible angels. As Nobel laureate David Gross has said, appealing to unknowable initial conditions sounds like giving up.

Extra dimensions: Physicists Lisa Randall of Harvard University and Raman Sundrum of the University of Maryland have shown that an extra dimension with a "warped" geometry can explain gravity's weakness in comparison with the other known forces. If these extra dimensions are microscopic, we might not have noticed them yet, but their size and shape could have a dramatic effect on high-energy particle physics. In such models, rather than finding superpartners at the LHC, we may discover Kaluza-Klein modes, exotic heavy particles whose mass is actually their energy of motion in the extra dimensions.

Dimensional transmutation: Instead of invoking supersymmetry to *suppress* virtual particle effects, a new idea is to *embrace* such effects to explain where mass comes from. Consider for a moment the proton. The proton is not an elementary particle. It is made up of an assembly of three quarks, which have a minuscule mass, and gluons, which have no mass at all. The proton is much heavier than the sum total of the quarks and gluons inside of it. Where does this mass come from? It comes from the energy fields generated by the "strong" force that holds the proton together. Our understanding of these fields allows us to accurately predict the proton's mass based on just ordinary numbers such as pi.

It's an odd situation in particle physics. Usually we can compute masses only by starting with other masses. For example, the Standard Model gives us no way to predict the mass of the Higgs boson—we have to measure it. This seems like an obvious mistake, given how cleverly we can predict the mass of the proton. Building on seminal work by William A. Bardeen, a physicist at Fermilab, a few radical theorists are now suggesting that the Higgs mass scale is generated through a similar process called dimensional transmutation.

If this approach is to keep the useful virtual particle effects while avoiding the disastrous ones—a role otherwise played by supersymmetry—we will have to abandon popular speculations about how the laws of physics may become unified at superhigh energies. It also makes the long-sought connection between quantum mechanics and general relativity even more mysterious. Yet the approach has other advantages. Such models can generate mass for dark matter particles. They also predict that dark matter interacts with ordinary matter via a force mediated by the Higgs boson. This dramatic prediction will be tested over the next few years both at the LHC and in underground dark matter detection experiments.

The Higgs may hold other clues. The discovery of the Higgs boson shows that there is a Higgs energy field turned on everywhere in the universe that gives mass to elementary particles. This means that the vacuum of "empty" space is a busy place, with both Higgs energy and virtual particles producing complicated dynamics. One might then wonder if the vacuum is really stable or if some unlucky quantum event could one day trigger a catastrophic transition from our universe to a clean slate. Supersymmetry acts to stabilize the vacuum and prevent such mishaps. But without supersymmetry, the stability of the vacuum depends sensitively on the mass of the Higgs: a heavier Higgs implies a stable universe, whereas a lighter one implies eventual doom. Remarkably, the measured Higgs mass is right on the edge, implying a long-lived but ultimately unstable vacuum [*see box on opposite page*]. Nature is trying to tell us something, but we don't know what.

THE FUTURE

IF SUPERPARTNERS ARE DISCOVERED in the next run of the LHC, the current angst of particle physicists will be replaced by enormous excitement over finally breaching the threshold of the superworld. A wild intellectual adventure will begin.

Yet if superpartners are not found, we face a paradigm rupture in our basic grasp of quantum physics. Already this prospect is inspiring a radical rethinking of basic phenomena that underlie the fabric of the universe. A better understanding of the properties of the Higgs boson will be central to building a new paradigm. Experimental signals of dark matter, that lonely but persistent outlier of particle physics, may ultimately be a beacon showing the way forward. SA

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scientificamerican.com/magazine/sa

MEDICINE

Cancer's Off Switch

By releasing the brakes that tumor cells place on the immune system, researchers are developing a new generation of more powerful treatments against malignancy

By Jedd D. Wolchok

Illustration by Christopher Buzelli

Jedd D. Wolchok is chief of the Melanoma and Immunotherapeutics Service at Memorial Sloan Kettering Cancer Center in New York City. He consults for the pharmaceutical companies Bristol-Myers Squibb, Merck, MedImmune and EMD Serono but has no financial interest in the success of the medications mentioned in this article.

IN JUNE 2004 I WAS ASKED to examine a 22-year-old woman who had just graduated from college and was engaged to be married. During the months leading up to her graduation, Shirley (not her real name) had been plagued by a nagging cough. Eventually a computed tomographic (CT) scan revealed multiple masses in and around her lungs. A biopsy indicated metastatic melanoma that had spread from a skin cancer Shirley did not know she had. She immediately began chemotherapy treatments timed around a hastily rescheduled wedding.

Unfortunately, two rounds of chemotherapy and radiation treatments to her brain over the next two years slowed but could not stop the tumors' spread. Shirley was running out of options. I told her about a new study in which an innovative medicine designed to supercharge a patient's own immune system against cancer was being tested.

It was a randomized trial, meaning not every participant would get the new medicine, at the time known as MDX-010, but Shirley agreed to participate. After four treatments, a new set of CT scans showed that every trace of melanoma had disappeared. To this day, Shirley remains in complete remission; she has two beautiful, healthy children and, in her own words, has "gotten her life back."

For me, as a cancer specialist and a researcher, seeing Shirley's transformation validated many years of hope that scientists could develop powerful cancer therapies that would work by setting the body's own immune system against malignancies. Optimism grew throughout the medical community last year as we learned about similar successes with this and other immunotherapy treatments in patients with advanced leukemia and kidney and lung cancers. Although immunotherapy is by no means a panacea, the recent advances may allow us to make significantly more progress against the later stages of cancer than we have been able to achieve in recent decades.

MULTILAYERED DEFENSES

THE NOTION that the immune system could control cancer is not new. Attempts to harness host defenses against malignancy date back over 100 years to when William Coley, a surgeon at New York Cancer Hospital (now Memorial Sloan Kettering Cancer Center), tried using heat-killed bacteria for this purpose. After noticing that some patients seemed to live longer if they developed an infection after their cancer surgery, Coley hypothesized that the intrinsic defense system that had been mobilized against the pathogen could also affect the tumor.

During the ensuing decades, basic scientists have revealed much about the cells that make up this protective system, as well as the chemical mediators and molecular switches that precisely control it. In that time, they have learned how the immune system rapidly mobilizes to detect potentially dangerous infectious pathogens such as bacteria or viruses. Just as important, researchers have detailed the many checks and balances that usually signal the immune system to limit its response so that it does not wind up destroying too much normal tissue in the process. All told, they have gained detailed insights into how the immune system reacts to, and is affected by, cancer.

The first layer of defense against pathogens consists of a general response against bacteria and viruses that is coordinated by white blood cells known as neutrophils and monocytes. These cells belong to what is called the innate immune system, and their function is to recognize certain aspects of molecular anatomy common to all bacteria or viruses—such as parts of their outer coating or quirks in the structure of their DNA and RNA molecules that differ from what is found in higher organisms. Although these white blood cells do not target specific species or proteins for attack, they nonetheless manage to destroy many of the microbiological invaders and, as a result, generate molecular fragments, referred to as antigens, that other players of the immune system perceive as foreign.

Cells responsible for the second layer of defenses, called the adaptive immune system, take these antigens as the starting point for a much more precisely targeted response that, if successful, will create a living memory of the microbial invaders so that they can be more easily defeated in the future. Two different

IN BRIEF

Although conventional cancer therapies attack tumors directly, immunotherapy attempts to rally the body's own defenses against malignant growths.

To date, most immunotherapies try to drive an anticancer response the same way a driver increases a car's speed by applying pressure to the gas pedal.

A new approach to immunotherapy attempts to release the brakes that normally hold back an otherwise powerful immune response.

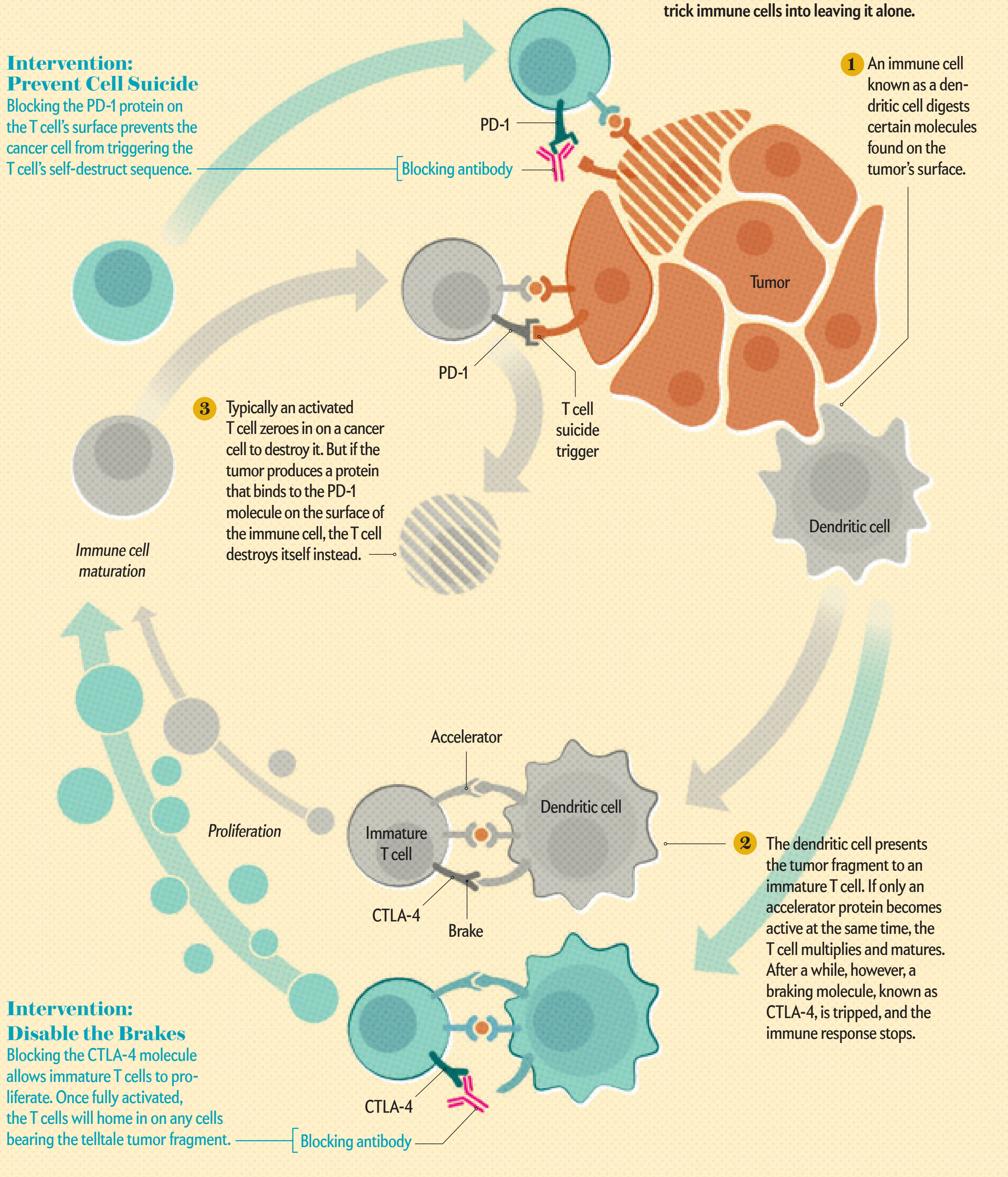
A handful of clinical trials have shown remarkable, long-lasting results in such diverse cancers as metastatic melanoma and advanced kidney and lung cancer.

Delivering a One-Two Punch

Basic research into how the immune system tries—and sometimes fails—to fight cancer (*gray pathway below*) prompted investigators to develop two new approaches (*depicted in blue*) to help turbocharge the body's own defenses against a tumor.

Why Nature Needs a Boost

Normally you would expect the immune system to destroy tumors, but the body's own internal checks and balances can hamper its ability to attack malignant growths. In addition, some cancers actively interfere with the immune response. Here we show how the immune system might recognize a tumor (1) and then stifle itself (2), as well as one way (3) a malignant growth can trick immune cells into leaving it alone.



Graphic by Jen Christiansen

types of cells—T cells and B cells—lie at the heart of this adaptive response. There are various types of T cells, but all descend from precursors that emerge from the thymus gland, a small organ that sits just on top of the heart in the center of the chest. B cells, for their part, are originally derived from the bone marrow and give rise to antibody molecules. Antibodies and certain molecules on T cells home in on specific antigens, thereby allowing the immune system to target and destroy bacteria and infected cells that display these antigens on their surface.

When the immune system is working optimally, both its general and adaptive branches cooperate to identify and rid the body of dangerous pathogens. In addition, a subset of T cells retains a long-term molecular memory of the original threat so that it can be neutralized more quickly at a future date if it is encountered once again.

One in five patients with metastatic melanoma given ipilimumab is alive after three years versus an average survival time of eight months.

Cancers are not infections, of course. They arise when the body's own cells undergo certain genetic and other changes. Even so, the immune system ought to be able to recognize malignant cells because they display abnormal molecular fragments, which should look foreign to T and B cells. For various reasons, however, the immune system often fails to fight cancers effectively. Through the years, efforts to pump up the response have met with mixed results. The recent, more consistently successful approaches take a different tack. It turns out that cancers sometimes co-opt the usual shutoff switches of the immune system and actively dampen immune responses to malignancies. The new approaches attempt to disable those brakes.

CHECKS AND BALANCES

THE EXPERIMENTAL MEDICATION that saved Shirley's life fits into the new paradigm. It grew out of research into a protein called CTLA-4, which is present in many kinds of T cells but jumps into action only after certain T cells recognize their target and receive a "go" signal from other molecules. When activated, CTLA-4 and a number of other proteins work like a series of molecular brakes or checkpoints that prevent the immune system from becoming overly destructive.

The necessity of these checkpoints can be seen in animals deficient in them. Mice that have been genetically engineered so that they lack the CTLA-4 protein die within three to four weeks of age. With nothing to stop the escalation of the immune response, activated T cells infiltrate all the normal organs in the body, causing their complete destruction. This finding, published in 1995, showed that the permanent lack of this single molecule could cause a devastating autoimmune reaction.

That same year, James Allison, then working at the University of California, Berkeley, hypothesized that if the CTLA-4 molecular brake could be temporarily disabled, the immune system would be able to launch a more vigorous attack on cancer cells, resulting in the shrinkage of tumors. Allison and his colleagues set out to test that hypothesis in mice by delivering a synthetically developed antibody that obstructs CTLA-4 activity.

Sure enough, blocking CTLA-4 resulted in the regression of several types of tumors—including colon cancer and sarcoma—that had been transplanted into the laboratory animals. In other experiments, melanoma tumors shrank considerably when mice were treated with the CTLA-4-blocking antibody and an experimental vaccine, made from altered melanoma cells, that was designed to incite an immune attack specifically against that cancer.

The next step was to try this approach, technically referred to as immunologic checkpoint blockade, in people. Allison turned to the biotechnology company Medarex, which developed a fully human version of a CTLA-4-blocking antibody (originally called MDX-010 and now known as ipilimumab), and began clinical trials in patients who had very advanced cancers that had not responded to other therapies. Medarex was later bought by Bristol-Myers Squibb, which further developed the drug and won regulatory approval for it in 2011.

Starting with the first experiment and continuing with subsequent ones, some patients experienced profound tumor regressions. But before they did, early tests of whether the treatment was working gave curious results. Investigators soon learned that when it comes to immunotherapy, the usual ways of assessing whether a cancer treatment is working could be misleading.

SUCCESS RATES

ONCOLOGISTS CAN USUALLY TELL fairly quickly how well a patient is responding to standard anticancer treatments. We use various imaging techniques—CT, positron-emission tomography or magnetic resonance imaging to measure the size of a tumor immediately before starting treatment and then again about six weeks later. If the malignant growth is appreciably smaller, we can decide to continue treatment because we know it is having an effect, consider a different approach or stop treatment altogether.

Making such decisions about immunotherapy is not quite as straightforward. For starters, we have to allow more time for the immune system to become activated, so we generally do not take a second measurement of the tumor's size until 12 weeks after treatment has begun. Even considering the additional six weeks of observation and treatment, however, the results of the CTLA-4-blocking experiments were perplexing. Some patients had scans that were clearly better, whereas others showed enlargement of preexisting tumors and even the appearance of new growths. Yet some of the patients with bigger tumors actually felt better.

We now see two plausible explanations for why tumors grow after immunotherapy: the treatment is not working, or a large number of T cells and other immune cells have begun flooding the malignant growth. In other words, bigger tumors might, paradoxically, mean that the treatment is actually working; we just have to wait a little longer for the growths to shrink. Given how

SCIENTIFIC AMERICAN ONLINE Watch a video of Wolchok explaining his research at ScientificAmerican.com/may2014/wolchok-video

difficult it can be to measure progress during immunotherapy, researchers testing ipilimumab now use the simple and important assessment of overall survival (how long patients live) as the most appropriate end point for their analyses.

Results of the latest clinical studies show that just over 20 percent of patients with metastatic melanoma who are treated with ipilimumab demonstrate long-term control of their disease, remaining alive for more than three years since beginning treatment. This is an important fact to note because before the development of modern medicines such as ipilimumab, median life expectancy for metastatic melanoma was seven to eight months. Indeed, some of the earliest recipients, like Shirley, are alive more than five years after treatment.

Meanwhile research has progressed on a second immune system–braking molecule called PD-1, which dots the surface of many T cells. When bound by certain other molecules, PD-1 compels the cells on which it is found to destroy themselves—a normal process that, as with the closely related CTLA-4 protein, helps to bring an ongoing immune reaction to a safe stop. Some tumor cells, however, have evolved to defend themselves by covering their surface with molecules that trick the PD-1 proteins on T cells into starting the self-destruct sequence too soon. As a result, any T cell that attacks a cancer cell receives a signal to destroy itself instead. This striking example is one of the many ways that tumors can render the immune system ineffective.

Half a dozen companies—Bristol-Myers Squibb, CureTech, EMD Serono, Genentech, Merck and MedImmune—have now developed antibodies that block various tumors from inducing PD-1-mediated suicide in T cells. In recent trials, these experimental compounds have shown long periods of remissions, some lasting years, in more than 30 percent of patients with advanced melanoma. Several of my colleagues at Memorial Sloan Kettering and collaborators at many other centers have tried these PD-1-blocking agents in patients with a type of lung cancer. More than 20 percent of participants had durable regressions.

The lung cancer results, which were reported in June 2012, proved to be a turning point for the field of immunotherapy. No longer can skeptical clinicians dismiss the approach as likely to be viable for only a few specific kinds of tumors, such as melanoma and kidney cancer, that have previously been shown to be particularly sensitive to immune treatments. Immunotherapy now appears to work for a broader range of cancers as well. Odds are that this approach will soon join chemotherapy and radiation as a standard treatment for many kinds of tumors.

As with most cancer treatments, these immunotherapies trigger some side effects. Patients receiving anti-CTLA-4 medication, for example, may suffer inflammatory reactions in the skin and large intestine that are caused when immune cells release an overabundance of excitatory chemicals. The resulting rashes and painful bouts of cramps and diarrhea are typically controlled with immunosuppressing steroids such as prednisone. Patients who are given PD-1-blocking therapy may also experience these flare-ups—particularly in the kidneys, lungs and liver—but they are generally less frequent and usually of lower severity compared with those of a CTLA-4 blockade. Fortunately, the use of anti-inflammatory drugs does not seem to dampen the therapeutic effect of either drug on tumors.

Inflammation can lead to greater problems. For a long time, researchers worried that the excitatory cascade could lead to full-blown autoimmune reactions, in which the immune system cannot be stopped from targeting ever larger amounts of normal tissue for destruction. Unlike a true autoimmune disease, however, these inflammatory side effects appear to be transient and do not recur after they are initially treated.

Because antibodies against PD-1 and CTLA-4 seem to boost the immune response to tumors in different ways, it makes sense to investigate whether concurrent treatment with the drugs can be safe and effective. In 2007 experiments on lab animals with colon cancer and melanoma showed that the combination of CTLA-4 and PD-1 blockade was more effective than using either agent alone. Therefore, in 2010 my group, working together with Mario Sznol of Yale University, decided to undertake a small safety study of ipilimumab and the PD-1-blocking drug nivolumab in 53 patients with metastatic melanoma.

The results, which we reported at a medical conference last year, were impressive. More than 50 percent of patients treated with what we considered to be optimal doses of the antibodies showed tumors shrinking by more than half their original size. These responses appear to be dramatically different from those seen with either agent by itself. Side effects were more common than with each medicine alone but were controllable, as before, with corticosteroids. It is important to note that these are early results in a modestly sized study and may not appear as favorable in a larger or longer trial. We are currently conducting a more extensive study of a combined blockade with ipilimumab and nivolumab in more than 900 melanoma patients.

Other researchers are investigating this combined immunotherapy for treating lung cancer, kidney cancer, gastric cancer, breast cancer, head and neck cancer, and pancreatic cancer. It is also possible that the addition of direct attacks on the tumor—with chemotherapy or radiation—may render immunotherapy even more effective if the cancer cells die in a way that triggers the innate branch of the immune system. The result could be a perfect therapeutic "storm" of killing tumor cells and allowing the debris to be recognized more avidly by the immune system. Such a combination should also allow the formation of memory T cells that will maintain an enhanced vigilance against further cancer growth long after treatment has stopped. Whether this kind of immunotherapy could or should be combined for potentially greater effect with some of the other types of immunotherapy now being developed—such as cancer vaccines—remains to be seen.

All in all, I believe it is finally time to start thinking realistically about long-term remissions, even cures, because we can now combine standard therapies that target the tumor with immunotherapies that boost a patient's own defenses. SA

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PALEONTOLOGY

Fossil GPS

Luck has played a big part in many of the world's great fossil discoveries.

FOSSIL HUNTING in an area as vast as Wyoming's Great Divide Basin (*pictured here*) has long been akin to searching for the proverbial needle in the haystack. But a new technique improves the odds of finding ancient bones.

New models predict where the bones are and put serendipity in the backseat

By Robert L. Anemone and Charles W. Emerson

Robert L. Anemone is a professor and head of the department of anthropology at the University of North Carolina at Greensboro. A paleontologist interested in human and primate evolution, he has conducted fieldwork in Wyoming, Montana, Kenya and South Africa.

Charles W. Emerson is an associate professor of geography at Western Michigan University. In addition to his work on developing predictive maps to find fossils, he is collaborating on a project aimed at using satellite imagery to evaluate how economic factors and environmental protection policies affect grazing lands in rural China.

ON A BROILING DAY IN JULY 2009, A CARAVAN OF FOUR-WHEEL-DRIVE VEHICLES traveled a faint, two-track dirt road in southwestern Wyoming's Great Divide Basin. The expedition was headed for an area known as Salt Sage Draw in search of buried treasure: fossils dating to between 55 million and 50 million years ago, at the start of the Eocene epoch, when the ancestors of many modern orders of mammals were beginning to replace the more archaic mammals that had existed during the earlier Paleocene epoch. One of us (Anemone) had been leading field crews of anthropologists, paleontologists and geologists to the basin since 1994, and Salt Sage Draw had proved a fruitful hunting ground over the years, yielding fossils at several localities. Yet this time I was having trouble finding the site. It dawned on me that the road we were on was not the one we had used in previous years. My error would turn out to be very fortunate indeed.

As the tracks began to disappear in the sagebrush and tall grass, I stopped the caravan and walked a ways to see if I could spot the road ahead. Rounding a small hill, I noticed an extensive bed of sandstone in the near distance and the elusive road right alongside it. Because sandstone in the Great Divide Basin and many other sedimentary basins in the American West often harbors fossils, I decided to spend some time searching these deposits before we resumed our trip to Salt Sage Draw. After about an hour of systematically scanning the rock on hands and knees, my then graduate students Tim Held and Justin Gish shouted that they had found a couple of nice mammal jaws. I eagerly joined them. Fossil jaws with teeth are prized because they contain enough information to identify the kind of animal they came from, even in the absence of other parts of the skeleton, and because they reveal what the animal ate.

What came next can only be described as every paleontologist's dream. My students had located a fossil "hotspot." But this was no ordinary hotspot with a handful of jaws or a few dozen teeth and bones eroding out of the sandstone. Rather they had found an extraordinary trove from which we have now collected nearly 500 well-preserved jaws and several thousand teeth and bones from more than 20 different fossil mammal species that lived here approximately 50 million years ago. We call the spot "Tim's Confession," and today it remains not only our best site in the Great Divide Basin but also one of the richest caches of early Eocene mammals in the entire American West.

Mine is hardly the first team to make a major fossil discovery more or less by accident. The history of paleontology is littered with such tales of serendipity. In fact, the ways that vertebrate paleontologists attempt to locate productive fossil sites have not changed much since the earliest days of our science. Like the 19th-century pioneers of our field, we use geologic and topographic evidence to determine where we might have the best chance of finding fossils eroding out of ancient sediments. But beyond that, whether we hit pay dirt is still largely a matter

IN BRIEF

For more than a century paleontologists have used geologic and topographic information to inform their search for fossils. Yet the discovery of fossils is still largely a matter of luck.

New computer models that look for hidden patterns in satellite images can generate maps of where fossils are likely to be located, thus helping fossil hunters narrow their search.

Ground truthing of such predictive maps in the American West has shown that they do indeed improve the odds of finding fossil sites. In theory, this approach could be used anywhere in the world.

PRECEDING PAGES: ANDREW GEIGER

PALEONTOLOGISTS ACCIDENTALLY found a trove of 50-million-year-old fossils at a site dubbed Tim's Confession in Wyoming's Great Divide Basin (*right*) in 2009. Among the finds were hundreds of well-preserved mammal jaws (*above*). Computer models have since enabled the team to focus its efforts in those areas most likely to yield fossils, including this spot south of an extinct volcano known as the Boar's Tusk (*below*).

COURTESY OF ROBERT L. ANEMONE

of luck, and more often than not the hard work of looking for fossils goes unrewarded.

Our experience at Tim's Confession got me thinking about whether there might be a better way to determine where my field crew should spend its efforts searching for new fossil sites. We knew that the fossils we were interested in occur in sandstone dating to between 55 million and 50 million years ago, and we knew where in the basin some of these sedimentary layers were exposed and thus suitable for exploration. But although that information helped to narrow our search somewhat, it still left thousands of square kilometers of ground to cover and plenty of opportunities to come up empty-handed.

Then one night in camp, an idea began to germinate. Out in the field, kilometers away from the nearest source of light pollution, we often noticed satellites passing overhead. I wondered whether we could somehow combine our expert knowledge of the local geology, topography and paleontology of the Great Divide Basin with a satellite's view of the entire 10,000-square-kilometer area to, in essence, map its probable fossil hotspots. Perhaps satellites could "see" features of the land invisible to the naked eye that could help us find more sandstone outcrops and distinguish those that contain accessible fossils from those that do not.

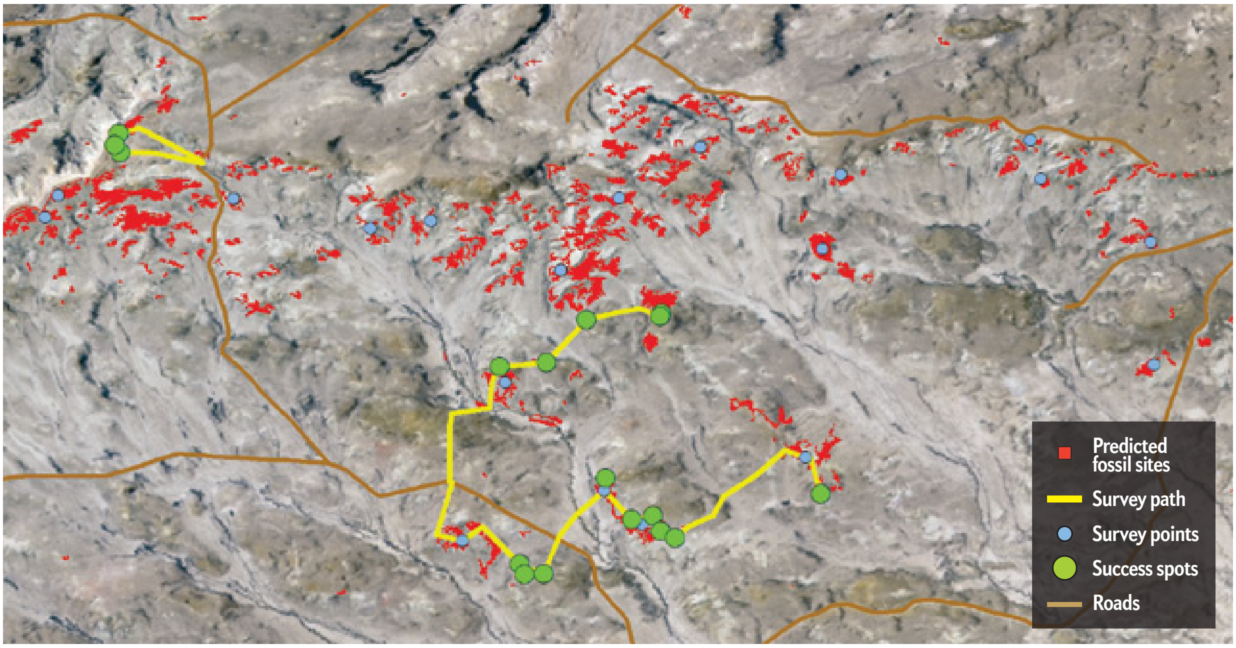
EYES IN THE SKY

OTHER PALEONTOLOGISTS, of course, have speculated about whether satellite imagery might improve our ability to find fossils in the field. As a specialist in the fossil record of primate and human evolution, I knew that in the 1990s, Berhane Asfaw of the Rift Valley Research Service and his colleagues had used such images to identify rock exposures in Ethiopia that might yield fossils of human ancestors. At around the same time, Richard Stucky of the Denver Museum of Nature & Science demonstrated that different rock units in the fossil-rich Wind River Basin in central Wyoming could be distinguished and mapped based on analysis of satellite imagery of the region. Both these projects involved collaborations between paleontologists and remote-sensing specialists from NASA and proved the value of such cross-disciplinary efforts. But I wondered if there was a way to tease more information out of the satellite images and thus better focus our search.

I turned to a geographer, the other author of this article (Emerson), and the two of us soon sketched out a plan. We would obtain freely available images of the basin from the Landsat 7 satellite and its so-called Enhanced Thematic Mapper Plus sensor, which detects radiation reflected or emitted from the earth's surface in wavelengths spanning the electromagnetic spectrum—from the blue to the infrared—and represents it in eight discrete spectral bands. The bands can be used to distinguish

Treasure Map

Computer models can analyze satellite images of an area's known fossil sites to identify their shared radiation profile. The models can then assess the broader region to find other spots that share that profile and thus may harbor fossils of interest. This technique enabled the two of us to generate a predictive map of fossil localities (*red*) in the Great Divide Basin that helped to guide our search for fossils there (*yellow*). Restricting our surveying to focus on some of these areas (*blue*) greatly increased our success rate in finding fossil sites (*green*), compared with that of previous expeditions conducted without such a map. —*R.L.A. and C.W.E.*



soil from vegetation, for example, or to map mineral deposits. Then we would develop a method that would allow us to characterize the radiation profiles of known productive fossil localities in the Great Divide Basin based on satellite imagery and see if they shared a telltale spectral signature. If so, we could search the entire Great Divide Basin from our computers to locate new sites that share this spectral signature and thus have a high probability of bearing fossils. We could then visit those places (as well as places with different spectral signatures) in person and exhaustively search them for fossils to test the model.

Determining whether our known fossil sites shared a distinctive spectral signature was no small task, because for each site we had to assess the combination of values in six bands of the electromagnetic spectrum provided by the Landsat data. Our problem was essentially one of pattern recognition in multiple dimensions, something that humans do not do particularly well but that computers excel at. So we enlisted a so-called artificial neural network—a computational model capable of learning complex patterns.

Our artificial neural network revealed that the basin's known fossil sites do indeed share a spectral signature, and it was able to easily tell these sandstone localities apart from other types of ground cover, such as wetlands and sand dunes. But the model had its limitations. Neural networks, by their very nature, are analytical "black boxes," meaning they can distinguish patterns, but they do not reveal the actual factors that allow different patterns to be distinguished. So whereas our neural network could easily and accurately distinguish fossil localities from wetlands or sand dunes, it could not tell us how the spectral signatures of different land covers actually differed in the six bands of the Landsat data—information that could conceivably help us conduct a more targeted search. Another limitation of the neural network approach is that it is based entirely on the analysis of individual pixels. The problem is that the area of an individual Landsat pixel, which measures 225 square meters, does not necessarily correspond to the size of a fossil locality: some localities are larger than an individual pixel; some are smaller. Thus, the neural network's predictions about the location and extent of potential fossil sites (or a certain type of ground cover, for that matter) do not always match up with reality.

To overcome these constraints, we needed to be able to analyze multiple adjacent and spectrally similar pixels and to statistically describe the distinctive spectral signature of the entire area, whether it was a fossil site or a forest. We turned to a technique known as geographical object-based image analysis and to commercially available, high-resolution satellite imagery in which individual pixels were less than one meter in diameter. Unlike an artificial neural network, this approach allows satel-

COURTESY OF U.S. GEOLOGICAL SURVEY (*satellite image*); COURTESY OF CHARLES W. EMERSON AND ROBERT L. ANEMONE (*points*)

SCIENTIFIC AMERICAN ONLINE For more photographs from expeditions to the Great Divide Basin, visit ScientificAmerican.com/may2014/fossil-hunting

lite images to be segmented into image objects—that is, groups of spectrally homogeneous pixels—that can then be characterized by statistical parameters such as mean or median brightness or texture. These image objects more closely match points of interest on the ground, such as fossil sites or stands of forest. Using this image-analysis technique, we were able to develop an independent set of predictions about where to find fossils.

MOMENT OF TRUTH

BOTH OUR PREDICTIVE MODELS yielded maps of the Great Divide Basin that pinpointed unexplored areas whose spectral signatures most closely resembled those of the known localities. Although the models exhibited a good degree of overlap in their predictions, they also diverged in some cases. We chose to focus on those places that both models identified as high-priority potential sites. Maps in hand, we headed out to Wyoming during the summers of 2012 and 2013 to see if our models would lead us to new fossil caches in the Great Divide Basin. Gratifyingly, they did exactly that.

We searched for fossils at 31 separate places on the landscape that our model indicated were spectrally similar to known localities and found vertebrate fossils at 25 of these places.

The artificial neural network model turns out to be extremely efficient at identifying sandstone deposits, which are almost always worth exploring because so many of the ones in this basin contain fossil vertebrates. One of the first sandstones it led us to in July 2012 yielded a dozen fossils of characteristic Eocene mammals, including the five-toed horse *Hyracotherium,* the early primate *Cantius* and several other creatures belonging to an extinct group of hoofed mammals known as the Condylarthra. The neural network also guided us to several spots that yielded aquatic fossil vertebrates, including fish, crocodiles and turtles.

Our geographical object-based image analysis model took us to new sites, too. After a slow start in which the first three or four places the model pointed us to gave up no fossils, we moved to the northern part of the Great Divide Basin, near a place called Freighter Gap, for a week of intensive "ground truthing" of our new technique. Graduate student Bryan Bommersbach, who a week before had led us on a long hike to a place that was entirely barren of fossils (we dubbed it "Bryan's Folly"), took the lead in choosing which areas to survey based on the model's predictions. Almost immediately, we began to find bones at many of these locations. We searched for remains at 31 separate places on the landscape that our model indicated were spectrally similar to known localities and found vertebrate fossils at 25 of these places, which is a much higher success rate than is typical when surveying without the help of a predictive map. Mammal fossils emerged from 10 of these localities, one of which dates to the latest part of the Paleocene—an extremely rare find.

We have every reason to believe that predictive models akin to the ones we developed will work in regions other than the Great Divide Basin. In fact, they should work virtually anywhere in the world. In theory, as long as one has satellite images of the region in question and a handful of known fossil localities with which to train the model, one can generate a custom map showing those spots in the region that are likely to contain fossils of interest.

In a conservative test of this approach, we used the neural network we developed for the Great Divide Basin to predict the locations of fossil-bearing sedimentary deposits in the nearby Bison Basin, which is known to harbor Paleocene mammal fossils. (We did not train the model with fossil sites specifically from Bison Basin, because it contains the same kinds of fossil deposits as the Great Divide Basin.) Encouragingly, our neural network predicted the three most productive fossil localities known in the Bison Basin. Thus, a field crew exploring this vast area for the first time using our predictive model would have had a far better chance of discovering these sites than a crew using traditional survey methods.

Our trial runs in 2012 and 2013 in Wyoming showed that the use of satellite imagery in combination with geospatial predictive models greatly increased the effectiveness of our fieldwork, helping us to find more fossils in less time. But we still have more to do. We are now focused on refining our models to better characterize and differentiate the spectral signature of productive localities. And we are working on ways to apply more constraints to our predictive models to limit the number of false positive results in the maps we generate and thus improve our ability to determine the highest-priority areas to survey.

We are convinced that with these tools we can put the future of paleontological exploration on a more secure and scientific footing and reduce the role of serendipity in finding important fossils. Achieving that goal will be well worth the effort required. Piecing together the origin and evolution of life on earth is far too interesting and important an endeavor to leave to chance. And we can't afford to wait another 15 years to find the next Tim's Confession. SA

MORE TO EXPLORE

GIS and Paleoanthropology: Incorporating New Approaches from the Geospatial Sciences in the Analysis of Primate and Human Evolution. R. L. Anemone, G. C. Conroy and C. W. Emerson in *American Journal of Physical Anthropology,* Vol. 54, Supplement No. 53, pages 19–46; 2011.

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For more on this research, including its funding source, visit **ScientificAmerican.com/may2014/anemone**

FROM OUR ARCHIVES

First of Our Kind. Kate Wong; April 2012.

scientificamerican.com/magazine/sa

NEUROSCIENCE

Is Anybody in There?

Communicating with patients who appear to lack consciousness is becoming a reality

By Adrian M. Owen

Photograph by Gerald Slota

Adrian M. Owen holds the Canada Excellence Research Chair in cognitive neuroscience and imaging at Western University in Ontario, where he studies brain injuries that result in disorders of consciousness and the cognitive impact of neurodegenerative diseases.

I CAN TRACE MY SEARCH FOR CONSCIOUSNESS IN NONRESPONSIVE PATIENTS TO THE MOMENT IN 1997 when I met Kate, a young teacher from Cambridge, England, who had lapsed into a coma after a flulike illness. Within a few weeks Kate's doctors had declared her to be vegetative—meaning that although she had sleep-wake cycles, she lacked conscious awareness. Her eyes would open and close, and she would appear to look fleetingly around the hospital room, but she showed no signs of inner life and no responses to prompting by her family or doctors.

I was developing new brain-scanning methods at the University of Cambridge, and David Menon, my colleague there, who is an expert on acute brain injury, suggested that we put Kate into our positron-emission tomography (PET) scanner to see whether we could detect any signs of cognitive activity in her brain. It was a long shot, but we suspected that some of our new brain-imaging approaches just might work. While Kate was inside the machine, we showed her pictures of her friends and family by flashing them on a computer screen, and we looked for any signs of a response from her brain. The results were extraordinary. Not only did her brain respond to the faces, but the pattern of brain activity was strikingly similar to what we and others had seen when showing the faces of loved ones to healthy, aware individuals.

What did it this mean? Was Kate actually conscious despite her outward appearance, or was this some sort of reflexive response? It would take more than 10 years of research and improved methodology before we would know how to answer such questions.

Finding answers had become increasingly urgent. In recent years improvements in trauma care, roadside medicine and intensive care had led to more people surviving serious brain damage and ending up as Kate had—alive but with no evidence of preserved awareness. Such patients can be found in virtually every city and town with a skilled nursing facility. Determining their care and treatment—how much life support to give, how to weigh family wishes and the patient's advance directives (if they exist)—is a thorny ethical thicket, involving anguish and sometimes lawsuits. Some of these patients go on to recover to an extent, although it is difficult to predict which ones will and how much. Others enter a state of minimal consciousness, demonstrating inconsistent but reproducible signs of awareness [*see box on opposite page*]. And still others remain vegetative, sometimes for the rest of their days—which can last decades. Being able to distinguish among these states can make all the difference in determining what decisions are in a patient's best interests.

IMAGINE PLAYING TENNIS

IN THE YEARS FOLLOWING KATE'S SCAN, our team at Cambridge tried many ways to detect hidden awareness—what we call covert consciousness—in patients who had been declared vegetative. We played speech for them—long streams of spoken prose—and compared the response in their brain to what happened when we played speechlike noises that contained no real language. In a number of cases, we observed brain activity in putatively vegetative patients that looked like that of healthy participants—speech-perception regions of the brain would often respond when we played them speech but did not respond when we played them the speechlike noises. As before, however, we were unsure if the seemingly normal brain responses reflected an undetected consciousness or if they were more basic, automatic neural signals, largely independent of any higher-level conscious processing.

IN BRIEF

Improved trauma care has led to more people surviving brain injury but ending up in vegetative or minimally conscious states. Researchers are devising imaging techniques to determine which patients retain some awareness or might regain consciousness.

Functional magnetic resonance imaging has revealed, surprisingly, that a portion of patients who are labeled "vegetative" are conscious. Some can answer questions by imagining one activity for "yes" and another for "no."

Investigators are now turning to electrocardiographic technology to try to devise an easier, bedside approach to detecting consciousness. On the more distant horizon are brain-computer interfaces that would enable patients with hidden consciousness to communicate.

DISORDERS OF CONSCIOUSNESS

Lost in the Gray Zone

Consciousness seems like an all-or-nothing affair—either the lights are on, or they are off. But in fact, it can be present in degrees. Conditions in which it is compromised are known as disorders of consciousness (*below*). Most often they stem from trauma to the head or events, such as stroke or cardiac arrest, that result in a loss of oxygen to the brain: outcomes tend to be worse for loss of oxygen than for trauma. Patients may progress or regress from one category to another, except in the case of brain death, from which there is no recovery.

Brain death: All functions of the brain and brain stem have permanently ceased.

Coma: Loss of consciousness is complete; cycles of waking and sleeping disappear, and the eyes remain closed. Coma, which rarely lasts more than two to four weeks, is usually temporary; afterward, patients emerge into consciousness or one of the states below.

Vegetative state: Sleep-wake cycles occur, and the eyes may open spontaneously or in response to stimulation, but the only behaviors displayed tend to be reflexive. *Famous cases:* Terri Schiavo, Karen Ann Quinlan.

Minimally conscious state: Patients may seem vegetative but sometimes show signs of awareness, such as reaching for an object, following a command or responding to their environment. *Famous case:* Terry Wallis, who regained consciousness after 19 years.

Locked-in syndrome: Technically, this state is not a disorder of consciousness, because patients are fully conscious; however, they cannot move and may mistakenly be deemed vegetative or minimally conscious. Many patients do retain the ability to blink and move their eyes. *Famous case:* Jean-Dominique Bauby, who dictated a memoir by blinking his left eye.

I carried out a critical follow-up experiment with Menon, neuroscientist Matt Davis and others at Cambridge. We decided to sedate a group of healthy participants—in this case, a group of anesthesiologists—and expose them to the same combination of speech and nonspeech sounds that we had shown could elicit normal patterns of brain activity in some vegetative patients. Surprisingly, when these healthy subjects were rendered unconscious with the short-acting anesthetic propofol, the speech-perception areas of the brain were activated just as strongly as when the participants were wide awake. This crucial piece of evidence showed us that "normal" brain responses to speech in vegetative patients are not a reliable indicator of covert awareness. It seems that the brain processes speech automatically, even when we are not conscious and aware that we are doing it.

It was time to go back to the drawing board. We had to look at the issue of covert consciousness in a different way. The real question was not how we could activate these patients' brains but rather what kind of activity we would have to observe to be convinced that a patient was conscious. We drew our answer from the classic, clinical assessment of consciousness: response to command. This is the familiar squeeze-my-hand-if-you-can-hear-me test so often depicted in medical dramas on television. Of course, our patients were too injured to produce physical responses to commands, but could they produce a measurable brain response by just thinking about it?

Working with Mélanie Boly, a neurologist in Steven Laureys's laboratory at the University of Liège in Belgium, we set about measuring brain activity while healthy participants imagined doing various tasks, ranging from singing Christmas carols to walking from room to room in their home to playing a vigorous game of tennis. For many such scenarios, mentally performing the task generates a robust and reliable pattern of brain activity that is similar to actually performing the task.

Using functional magnetic resonance imaging (fMRI), which, unlike PET, requires no injection of tracer chemicals, we found that two of the best tasks were playing the imaginary game of tennis and mentally walking from room to room in one's home. Indeed, in every healthy participant we scanned, the tennis task elicited strong fMRI activity in the premotor cortex, a brain region that plays a role in planning movement. On the other hand, mentally touring one's home activated the parietal lobe and a deep-brain region called the parahippocampal gyrus, both of which are involved in representing and navigating spatial locations. Just like the TV doctor who tells the patient to "Squeeze my hand if you can hear me," we found we could elicit a reliable response to a command, visible by fMRI, by asking the volunteers to "Imagine playing tennis if you can hear me."

To our amazement, the technique worked the very first time we tried it with a seemingly vegetative patient. The young woman in question was involved as a pedestrian in a complex traffic accident and had sustained quite severe traumatic brain injuries. She had remained entirely unresponsive for five months before her fMRI scan, and she fulfilled all internationally agreed criteria for a vegetative-state diagnosis. During the scanning session, we instructed her to perform the two mental-imagery tasks repeatedly and in a given sequence. Remarkably, whenever she was asked to imagine playing tennis, significant brain activity showed up in the premotor cortex, just as in the healthy volunteers we had scanned earlier. And when she was asked to imagine walking through her home, we observed significant activity in the parietal lobe and parahippocampal gyrus, again, like the healthy volunteers. On this basis, we concluded that despite her inability to respond physically to external inputs, the patient was conscious. This finding changed how others treated her, including doctors, nurses and her family. While I cannot give details about specific patients, I can say that, in my experience, discovering that a patient is conscious spurs others to communicate, visit, reminisce, joke and otherwise improve the quality of that patient's life.

PUTTING OUR METHOD TO THE TEST

OVER THE NEXT FEW YEARS we tried this technique with as many patients as we could to test its reliability and to seek ways to improve it. By 2010, in another collaboration with Laureys and his group in Liège, we reported in the *New England Journal of Medicine* that of 23 patients who had been diagnosed as vegetative, four (17 percent) were able to generate convincing responses in the fMRI scanner. As part of the study, we explored the possibility of using the imaging tasks to have patients answer yes or no questions. One such patient had suffered a traumatic brain injury five years earlier and been repeatedly diagnosed as vegetative. While in the fMRI machine, he was told he would be asked a series of simple questions and should reply by imagining playing tennis (for "yes") or imagining moving from room to room in his house (for "no"). Incredibly, using this technique, he was able to successfully convey the answers to five questions about his life. He was able to indicate, for example, that "yes," he had brothers, "no," he did not have sisters, and "yes," his father's name was Alexander. (The name is changed here to protect confidentiality.) He also confirmed the last place he had visited on vacation before his injury. Researchers who interpreted the scans as yes or no did not know the answers to these questions, which were constructed based on input from the family [*see box at right*].

Given the complexity of the tasks used, it was evident that the patient had more going on cognitively than mere awareness of his surroundings. He retained a number of higher-level functions: he could switch, sustain and select his focus of attention, comprehend language and choose appropriate responses, maintain and manipulate information in working memory—for example, keeping the instructions for answering yes or no in mind while processing each new question—and recall events from before his accident. Although this patient could reliably and effectively "communicate" with us from within the scanner, no one was able to establish any form of communication at the bedside. Nevertheless, after the fMRI analysis was done, a thorough retesting using standard techniques led doctors to change his assessment to "minimally conscious"—a reminder that diagnosis can be uncertain and changeable for these patients.

In January 2011 I moved my entire research group to Western University in Ontario to pursue this problem with better resources, a bigger team and generous funding from the Canada Excellence Research Chair (CERC) program. This move allowed us to expand and refine our investigations to tackle a number of crucial questions, including whether we could use our technique to improve patient care. In the case of one young man who had been diagnosed as vegetative for 12 years, we were able to ask a question that could potentially change his life: "Are you in any pain?" In a dramatic moment that was captured for television by a BBC documentary team, he answered, "No," much to our relief.

Another question was more technical. Could we find a test that did not require an fMRI scanner? Performing fMRI in severely brain-injured patients is enormously challenging. In addition to considerations of cost and scanner availability, the physical stress on patients can be high as they are transferred, usually by ambulance, to a suitably equipped fMRI facility. Some patients are unable to remain still in the scanner, whereas metal implants, including plates and pins, which are common following a serious injury, may rule out fMRI altogether.

Our recent efforts have focused on building a less costly, more portable way of assessing brain activity using electroencephalography (EEG). EEG relies on noninvasive electrodes attached to the scalp and measures the activity of groups of neurons in the cortex, the deeply folded outer layers of the brain. It is unaffected by metallic implants and, perhaps most important, can be done at the bedside. Unfortunately, EEG does not easily detect changes

FINDINGS

Reading Minds

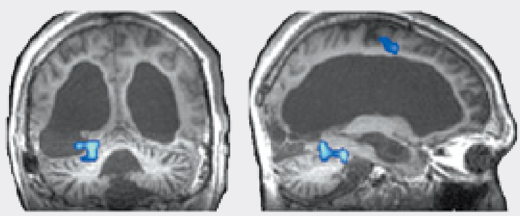
To test a way of detecting consciousness and communicating with unresponsive patients, the author and his colleagues scanned the brain of a man who for five years was thought to be vegetative. They asked him various questions and told him to reply "yes" by imagining playing tennis and "no" by imagining touring his home. FMRI scanning of healthy people has shown that the tennis task increases blood flow to motor-planning regions of the brain and that the house tour increases it to spatial regions, making responses easy to distinguish. Remarkably, the man answered five questions correctly, including the two below.

The patient was asked, "Is your father's name Alexander?" He answered "yes" by visualizing himself playing tennis, which lit up a premotor region (*orange* and *yellow*). (The father's name is altered here for confidentiality.) The patient's scan pattern closely matched that of a healthy control subject imagining playing tennis.

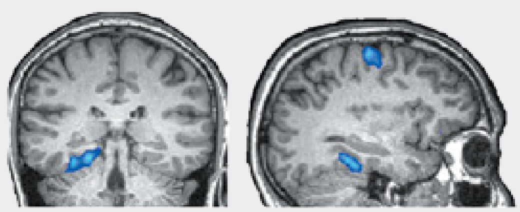
Patient

Control subject

The patient was asked, "Is your father's name Thomas?" He replied "no" by visualizing going from room to room in his home, which lit up spatial regions (*blue*). His scan was strikingly similar to that of the healthy control subject doing the same task.



Patient



Control subject

SOURCE: "WILLFUL MODULATION OF BRAIN ACTIVITY IN DISORDERS OF CONSCIOUSNESS," BY MARTIN M. MONTI ET AL., IN *NEW ENGLAND JOURNAL OF MEDICINE*, VOL. 362, NO. 7; FEBRUARY 2010 in very deep brain structures, and its spatial resolution—its ability to detect a clear response in a particular brain region—is much lower than is the case with fMRI. To deal with these limitations, we adapted our mental-imagery tasks to produce activity on the surface of the cortex, in areas that control simple movements of the arms and legs. Damian Cruse, a postdoctoral fellow in my lab, found that if he asked healthy participants to imagine clenching their right hand or their toes, he could detect the difference, based on the EEG pattern that was generated. It did not work for everyone, but by 2011 it was reliable enough for us to start testing patients at their bedside.

We bought a Jeep (the "EEJeep"), fitted it with electrodes, amplifiers and the most powerful laptops we could find, and we hit the road, taking our equipment to patients. In November 2011 we reported our findings in the *Lancet*. They were similar to our results with fMRI: three out of 16 (19 percent) of the "vegetative" patients we tested using bedside EEG appeared to be conscious, based on their responses to commands to imagine squeezing their toes or hands. Not everyone was convinced by the study. EEG analysis is notoriously complicated, and the statistical algorithms we used were sufficiently novel and complex that they were challenged by another research group. Fortunately, we were able to confirm awareness in most of the patients who had responded well in the EEG study by using our more established fMRI technique. We subsequently tested and published a revised version of our EEG methodology that addressed the questions raised. With funding from the James S. McDonnell Foundation, we are collaborating with our counterparts in Liège and research teams in two other countries—including the team that initially challenged us—to develop standard protocols for using fMRI and EEG to detect covert consciousness in vegetative patients.

In principle, it is already possible to directly ask a patient if he or she wants to continue living in his or her current situation using our fMRI or EEG techniques.

WHAT NOW?

WHERE DO WE GO FROM HERE? The notion that we might one day be able to communicate by thought alone has preoccupied scientists and science-fiction writers for decades. The use of fMRI and EEG to detect awareness and begin to communicate with some otherwise nonresponsive patients paves the way for the development of true brain-computer interfaces that would relay a patient's thoughts to the outside world. It seems increasingly likely that such devices, when they become available, will work by translating specific thoughts into yes, no and perhaps other concepts. Creating systems that work for individuals who have sustained major brain injuries will be no easy task, however. Such patients rarely have control over their eye movements, ruling out interfaces that depend on blinking or directing one's gaze, and their depleted cognitive resources—a common result of brain injury—may preclude any system that requires extensive training, as the current ones do.

These obstacles notwithstanding, it seems likely, if not inevitable, that fMRI, EEG and perhaps newer technologies will increasingly be used to detect covert awareness in nonresponsive patients, raising a number of moral and legal questions. In cases where decisions have been made to withdraw nutrition and hydration, it is possible that evidence for covert consciousness could be used to overturn this decision. In principle, it is already possible to directly ask a patient if he or she wants to continue living in his or her current situation using our fMRI or EEG techniques. But would a yes or a no response be enough to signify that the patient has retained the cognitive and emotional capacity to make such an important decision? How many times would the question need to be asked and over how long a period? A 2011 survey of 65 patients with locked-in syndrome—a condition in which consciousness is intact, but the body is paralyzed—suggests that people have a surprising capacity to adapt to extreme disability: most expressed satisfaction with the quality of their lives. Clearly, new ethical and legal frameworks will be needed to guide exactly how such situations are managed and by whom.

As for Kate, a remarkable thing happened. Unlike most of the hundreds of vegetative patients I have seen over the years, she began to recover several months after her scan. She now lives at home with her family. She uses a wheelchair to get around and speaks with difficulty, but her cognitive faculties have returned, including her sense of humor and ability to appreciate the profound role that she—and her brain—has played in the process of scientific discovery. Although she did not remember her own brain scan when she first became fully conscious, Kate has since become passionate about the importance of such scans. "It scares me to think of what might have happened if I had not had mine," she wrote in a recent e-mail. "So please use my case to show people how good they are. I want more people to know about them. It was like magic—it found me." SA

MORE TO EXPLORE

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More information on the author's work: **www.owenlab.uwo.ca**

FROM OUR ARCHIVES

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scientificamerican.com/magazine/sa

ENGINEERING

Shape-Shifting Things to Come

Flexible, one-piece machines could soon make today's assemblages of rigid parts look like antiques

By Sridhar Kota

IRISES made from a single piece of material can change geometry by 100 percent when pressure is applied to the exterior ring.

Photographs by Greg Ruffing

In 1995 I was driving around Ann Arbor, Mich., one rainy day when I became fixated on my windshield wipers.

Sridhar Kota is Herrick Professor of Engineering at the University of Michigan and founder and president of FlexSys, Inc.

I was then an associate professor of mechanical engineering at the University of Michigan. In the preceding years I had done several studies of what is known in industry as "design for assembly." The goal of such a study is to reduce the number of parts in any given machine, thus reducing manufacturing and assembly costs. In the course of this work, I had begun to wonder what happened if you took design for assembly to its logical extreme. Could we design products for *no* assembly?

As I sat behind the wheel, it struck me that my windshield wiper was a ludicrous waste of engineering effort. The wiper frame, which holds the disposable blade, has to be highly flexible. It must keep the blade pressed against the glass as it moves back and forth across a variable contoured surface. Moreover, it must be able to do so on a number of car models, each of which has its own windshield geometry. Our response to this need for flexibility? A complicated system of rigid bars, links and pivots.

At the time I had another burgeoning interest—elastic, or compliant, design, which involves building flexible, strong machines from as few pieces as possible. My colleagues and I had already succeeded in building machines from a single piece of material. For instance, in 1993 my graduate students G. K. Ananthasuresh, Laxman Saggere and I built a no-assembly compliant stapler. But the windshield wiper struck me as a perfect test case. A one-piece, or monoform, wiper would virtually eliminate assembly. If successful, such a project would be more than an exercise in engineering minimalism. Most of the cost of manufacturing a windshield wiper goes into its assembly. It should surprise no one that the production of such assembly-intensive products moved offshore to low-wage countries long ago.

My colleagues and I did not get around to designing the one-piece windshield wiper right away. For the past two decades most of my research has focused on general principles for elastic design—developing the theoretical tools that engineers need to design and build compliant devices. But we did eventually design that windshield wiper. In fact, we have used elastic design to build miniature monoform motion amplifiers, flexible airplane wings, robot snakes, and other machines, each one an expression of a new engineering paradigm whose time has come.

LIVING MACHINES

WE ARE MORE FAMILIAR with compliant machines than we might think. Perhaps the earliest and most elegant example is an archer's bow. As the archer draws the bow, elastic energy is stored slowly and then released quickly to propel an arrow. This strong, flexible mechanism can be used many times with precision and without failure. A newer example is the cap of a shampoo bottle: it is a monoform device that combines an easy-opening cap and a screw-on sealing collar without a mechanical hinge. Here is another example: the disposable medical forceps widely used in hospitals, which are precise enough for an operating room but inexpensive enough to be discarded after each use.

The most successful elastic designs exist in nature. I began to realize this in 1995, when I started reading works by Steven Vogel, the renowned biologist at Duke University. In books such as *Life's Devices* and *Cats' Paws and Catapults,* Vogel masterfully explains the working of nature's designs and draws parallels to engineered devices. Tree branches, bird wings, crab legs and elephant trunks are all flexible and strong. Their components either grow out of one another or are bonded together with strong, self-regenerating interfaces. Unlike systems of gears, sliders and springs, they bend, warp and flex by exploiting their inherent elasticity.

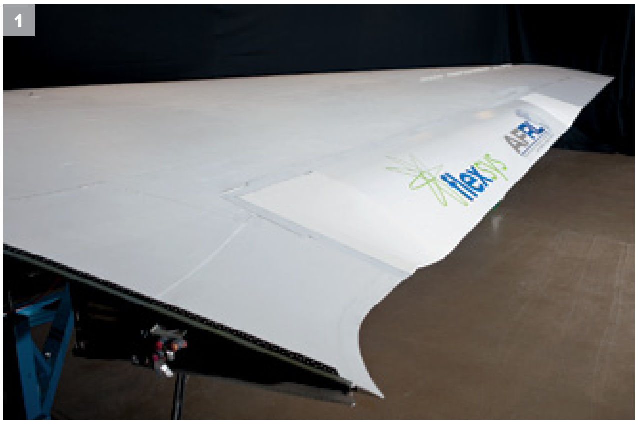
Humans have accumulated millennia of experience designing strong and rigid structures such as bridges and buildings. For the most part, we do this by using materials that are strong and stiff. If the stresses get too high, we simply add more mate-

IN BRIEF

Human-designed machines achieve flexibility through complex, frequently inefficient systems of rigid parts. Strength and flexibility are often mutually exclusive.

Elastic, or compliant, design, is an engineering approach that embraces flexibility, distributing loads across morphable devices made from as few parts as possible.

It could yield new machines such as shape-shifting airplane wings and snake robots, as well as ways to increase durability and efficiency in all kinds of devices.



WITH ELASTIC DESIGN, flexible, morphing surfaces can replace rigid wing flaps (*1*), windshield wiper frames can be molded from single pieces of material (*2*), and one chunk of plastic can do the work of a conventional stapler's nearly two dozen parts (*3*).

rial to share the load or increase its stiffness. Stiffness, in this paradigm, is good; flexibility, bad. Indeed, with rigid structures, deflection—the tendency to deform, or give under stress—is desirable only if you are designing for earthquake resistance.

Compliant design, in contrast, embraces deflection. If the stress on a flex point gets too high, we make it thinner, not thicker, because the function of a compliant structure is to exploit elasticity as a mechanical or kinematic function.

In the case of the shampoo bottle cap, the stress is focused on the thin polymer section that connects the lid to the base. Disposable forceps have much the same design. When the stresses are concentrated in a thin, discrete area, the flexion is referred to as lumped compliance. Researchers have been studying lumped compliance since the 1950s. More recently, Ashok Midha of the Missouri University of Science and Technology, Larry Howell of Brigham Young University, Shorya Awtar of the University of Michigan and Martin L. Culpepper of the Massachusetts Institute of Technology have all done excellent research on the subject, demonstrating applications of lumped compliance in precision instruments and nanopositioning devices.

The archer's bow, in contrast, has no such localized flexural zone: it displays "distributed compliance" throughout its whole length. Distributed compliance is essential for building flexible machines that have to do heavy work—wings that must keep planes in the air, for example, or motors that must run for millions of cycles. When I began my work in this field, I could find no theoretical underpinnings or general methods for designing machines with distributed compliance. Naturally, that is where I focused my efforts, and it is where my interest remains.

STARTING SMALL

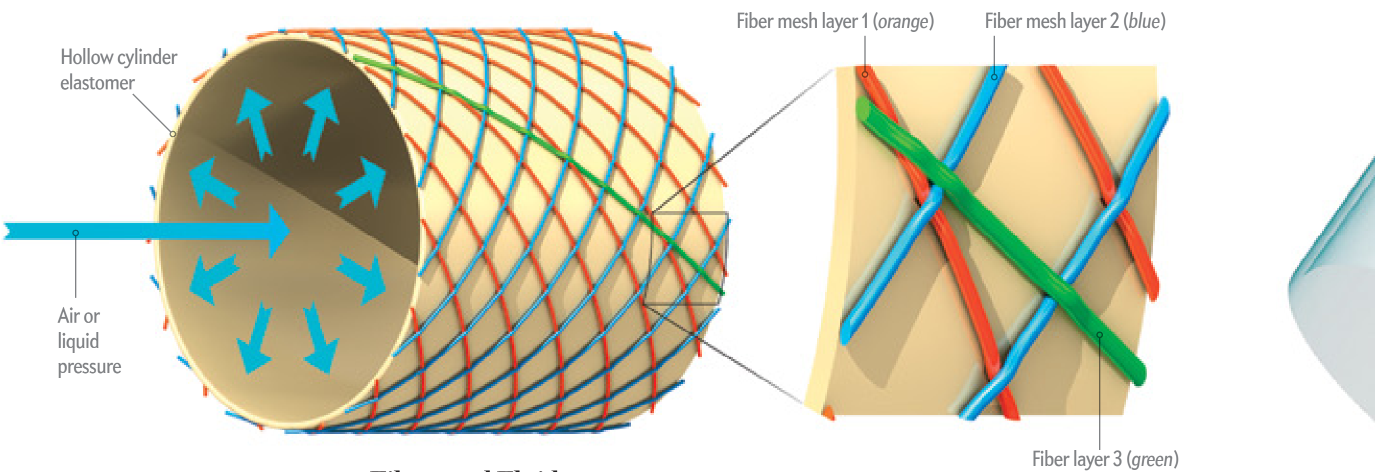
I STARTED WORKING on flexible, one-piece machines not because they seemed like intriguing novelties but because in certain applications, designing for no assembly is a necessity. I began my career studying large mechanical systems such as automotive transmissions. In the early 1990s, however, I found myself designing truly tiny machines—micro electromechanical systems (MEMS). This was largely a circumstance of that era. Telecommunications companies were starting to develop optical switches for fiber-optic networks; they would use minuscule motors to change the angle of mirrors very quickly to route an optical signal in one direction or the other. Not long after I began reading Vogel and exploring elastic design, I embarked on a project with Steven Rodgers and his team at Sandia National Laboratories' microsystems division, where a monoform design seemed perfect.

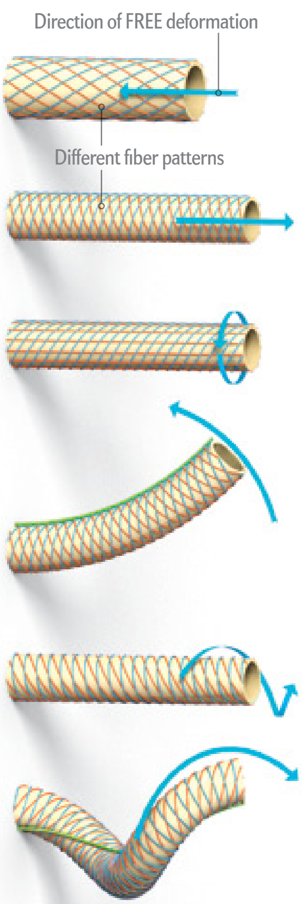
Sandia needed to build a linear motor with sufficient output displacement to do work—at least 10 microns. Yet the fabrication constraints of electrostatic motors limit their motion to two microns. I knew I could not simply miniaturize, say, a geared transmission. Even if we could find someone with steady enough hands to assemble gears, hinges and shafts with dimensions in the one- to two-micron range, the resulting machine would be too sloppy for modern engineering. At MEMS scale, a machine with a tenth of a micron of clearance is about as useful as a Tinkertoy. Besides, MEMS devices are batch-fabricated much the same way as integrated circuits, tens of thousands in an area the size of a thumbnail. Given all that, I designed a monoform motion amplifier to generate 20 microns of output motion when integrated with the electrostatic motor.

By 1998 we had the motor and amplifier humming away. I clearly remember standing in the laboratory, marveling at the tiny device. It had been running for more than 10 billion cycles with no end in sight. But to my mind, the most impressive thing

How to Build a Robot Snake

For worms, octopuses and other soft-bodied animals, a lack of a rigid skeleton is no handicap: they get around using elastofluidics. Their bodies are fiber-laden, muscular tubes surrounding a pressurized, liquid-filled cavity. The fibers serve as antagonists against the fluid pressure generated by muscle contraction; the orientation of the fibers determines the range of motion. Engineers at the University of Michigan are developing "robots" based on the same principle. Applications could include orthotic devices that assist in limb movement and robots capable of handling delicate objects and working safely alongside humans.



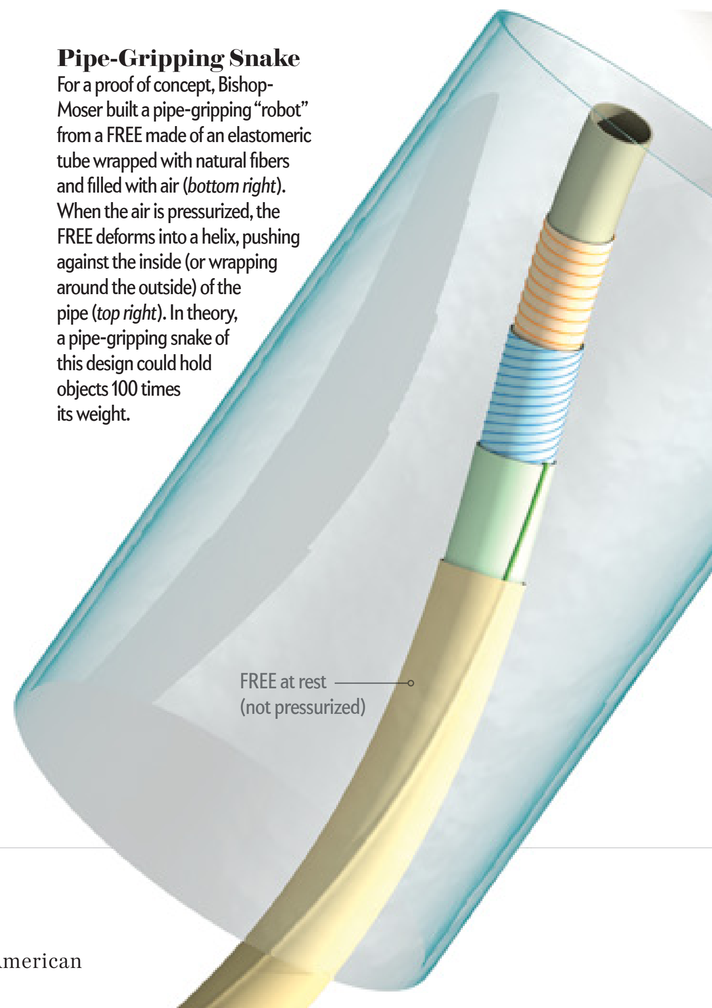


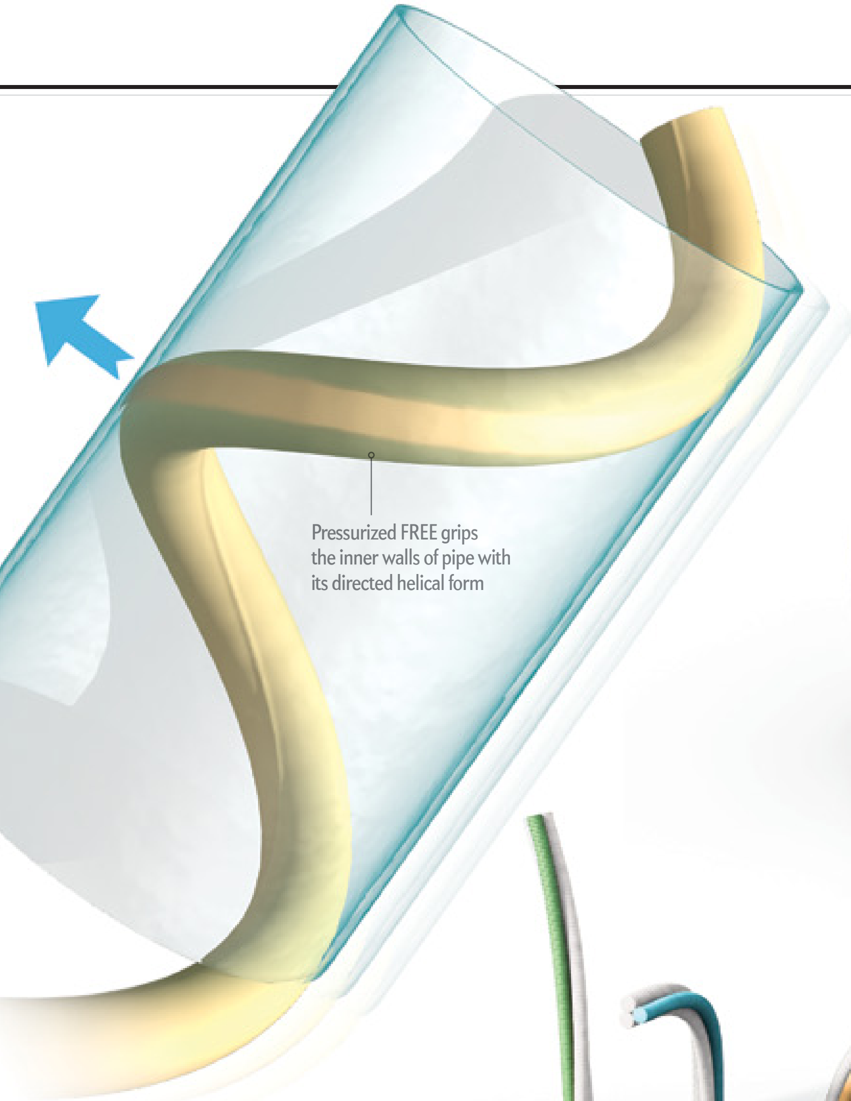
Fibers and Fluid

Most previous attempts to design snake robots used segmented bodies—long chains of individually actuated components. Kota and Joshua Bishop-Moser of the University of Michigan decided instead to use pressurized fluid inside a fiber-reinforced elastomeric enclosure (FREE). The FREE is a hollow cylinder of elastic polymer reinforced with two or three layers of fiber mesh (*above*). The angles at which the fibers spiral around the cylinder determine how the device changes shape when the fluid inside is pressurized (*left*).

Pipe-Gripping Snake

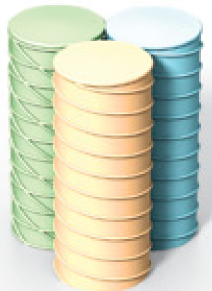
For a proof of concept, Bishop-Moser built a pipe-gripping "robot" from a FREE made of an elastomeric tube wrapped with natural fibers and filled with air (*bottom right*). When the air is pressurized, the FREE deforms into a helix, pushing against the inside (or wrapping around the outside) of the pipe (*top right*). In theory, a pipe-gripping snake of this design could hold objects 100 times its weight.

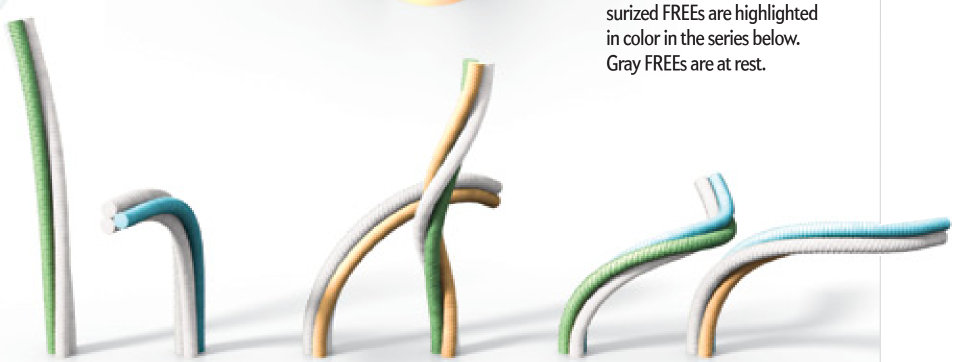




Snakes Join Forces

Because the length and orientation of its fibers are fixed, an individual FREE can deform in only one way under pressure. Girish Krishnan, now at the University of Illinois at Urbana-Champaign, and Bishop-Moser combined FREEs, making it possible to achieve a greater range of motion (*detail at left*). The compound device takes on various shapes depending on which of the component FREEs are actuated. Pressurized FREEs are highlighted in color in the series below. Gray FREEs are at rest.





Soft Robots on the Way?

Research on FREEs for soft robotics is just beginning, but Kota says applications could include medical devices, pipe inspectors, and even soft but dexterous factory-line robots (*left*) capable of handling fragile items that today's robots cannot.

Illustration by Bryan Christie

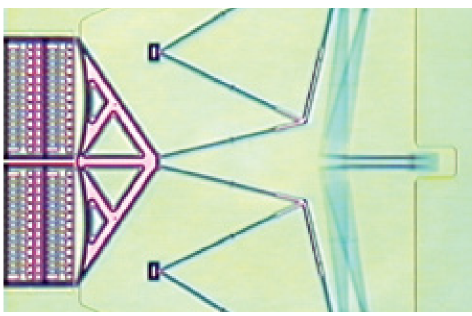
was that the entire motion amplifier, with all its complexity and flexibility, consisted of a single piece of polysilicon.

FLEXIBLE FLIERS

OF ALL OF THE REASONS that I have chosen to study compliant design, the one I find most compelling is shape adaptation, or "morphing." The ability to alter the geometry of a structure in real time enables nature's machines to operate with the utmost efficiency. Compare this adaptability with the fixed geometries of the engineered world—automotive drivetrains, airplane wings, engines, compressors, fans, and so on. These and practically all other conventionally designed machines are most efficient under very specific conditions. They operate suboptimally the rest of the time. An aircraft, for example, experiences a variety of flight conditions as it goes from point A to point B — changing altitude, speed, even weight as its fuel is consumed—which means that it is almost constantly operating less efficiently than it could. Birds, on the other hand, can take off, land, hover and dive by effortlessly adjusting the configuration or shape of their wings on demand.

Back in the mid-1990s, I wondered if anyone had ever attempted to change a wing's shape (camber) during flight to improve performance. I was amazed to discover that the Wright brothers had pioneered a different type of wing morphing—wing twist—in their original flier. I later learned that changing a wing's camber to meet different flight conditions on a modern aircraft had remained an elusive goal for decades. So one night I sat down at my dining room table and got to work on a design.

After a few months of study, I came across a small blurb in a newspaper about flexible-wing research that was conducted in the late 1980s at Wright-Patterson Air Force Base in Ohio. The engineers there called their goal a mission-adaptive wing (MAW). I knew nothing about the outcome of their work, but I understood that a morphing wing was not a wacky idea, so I contacted the researchers to ask whether they might be interested in reviewing my design. Their reaction was overwhelming.



FOR TINY MACHINES such as this micro electromechanical motion amplifier, one-piece design is a manufacturing necessity.

COURTESY OF SANDIA NATIONAL LABORATORIES

They explained that most, if not all, past attempts to create a morphing wing have employed rigid structures—complex, heavy mechanisms with scores of powerful actuators to make a wing structure flex to different geometries. One time, for example, engineers modified the wing of an F-111 fighter jet with flexible panels. Their adaptive wing showed aerodynamic promise, but the structure was deemed too heavy and complex for practical application.

This did not surprise me. Designing a practical variable-geometry wing would involve satisfying many conflicting requirements. The wing must be lightweight, strong enough to withstand thousands of kilograms of air loads, reliable enough to operate for hundreds of thousands of hours, easy to manufacture and maintain, and durable enough to withstand chemical exposure, ultraviolet radiation and significant temperature changes. The conceptual and software tools in use at the time were never intended to design monoform machines, let alone ones that satisfied so many competing demands.

The flexible-wing design I submitted to Wright-Patterson exploited the elasticity of the test components, which were completely conventional aerospace-grade materials. The wing had an internal structure designed to deform easily when a compact internal motor applied force, and it still remained stiff when powerful forces were exerted externally in the wind-tunnel test. The senior engineers at Wright-Patterson were excited about the design, and so was I. In fact, I was so enthusiastic that in December 2000 I founded a company, FlexSys, to develop practical applications of compliant design.

Six years later, after much development and several successful wind-tunnel tests, we managed to get a prototype of the flexible wing affixed to the underside of a Scaled Composites White Knight aircraft for flight tests in the Mojave Desert. The wing was mounted below the jet's body and fully instrumented to measure lift and drag. Its coefficient of lift varied from 0.1 to 1.1 without increasing drag; that translates to a fuel-efficiency boost of up to 12 percent in a wing designed to take full advantage of the new flexible flap. (Flexible flaps retrofitted to existing wings would give a boost of 4 percent or more.) Considering that U.S. airlines consume about 16 billion gallons of jet fuel every year, these seemingly small percentages could be significant. The wing was also simpler, with no moving parts in the morphing mechanism. As a result, it would be more reliable and have a better weight-to-power ratio.

The real test for shape-adaptive aircraft wings will come when flexible-control surfaces completely replace conventional flaps. We are putting the finishing touches on just such an endeavor. Working with U.S. Air Force research labs, FlexSys designed and built a continuous surface that bends (cambers) and twists spanwise to maximize aerodynamic performance in place of drag-producing trailing-edge flaps. We have retrofitted a Gulfstream Aerospace GIII business jet with our FlexFoil variable-geometry-control surfaces instead of conventional flaps. In addition to significant fuel savings, our design is expected to reduce aircraft noise: according to NASA, much of the noise involved in landing a plane is caused by vortices generated at the sharp edges and gaps between the deployed trailing-edge flaps and the fixed parts of the wing. We have included transition surfaces to eliminate these gaps. Flight tests at NASA's Neil A. Armstrong Flight Research Center are scheduled to take place in July.

CREEPERS AND CRAWLERS

IN THE PAST FEW YEARS my graduate students Joshua Bishop-Moser, Girish Krishnan and I have begun conducting elastic-design research inspired by the most flexible natural machines on earth—animals with no apparent skeletons. The most otherworldly among these life-forms, such as annelids and nematodes, conduct their business in ways that we are just starting to

SCIENTIFIC AMERICAN ONLINE Watch videos of Kota's flexible machines at ScientificAmerican.com/may2014/elastic-design

PIPE-GRIPPING HYDROSTATS such as this proof-of-concept device could eventually lead to soft, snakelike robots.

understand. More familiar examples, such as octopuses, provide an ideal for elastic engineers to strive for.

Soft-bodied animals such as worms and octopuses lack any apparent skeletal structure, and yet they can move vigorously and gracefully. For the most part, they accomplish this through what is called elastofluidics. In engineering terms, their bodies are hydrostats—they consist of an arrangement of connective tissue fibers and muscles surrounding a pressurized, liquid-filled cavity. A study of the anatomy of these creatures commonly reveals a cross-helical arrangement of fibers and muscles surrounding the internal organs, which occupy the liquid-filled core. The cross-helical fibers serve as antagonists against the fluid pressure generated by muscle contraction; the orientation of the fibers determines the range of motion.

Many variants of hydrostatic skeletons exist throughout the animal world. The arms of an octopus are muscular hydrostats. An elephant's trunk employs tightly packed muscle fibers around a hydrostatic body. An eel's fiber-reinforced skin acts like an external tendon, enabling the animal to generate a powerful propulsive force for swimming.

Our research on elastofluidics is still in its infancy, but our hypothesis is that these elements could serve as components for constructing "soft robots" and other devices that can safely interact with humans and the environment. The earliest applications, however, will most likely be in the field of orthotics. For instance, patients suffering from arm contracture caused by muscle hardening, joint deformity or joint rigidity could use a flexible orthotic device that gently forces their arm back into functional position for daily activities.

COMPLIANCE IS APPRECIATED

WITH THE ASSISTANCE of many talented graduate students at the University of Michigan's Compliant Systems Design Laboratory, the basic research we started in 1992 has resulted in a trove of useful insights and systematic design methods. Those graduate students, too numerous to mention here, are now doing work of their own on elastic design at Pennsylvania State University, the University of Illinois at Urbana-Champaign, the University of Illinois at Chicago, Bucknell University, the NASA Jet Propulsion Laboratory, Sandia National Laboratories, Air Force Research Laboratory, KLA-Tencor, Ford Motor Company, FlexSys, Raytheon and Intel. Thanks to the talented engineers at FlexSys, some of the devices we have developed over the years are nearing commercialization. We have completed weather testing and finished the production mold for our monoform windshield wiper frame, and discussions are under way with automakers and suppliers for implementing it as a rear wiper. The monoform wiper is made of glass-filled thermoplastic polymer and works properly in both frigid and hot conditions. It will not snap or twist even when breaking loose ice and snow. When it comes to market, it should be much more durable and reliable and cheaper to manufacture than any competing device.

Our flexible aircraft wings are technically ready for commercial implementation right now. Replacing the outer 15 percent of an existing flap with a variable-geometry subflap for cruise trim alone could save 5 percent in jet fuel. Replacing the entire flap with a seamless FlexFoil offers about 12 percent fuel savings on new designs. It might be another couple of years before we get certification from the Federal Aviation Administration, but once the industry gains confidence in flexible wings, we believe it is likely that they will replace hinged flaps completely in future fixed-wing aircraft of all types.

Cases abound in the automotive, appliance, medical and consumer sectors where elastic design could drastically reduce the number of parts used in any given device. The biggest challenge is getting the word out to industrial designers. Widespread use of novel products such as our compliant wiper should help make the argument for elastic design. Even then, however, a challenge remains: there are currently no easy-to-use software tools available for exploring elastic design. With a contract from the National Science Foundation, FlexSys is developing software along these lines.

It will take several years before elastic design reaches any kind of critical mass, but we feel that its widespread adoption is inevitable. The strength, precision, versatility and efficiency that elasticity offers will give engineers in many fields an entirely new set of tools to work with, and soon we will all start to appreciate the power of being flexible. SA

MORE TO EXPLORE

Better Bent Than Broken. Steven Vogel in *Discover*, pages 62–67; May 1995.

FROM OUR ARCHIVES

Organisms That Capture Current. Steven Vogel; August 1978.

scientificamerican.com/magazine/sa

J.E.N. Veron, the man who discovered more than 20 percent of the world's coral species, fears the reefs are in deeper trouble than most people realize

By Iain McCalman

OCEANOGRAPHY

THE GREAT CORAL GRIEF

SIR DAVID ATTENBOROUGH, THE WELL-KNOWN NATURALIST, STANDS AT THE LECTERN OF THE ROYAL Society in Carlton House Terrace in London, on July 6, 2009, about to bring the afternoon's speaker to the stage. A ripple of expectation passes through the audience, eagerly anticipating a lecture entitled "Is the Great Barrier Reef on Death Row?" Then Sir David introduces J.E.N. Veron, the then 64-year-old former chief scientist of the Australian Institute of Marine Science. "But," says Sir David, smiling broadly, "I'll call him Charlie, a name he carries because he shares Mr. Darwin's obsession with the natural world." Without specifically saying so, Sir David is telling us that we are about to hear from a modern-day Charles Darwin.

Many of the scientists in the room already know how apt this comparison is: there are uncanny resemblances and intellectual links between today's speaker and the Royal Society's greatest ever Fellow. All Charlie Veron's friends know, too, that he has made himself an internationally famous scientist without ever losing Darwin's fierce independence, unquenchable curiosity and passionate love of nature. Charlie, Sir David says, is one of the world's greatest scientific authorities on corals and coral reefs. He has discovered and described more than 20 percent of the known coral species—the tiny invertebrates that form skeletons of calcium carbonate and often join together into giant communities. And he has produced definitive catalogues of all the world's corals. But today—Sir David's voice takes on a somber note—Charlie comes with a different task: to show us how coral reefs are the keys that can unlock the truth about the bewildering changes we have unleashed in our climate. Perhaps he may answer the question that nags at us all: Do the reefs tell us that the future is worse than we realize?

When the applause subsides, Charlie walks to the lectern, a wiry, tanned figure wearing a red shirt and dark jacket. In his husky Australian voice, he thanks Sir David and begins to tell a spellbound audience why the Great Barrier Reef off the coast of Australia, the most massive in the world, and all the earth's reefs face a likely mass extinction within the life span of the youngest listeners present.

Adapted from The Reef: A Passionate History, *by Iain McCalman, by arrangement with Scientific American/Farrar, Straus and Giroux, LLC (US/CAN), Scribe Publications (UK), Penguin Books (AUS/NZ). Copyright © 2014 by Iain McCalman.*

HARDY? Despite its name, Hardy Reef is struggling with higher ocean temperatures and greater acidification, as are other sections of the Great Barrier Reef.

PETER WALTON *Getty Images*

The lecture and Charlie's 2008 book that underpins it, *A Reef in Time: The Great Barrier Reef from Beginning to End,* mark a shift in theme and tone for a man who has written so joyfully about coral reefs. For 40 years Charlie has celebrated their astonishing multiplicity and complexity. Now the audience hears him focusing all his intellect and passion to prophesy a reef apocalypse. It is obvious how much he would like to avert what he predicts. To have any chance of this, though, Charlie must answer the skeptic's question: How do you know? And then its brutal follow-up: Why should we care?

Iain McCalman is a professor of history at the University of Sydney, a Fellow of the Royal Historical Society and author of *Darwin's Armada* (2009) and *The Seven Ordeals of Count Cagliostro* (2004).

KNOWLEDGE BORN OF SORROW

THE BEGINNING of Charlie's answer stems from a nagging puzzle about the divergences between the same species of corals at different locations—a puzzle Charlie pursued for decades. His quest took him to hundreds of reefs in both hemispheres and across the vast Indian and Pacific oceans. He dived and collected in Japan, the Philippines, Indonesia, the Cocos (Keeling) Islands and then, further afield, in Zanzibar and at the remote Clipperton atoll in the eastern Pacific. Always he traveled by boat, always he worked with locals, and always he spent hours underwater, observing and memorizing. What he found was that over geologic spans of time, corals intermix to produce new variations, reconnections between former variations and even "fuzzy" hybrids.

As he researched the diversity and evolution of the world's corals, Charlie became aware of a grave, looming problem. His realization of the trouble had personal as well as intellectual roots. In the midst of his long, testing labors, a tragedy drove him to think intently about mortality. Just as Charles Darwin, struggling to finalize his theory of evolution, had been shaken by emotional loss and domestic strain, so it was with Charlie Veron. In April 1980 Charlie was working in Hong Kong when he received a phone call from his wife, Kirsty, to say with horror that one of their two daughters, 10-year-old Noni, had drowned while playing in a creek with a friend. Weighed down by sorrow, life for Charlie and his wife dragged, and although they remained supportive of each other, they eventually agreed to divorce.

Charlie's intense personal reminder of the contingencies and fragilities of life found echoes in his research, culminating in his powerful 1995 book *Corals in Space and Time.* The writing forced him to investigate the fate of the world's corals in the past and present. He studied analyses of previous reef extinctions and accrued more and more evidence of the effects of changing sea levels, temperature stresses, predation by crown-of-thorns starfish and human-influenced changes in nutrient levels. All this sharpened his long-gestating concern about the health of the Great Barrier Reef and other world reefs.

Ironically, the book offered Charlie a personal lift—the chance of a second romance, with Mary Stafford-Smith, the scientist who edited the book and who became his new partner. Charlie and Mary began discussing the idea of a glossy, coffee-table book about corals for a general audience, "to open the eyes of the world to what was emerging as an urgent need to conserve corals," he tells the audience. It was the crystallization of a new joint mission "to win some hearts as well as minds." Around 70 underwater photographers gave their work for free, and illustrator Geoff Kelly produced exquisite drawings and paintings. Charlie supplied most of the encyclopedic thumbnail analyses. In October 2000 the three-volume *Corals of the World* was launched to critical acclaim at the International Coral Reef Symposium in Bali, where its message of reef fragility and degradation added to a rising global alarm.

An instinctive conservationist, Charlie had been troubled way back in the 1970s by the extent of the damage caused by coral-eating crown-of-thorns starfish. He had become convinced that numbers of them were soaring because of overfishing of the starfish's natural predators and that survival of the millions of larvae expelled annually into the ocean currents was enhanced by the growing levels of chemical pollution. (Crown-of-thorns larvae thrive in polluted waters.) What provoked him to fury, though, was the way in which the vested interests of tourism developers and politicians, combined with the craven behavior of government bureaucracies, worked to deliberately discourage scientists from studying the problem. It was the onset of a process, ubiquitous today, whereby scientists were no longer free to pick their own questions or seek their own answers.

MASS BLEACHING

LOOKING BACK, Charlie says he realized that like most of his generation, he had taken for granted that "the oceans [were] limitless and the marine world indestructible," including the vast, relatively well managed region of the Great Barrier Reef Marine Park. The fact that the Central Indo-Pacific functioned as the prime disperser of coral biodiversity had always been worrying because of the region's lack of legal protection. Diver friends had long urged him to visit the spectacular reefs of eastern Indonesia, but by the time he got there in the early 1990s it was too late. Reefs that had run for thousands of kilometers were now masses of rubble.

Charlie had seen his first patch of coral bleaching off the

IN BRIEF

By exhaustively studying corals around the globe, J.E.N. Veron discovered how they evolve across millions of years and across the planet's oceans. His discoveries have also revealed how warming ocean temperatures and acidification of ocean water caused by climate change lead to coral bleaching and death.

Veron has been urging the public to spread the story of coral demise, as a last hope for preventing reefs worldwide from dying.

Great Barrier Reef's Palm Island in the early 1980s, a tiny clump of white skeleton that he photographed as a curio. "And then I saw a whammy, a mass bleaching event … where everything turns white and dies. Sometimes it's only the fast-growing branching corals, but some of the others are horrible to see; corals that are four, five, six hundred years old—they die, too."

The first recorded global mass bleaching occurred between 1981 and 1982. The next major spate of mass bleaching, between 1997 and 1998, hammered reefs in more than 50 countries, even among the hot-water corals of the Arabian Sea. On the Great Barrier Reef, the bleaching coincided with the warmest sea temperatures ever recorded. In an even worse mass-bleaching event in 2001–2002, the global damage also confirmed a close connection with El Niño weather cycles. Catastrophic global warming had arrived. Peculiarly susceptible to increases in heat and light, corals were now alerting scientists to climatic changes.

Charlie's research told him that during El Niño weather cycles, the surface seawaters in the Great Barrier Reef lagoon, already heated to unusually high levels by greenhouse gas–induced warming, were being pulsed from a mass of ocean water known as the Western Pacific Warm Pool onto the reef's delicate living corals. When corals are exposed to temperatures two or three degrees hotter than their evolved maximum (31 degrees Celsius for Great Barrier Reef species), along with increased levels of sunlight, it is lethal. The powerhouse algae that live in the corals' tissues, providing their color and food through photosynthesis, pump out oxygen at levels toxic to their polyp hosts. The corals must expel their symbiotic life supports or die. Row on row of stark white skeletons are the result.

Charlie apologizes to the audience for having given such a miserable talk. "Use your influence," he pleads. "Get this story recognized. It is not a fairy tale. It is reality."

These damaged corals are capable of regeneration if water temperatures return to normal and water quality remains good, but the frequency and intensity of bleaching outbreaks are now such that the percentage of reef loss from coral deaths will increase dramatically. Charlie predicts that the widening and deepening of the Western Pacific Warm Pool through climate change will mean that "every year will effectively become an El Niño year as far as the corals are concerned."

PAST PREDICTS THE FUTURE

CHARLIE'S HOPE is that some as yet unknown strains of symbiotic algae, better able to cope with a heat-stressed world, might eventually form partnerships with corals. Or that the adaptive energies of fast-growing corals such as *Acropora* might somehow outpace the rate of bleaching. Or that pockets of corals lying in shadowed refuges on cool, deep reef slopes or in deep waters might survive to become agents of future renewal.

But heat is not the only problem corals face. Other destructive synergies may be impossible to stop. Reefs, Charlie points out, are nature's archives. They are complex data banks that record evidence of environmental changes from millions of years ago up to the present. Imprinted in fossil typography are the stories of the mass extinction events of the geologic past, including their likely causes. These archives tell us that four out of the five previous mass extinctions of coral reefs on our planet were linked to the carbon cycle. They were caused by changes to the ocean's chemistry brought about by absorption of two primary greenhouse gases, carbon dioxide and methane, through a process of acidification of ocean water.

Today's culprits are the same gases, although their increased presence is not the result of the meteor strikes or volcanoes that caused earlier catastrophes. We humans are doing that work, knowingly pumping these gases into the atmosphere at unprecedented rates. Already the oceans, the planet's usual absorber of these gases, have reached a third of their capacity to soak them up and balance them chemically. Stealthily, the oceans have begun the process that scientists call commitment, the unstoppable inevitability of acidification that presages destruction long before it is clearly visible. Eventually—possibly as early as 2050—we will have reached the point where coral skeletons become soluble in seawater. Carbonate rock, including reefs, will start dissolving, like "a giant antacid tablet," as Charlie describes it.

Phytoplankton, the food of tiny krill, a key element in the food web of the southern oceans, will be equally affected by acidification. And who knows what terrible chain of ecological consequences will follow? The earth's sixth mass extinction event will have arrived.

So, Charlie Veron, a man who has lived and worked on the Great Barrier Reef for most of his life, finds himself in the agonizing position of having to be a prophet of its extinction. We cannot wonder that he feels "very very sad. It's real, day in, day out, and I work on this, day in, day out. It's like seeing a house on fire in slow motion.… There's a fire to end all fires, and you're watching it in slow motion, and you have been for years."

I know of few more poignant sights than the closing moments of Charlie's speech in July 2009 in that hushed room of scientists and citizens. Tossing aside his notes, he apologizes to the audience in a strained, faltering voice for having delivered such a miserable talk. He urges his listeners to think about what they have heard.

"Use your influence," he pleads. "For the future of the planet, help get this story recognized. It is not a fairy tale. It is reality." SA

MORE TO EXPLORE

Corals of the World. J.E.N. Veron. Australian Institute of Marine Sciences, 2000.
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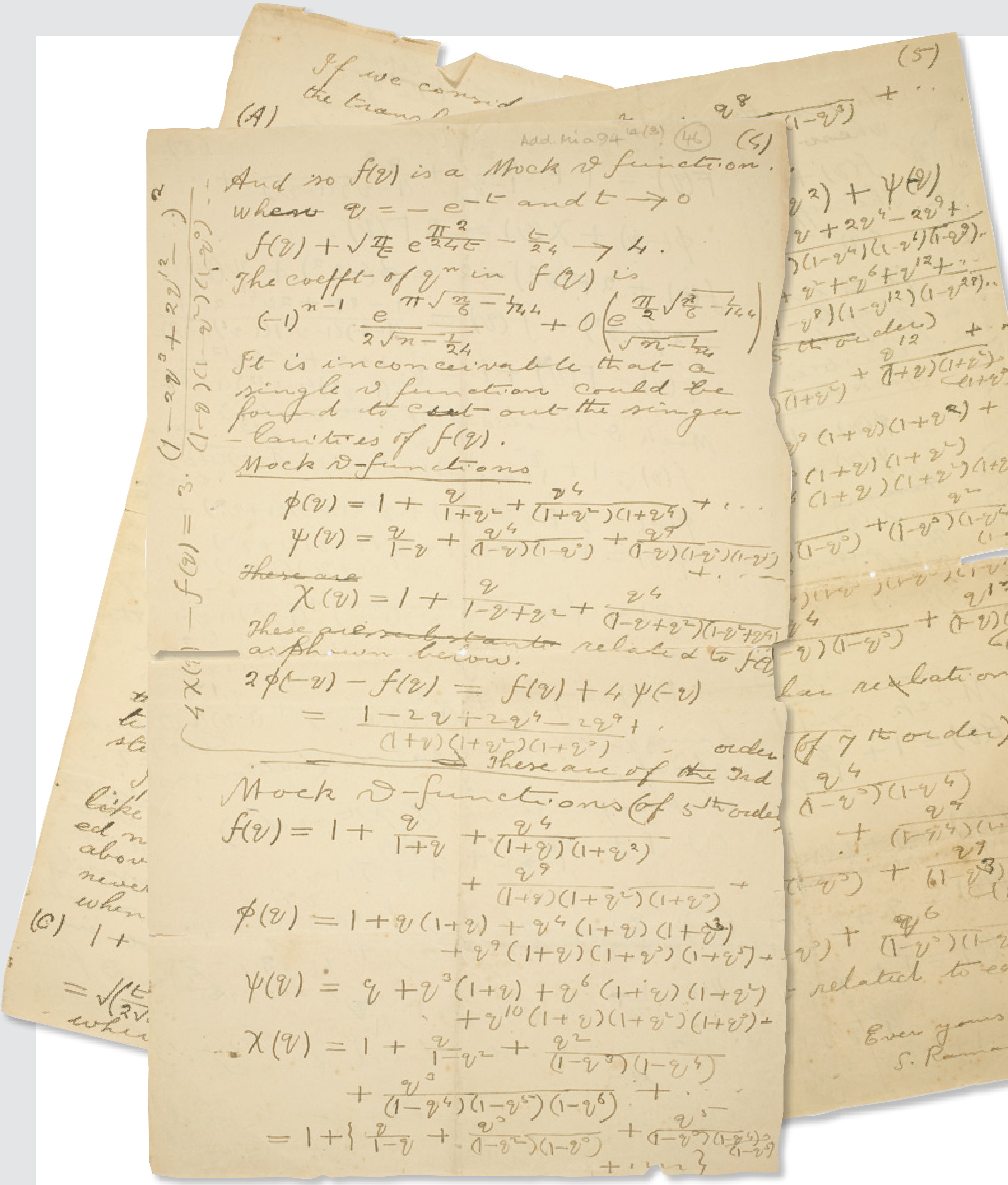
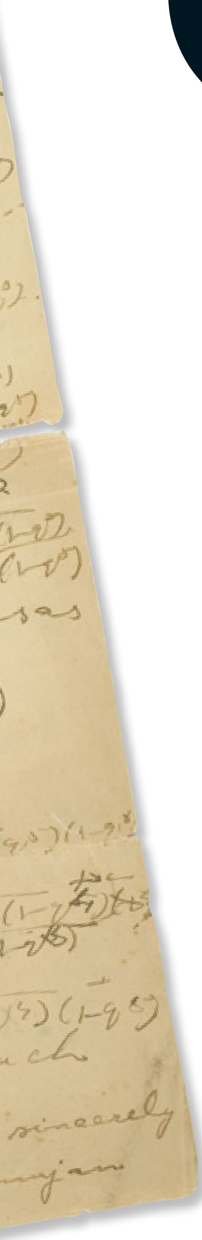


RAMANUJAN (*opposite page*), who died in 1920 at age 32, filled several notebooks with more than 3,000 often profound statements about how numbers behave. His papers (*above*) have inspired mathematicians ever since.

The Oracle



Mathematician Ken Ono has solved long-standing puzzles using insights hidden in the unpublished papers of Indian prodigy Srinivasa Ramanujan

By Ariel Bleicher

Ariel Bleicher is a freelance writer based in New York City.

ON A SATURDAY MORNING IN 1984, WHEN KEN ONO WAS IN HIGH school, he opened his family's mailbox in Baltimore and found an envelope as thin as rice paper covered in brilliantly colored stamps. It was addressed to his father, a reserved Japanese mathematician. When Ono handed over the mail, the elder Ono looked up from the yellow legal pad on which he was always scribbling equations and set down his ballpoint pen. Gently, he pried open the seal and unfolded the letter inside.

"Dear Sir," it began. "I understand … that you have contributed for the sculpture in memory of my late husband.… I am happy over this event." It was signed "S. Janaki Ammal," whom the red-inked letterhead identified as the widow of the "(Late) Srinivasa Ramanujan (Mathematical Genius)."

That was the first time the younger Ono had heard of the legendary Ramanujan. A self-taught mathematical prodigy from India, he made cryptic claims around a century ago that "seemed scarcely possible to believe," his British collaborator Godfrey Harold ("G. H.") Hardy once wrote. Yet his work has inspired entirely new fields of mathematics and hinted at theories that, in several cases, won their inventors the Fields Medal—mathematics' equivalent of the Nobel Prize.

As Ono studied to become a mathematician—he is now a professor of number theory at Emory University—he never had reason to pay Ramanujan much mind. As far as he knew, the "Mathematical Genius" had not left behind new insights into Ono's particular specialty in number theory, modular forms—abstract two-dimensional objects revered for their remarkable symmetry.

Ramanujan resurfaced in Ono's life in a big way in 1998, when he was 29. While assembling an anthology of the prodigy's work, mathematician Bruce C. Berndt of the University of Illinois at Urbana-Champaign had come on a largely neglected manuscript. Because the paper dealt with modular forms, Berndt e-mailed Ono a digital scan, thinking he might be able to decipher some strange claims.

Two thirds of the way through the text, Ono stopped. In neat schoolboy script, Ramanujan had penned six bold mathematical statements that seemed utterly bizarre to Ono, even though they touched on his area of expertise.

Ono was dumbfounded. He was certain the statements were false. "I looked at them and I said, 'No way. This is crap.'"

His first instinct was to try to prove Ramanujan wrong.

PART AND PARCEL

IT IS A MYSTERY how Ramanujan thought up much of the mathematics he wrote down. He educated himself using an outdated English tutoring book, and in his mid-20s, while working as a

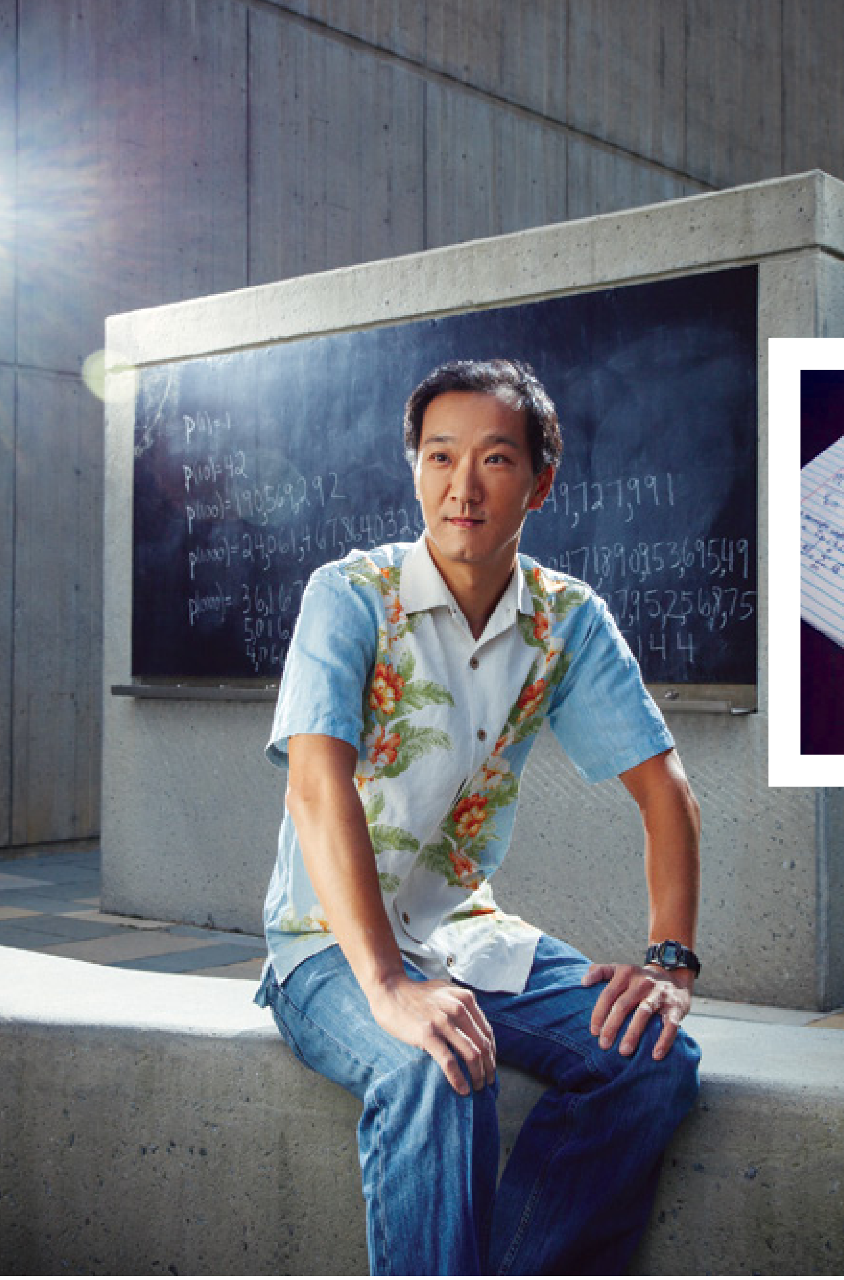
IN BRIEF

A self-educated prodigy, Srinivasa Ramanujan filled notebooks with often mysterious theorems about numbers, many of which turned out to be correct and eventually launched entire new fields of math.

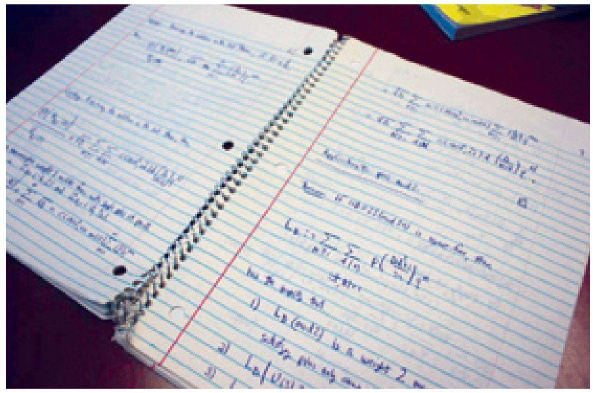
Now Emory University mathematician Ken Ono and his colleagues have made surprising discoveries using previously unrecognized insights in some of Ramanujan's unpublished papers.

As well as helping solve some big mysteries about mathematical machines called functions, these discoveries could advance more secure ways to encrypt computer data and new approaches to studying black holes.

PRECEDING PAGES: COURTESY OF JON SMITH *Trinity College, University of Cambridge (notebook pages);* SCIENCE SOURCE *(Ramanujan)*



MATHEMATICIAN Ken Ono of Emory University (*left*) does a lot of his theorizing in his head, but, like Ramanujan, he sometimes gets his thought process down on paper (*below*).



AUDRA MELTON (*Ono*); COURTESY OF MCKENZIE WEST (*notebook*)

government clerk, he began broadcasting his ideas in letters to mathematicians in England. He received one reply. It came from Hardy, then an up-and-coming professor, who invited Ramanujan to come work with him in Cambridge. After just three years abroad, Ramanujan fell ill during the food shortages of World War I. Emaciated and feverish, he returned to India and died in 1920. He was 32 years old.

In addition to 37 published papers, Ramanujan left behind a small library of letters, partially completed manuscripts and three leather-bound notebooks. Examining them, Hardy and others found that he had rediscovered classic theorems—rules about how numbers behave—that were first recorded by mathematicians at the tops of their fields. And Ramanujan noticed more patterns that no one else saw. A trained mathematician would know to back up each finding with a proof, a sequence of logical arguments that would convince her or his colleagues of its truth. But Ramanujan did not bother. He filled page after page with long lists of theorems and calculations that he worked out in his head or on a chalk slate, rarely pausing to explain how he arrived at them. The three notebooks alone contain more than 3,000 such conclusions about the nature of numbers, which mathematicians have worked hard to prove or disprove since Ramanujan's death.

Berndt began digging through the Ramanujan archive in the 1970s. He was still at it more than two decades later, when he got to the manuscript with the six arresting statements—the ones Ono was determined to prove wrong. They drew a parallel between modular forms and so-called partition numbers, which are a sequence of integers (that is, whole numbers) that represent all the ways you can add up smaller integers to get the one you started with. Partition numbers come from the partition function, which, like any function, describes a relation between two things: it takes a given input x and spits out the corresponding output $f(x)$. The partition function, $p(n)$, counts the combinations of positive integers that sum to a given integer n. For example, $p(4)$ is 5: 1 + 1 + 1 + 1, 1 + 1 + 2, 2 + 2, 1 + 3 and 4.

The partition function and the numbers that it generates might seem straightforward, but for centuries theoreticians have struggled to find patterns among these numbers so that they can predict them, calculate them, or relate them to other functions and theorems. Ramanujan made one of the first real breakthroughs. He and Hardy together devised a method to quickly approximate partition numbers. To check the accuracy of their approximations, they solicited a retired British artilleryman and calculation wizard named Percy Alexander MacMahon (aka Major MacMahon) to work out the first 200 partition numbers by hand. As it turned out, Ramanujan and Hardy's approximations were impressively precise. Even more important, studying MacMahon's list led Ramanujan to one of his most famous observations. MacMahon had arranged the values of $p(n)$, starting with $n = 0$, in five columns. Ramanujan noticed that every entry in the last column—that is, every fifth partition number starting with $p(4)$—is divisible by 5, and he proved that this pattern continues forever. It was a stunning revelation. Remember, partitions are about *adding* numbers. No one imagined that they could have properties involving division.

1	1	2	3	5
7	11	15	22	30
42	56	77	101	135
176	231	297	385	490
627	792	1,002	1,255	1,575

Ramanujan noticed that every fifth partition number is divisible by 5 (*rightmost column*), and he proved that this pattern continues forever. It was a stunning revelation.

Ramanujan saw there were even more patterns like this. He proved, for example, that every seventh partition number starting with $p(5)$ is divisible by 7. Similarly, every 11th partition number starting with $p(6)$ is divisible by 11. Mysteriously, the "Ramanujan congruences" stop there. "It appears that there are no equally simple properties for any moduli involving primes other than these," Ramanujan wrote in a 1919 paper, referring to the prime numbers 5, 7 and 11.

After he died, mathematicians wondered if partitions might have some not so simple properties, and they tried to find them. Yet by the late 1990s they had not dug up more than a handful of additional congruences involving seemingly random primes and powers of primes, including 29, 17^3 and 23^6. They began to suspect that such patterns were unpredictable—and very, very rare.

After grappling with those six bygone statements in Ramanujan's manuscript, however, Ono was shocked to realize that those suspicions might be very, very wrong. Mathematicians had long believed partition numbers were related only to a small subset of modular forms. To Ono's bewilderment, Ramanujan's six statements linked the two fields in a profound way that no one had anticipated.

Because Ramanujan did not record proofs, Ono could not directly identify errors in the prodigy's thought process. So he decided to plug some numbers into the formulas Ramanujan included in the statements, hoping these examples might reveal some flaws. Yet the formulas worked every time. "Holy cow!" Ono said to himself. He realized that Ramanujan had to be right "because you couldn't possibly be creative enough to make something like that up and have it be true 100 times unless you knew why that formula was true, always." Then he closed his eyes and thought hard about what Ramanujan understood that no one else had.

Ono knew that modular forms "are littered with congruences"—those same patterns of divisibility that Ramanujan had found a few instances of among the partition numbers. As Ono contemplated the six statements, it occurred to him that if he thought of the partition function as a modular form in disguise, he could show that they were true.

Another thought immediately followed: he realized, laughing out loud, that with a few adjustments, the theories he had developed about modular forms could be powerful tools not just for verifying Ramanujan's genius but also for unearthing deeper secrets about the partition function. "It was something like getting a fancy new telescope," Ono reminisces. "Once you have it, if you start scanning space—where in this space the stars are the partition numbers—you'll see there are lots and lots of galaxies."

In this way, Ono was able to prove that partition congruences are not rare at all. Mathematicians had assumed there were few beyond 5, 7 and 11. But in fact, as Ono discovered, there are infinitely many.

Ono's peers hailed the finding as groundbreaking. He was not satisfied, however. Even though he could prove that partition congruences are everywhere, he could not tell you where to find them. If you lined the partition numbers in order, you might want to know how often a congruence would turn up. If you saw one, could you predict when you would see the next? Ono did not have a clue.

When a problem stumps Ono, he refuses to obsessively chew on it in his mind until it is as inelastic as old gum. Instead he files it away inside his head alongside other unsolved problems until it resurfaces. The problem of how to predict partition congruences lay dormant for five years, until postdoctoral fellow Zachary A. Kent arrived at Emory in the spring of 2010. It just popped up one day in conversation, and soon they were talking about it all the time—in their offices, over coffee and on a long walk in the woods north of Atlanta.

Little by little, they built in their minds a labyrinthine superstructure into which the partition numbers could be neatly arranged. They discovered this organization using a theoretical device, which mathematicians call an operator. The particular operator they chose takes any prime number (13, say), selects powers of that prime (13^2, 13^3, and so on), and divides them into the partition numbers. Incredibly, the numbers it spits out obey a fractal structure—they repeat in near-identical patterns at different scales, like the branches of a snowflake. This outcome shows that the partition numbers are not just a random sequence of numbers with incidental symmetries sprinkled among them willy-nilly. Rather these numbers have a "beautiful inner structure," Ono says, that makes them predictable and much more fascinating to study.

It took several months for Ono, Kent and their collaborator Amanda Folsom of Yale University to work out all of the kinks in their new theory. But at last, they were able to prove that partition congruences appear in a calculable manner. They exist for every prime and every prime power. Beyond 11, though, the patterns get much more complex, which is probably why Ramanujan never worked them out.

Ono and his collaborators presented their findings at a specially convened symposium at Emory in 2011. Afterward, messages of congratulations flooded Ono's in-box. "It's a dramatic and surprising discovery," says George E. Andrews, an expert on partitions at Pennsylvania State University. "I don't think even Ramanujan could have dreamt it."

BEAUTIFUL ANSWERS

INVESTIGATING RAMANUJAN'S INSIGHTS has led Ono to other revelations that may one day be useful in fields outside mathematics. By melding Ramanujan's prescience with modern mathematics, Ono and his colleagues have devised powerful computational tools. Beyond advancing understanding in pure mathematics, these tools could lead to better ways of encrypting computer data and studying black holes.

Working with Jan Bruinier of the Technical University of Darmstadt in Germany, Ono constructed a formula for computing large partition numbers quickly and exactly—the holy grail Ramanujan never obtained. Ono calls this calculator "the Oracle." In addition to crunching partitions, he says, it could be used to study certain kinds of elliptic curves—geometric objects that look something like the surface of a doughnut.

Cryptographers use elliptic curves to create algorithms for encrypting computer data. The success of these schemes hinges on their ability to generate mathematical puzzles that are impossible to solve in a timely manner. A common algorithm called RSA, for example, rests on the difficulty of factoring the product of two very large prime numbers. Newer methods use points on an elliptic curve, whose relations are even harder to discern. If the Oracle or related discoveries can shed light on other, more elusive connections, cryptographers could potentially use this knowledge to devise stronger encryption systems.

Ono's work has also unveiled one of the greatest mysteries of Ramanujan's mathematical legacy. Three months before he died, Ramanujan, bedridden by fever and pain, dashed off one last letter to Hardy in England. "I am extremely sorry for not writing you a single letter up to now," he wrote. "I discovered very interesting functions recently which I call 'Mock' theta functions.… They enter into mathematics as beautifully as the ordinary theta functions."

Theta functions are essentially modular forms. Ramanujan surmised that it is possible to describe new functions—the mock theta functions—that look nothing like modular forms and yet behave similarly at special inputs called singularities. Nearing these points, the outputs of a function balloon to infinity. Consider, for example, the function $f(x) = 1/x$, which has a singularity at $x = 0$. As an input x gets closer and closer to 0, the output $f(x)$ grows infinitely large. Modular forms have an infinite number of such singularities. Ramanujan intuited that for every one of these functions, there is a mock theta function that not only shares the same singularities but also produces outputs at these points that climb toward infinity at almost exactly the same rates.

It was not until 2002 that a Dutch mathematician, Sander Zwegers, formally defined mock theta functions, using ideas shaped decades after Ramanujan's death. Yet still mathematicians could not explain Ramanujan's assertion that these functions mimic modular forms at their singularities.

The machinery behind Ono and Bruinier's Oracle finally solved the puzzle. With Folsom and Robert Rhoades of Stanford University, Ono used it to derive formulas for calculating the outputs of mock theta functions as they approach singularities. And indeed, they found that Ramanujan's conjecture was correct: these outputs were remarkably like the outputs near corresponding singularities in modular forms. In one case, for instance, the mathematicians found that the difference between them gets very close to 4, a surprisingly neat and almost negligible divergence in this universe of infinite numbers.

Physicists have recently begun using mock theta functions to study a property of black holes called entropy—a measure of how close a system is to achieving a perfect state of energy balance. Some scientists believe that formulas akin to Ono's may allow them to probe such phenomena with finer precision.

Ono cautions that we should not make too much of potential applications for his work. Like many theoreticians, he believes that practical purposes are not what make such discoveries great. Great discoveries, he argues, are great the way a painting or sonata is great. "Ken's theorems aren't going to supply us with an infinite amount of green energy or cure cancer or anything like that," Andrews agrees. Mathematical discoveries often assume important roles in science and technology only after they sit around for a few decades. It is difficult, if not impossible, to predict what those roles will be.

Ono can still recall the giddy pleasure of seeing Ramanujan's congruences written out for the first time, his father's steady hand scripting the unfamiliar symbols on his yellow legal pad. "Why just three?" he remembers asking. "Nobody knows," his father told him.

As he recounts this story, Ono is sitting in his family dining room in Georgia. On the wall behind him is a framed photograph of the bronze bust of Ramanujan that was commissioned for his widow with $25 donations from Ono's father and hundreds of other mathematicians and scientists around the world. "I never in my wildest dreams imagined I'd one day get to say, 'You know what, Dad? Those congruences aren't the only ones—not by a long shot.'" SA

MORE TO EXPLORE

ℓ-Adic Properties of the Partition Function. Amanda Folsom, Zachary A. Kent and Ken Ono in *Advances in Mathematics,* Vol. 229, No. 3, pages 1586–1609; February 15, 2012.

Ramanujan's Mock Theta Functions. Michael Griffin, Ken Ono and Larry Rolen in *Proceedings of the National Academy of Sciences USA,* Vol. 110, No. 15, pages 5765–5768; April 9, 2013. **www.ncbi.nlm.nih.gov/pmc/articles/PMC3625272**

FROM OUR ARCHIVES

Srinivasa Ramanujan. James R. Newman; June 1948.

Cracking a Century-Old Enigma. Davide Castelvecchi; April 2011.

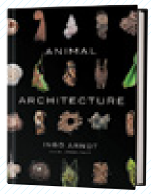
scientificamerican.com/magazine/sa

MORE TO EXPLORE For more recommendations and an interview with author Mark Miodownik, go to ScientificAmerican.com/may2014/recommended


TOWER built by compass termites in Australia

Animal Architecture

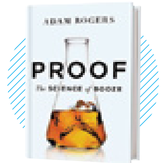
by Ingo Arndt and Jürgen Tautz. Abrams, 2014 ($29.95)



Massive beaver dams, woven wasp nests and lofty termite towers are among the impressive constructions documented in this large visual book. Photographer Arndt traveled the world to capture animal architecture that is functional, beautiful and complex. Some creations, such as sculptures that carrier snails make of shells and pebbles held together with the snails' own bonding secretions, would not seem amiss in the world's best art museums. Text from biologist Tautz complements Arndt's photographs to explain these wonders of animal industry.

Proof: The Science of Booze

by Adam Rogers. Houghton Mifflin Harcourt, 2014 ($26)



Wine lovers, beer hounds, whiskey connoisseurs and even teetotalers are all likely to find something to interest them in this look at the science of liquor. Journalist Rogers follows "a sip of booze on a birth to death journey via your tummy," delving into the biochemistry of fermentation and distillation, the history of alcohol production, and the physiological and psychological effects of drinking. To tell his tale, he makes pilgrimages to Scottish whiskey distilleries, storied cocktail bars in New York City's Chinatown and the laboratories of mixologists, who deploy complex chemistry equipment in pursuit of the perfect drink.

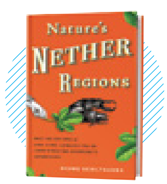
Stuff Matters: Exploring the Marvelous Materials That Shape Our Man-Made World

by Mark Miodownik. Houghton Mifflin Harcourt, 2014 ($26)

Pick up this book during a meal, and you might find yourself pausing to marvel at the amazing properties of the steel in your fork, the ceramic of your plate, the textiles on your chair and myriad other materials. Miodownik, a materials scientist, explains the history and science behind things such as paper, glass, chocolate and concrete with an infectious enthusiasm. He explores the microscopic reasons "why some materials smell and others are odorless; why some materials can last for a thousand years and others become yellow and crumble in the sun; how it is that some glass can be bulletproof, while a wineglass shatters at the slightest provocation."

Nature's Nether Regions: What the Sex Lives of Bugs, Birds and Beasts Tell Us about Evolution, Biodiversity, and Ourselves

by Menno Schilthuizen. Viking, 2014 ($28.95)



The science of genitals is a relatively new field for biologists, who have long overlooked the evolutionary importance of species' private parts. Biologist Schilthuizen balances the silly and the serious to describe researchers' latest efforts to understand how "evolution has graced the animal kingdom with such a bewildering diversity of reproductive organs." Schilthuizen tours some of nature's weirdest inventions, such as the chicken flea penis, which is "actually a profusion of plates, combs, springs, and levers" and looks like "an exploded grandfather clock."

The Tale of the Dueling Neurosurgeons: The History of the Human Brain as Revealed by True Stories of Trauma, Madness, and Recovery

by Sam Kean. Little, Brown, 2014 ($27)

Some people's tragedies have been science's miracles, particularly in the field of neuroscience, where researchers have long relied on rare brain traumas to reveal the workings of the mind. "Despite the (often overhyped) advances of fMRI and other brain-scanning technologies, injuries remain the best, and only, way to infer certain things about the brain," writes journalist Kean. In this compilation of patients' stories, he details some of the unexpected truths revealed by accidents: "Destroy one small node of neurons, and people lose the ability to recognize fruits and vegetables, but not other food. Destroy another node and they lose the ability to read—even though they can still write." Beyond paying tribute to the scientific advances these patients made possible, Kean humanizes the patients themselves.

INGO ARNDT *Abrams*

Viewing the world with a rational eye

Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com). His next book is *The Moral Arc of Science.* Follow him on Twitter @michaelshermer

The Genesis of Justice

Before all learning, an infant's mind has a sense of right and wrong

On the platform of a subway station, a woman and two men are talking a few feet away from the open track pit. Without warning, one of the men shoves the woman. She staggers backward toward the edge. The other man reaches out to catch her, but he is too late, and down she goes onto the tracks. In an instant, he reacts. He turns on his heels and coldcocks the culprit. It is a magnificent roundhouse to the face that snaps the wrongdoer's head back. Satisfied with this act of revenge, he turns, hesitates and dashes over to pull the woman to safety. He reassures her, then takes off after the malefactor, who has beat a hasty retreat. The entire incident takes 20 seconds, and you can see it yourself on YouTube (http://goo.gl/WQEWOA at the 1:52 mark).

In that moment—too brief for rational calculation—a conflict of pure emotionality unfolds between rescue and revenge, helping and hurting. In a flash, two neural networks in the rescuer's brain are engaged to act: help a fellow human in trouble or punish the perpetrator. What is a moral primate to do? In this case, because no train was coming, he could afford that problematic first choice. Rescue is sweet, but so is revenge.

This vignette illustrates our multifaceted moral nature, which evolved to solve several problems at once in our ancestral environment: be nice to those who help us and our kin and kind and punish those who hurt us and our kin and kind. Evidence that these moral emotions are deeply entrenched in human nature may be found in a series of experiments with babies, brilliantly synthesized in the book *Just Babies: The Origins of Good and Evil* (Crown, 2013) by Yale University psychologist Paul Bloom. Testing the theory that we have an innate moral sense, as proposed by such Enlightenment thinkers as Adam Smith and Thomas Jefferson, Bloom provides experimental evidence that "our natural endowments" include "a moral sense—some capacity to distinguish between kind and cruel actions; empathy and compassion—suffering at the pain of those around us and the wish to make this pain go away; a rudimentary sense of fairness—a tendency to favor equal divisions of resources; a rudimentary sense of justice—a desire to see good actions rewarded and bad actions punished."

In Bloom's laboratory, a one-year-old baby watched puppets enact a morality play. One puppet rolled a ball to a second puppet, who passed the ball back. The first puppet then rolled the ball to a different puppet, who ran off with the ball. The baby was next given a choice between taking a treat away from the "nice" puppet or the "naughty" one. As Bloom predicted, the infant removed the treat from the naughty puppet—which is what most babies do in this experiment. But for this little moralist, removing a positive reinforcement (the treat) was not enough. "The boy then leaned over and smacked this puppet on the head," Bloom recounts. In his inchoate moral mind, punishment was called for.

There are numerous permutations on this research paradigm—such as a puppet trying to roll a ball up a ramp, for which another puppet either helps or hinders it. Time and again, the moral sense of right (preferring helping puppets) and wrong (abjuring hurting puppets) emerges in people between three and 10 months of age, far too early to attribute to learning and culture. Morality, Bloom concludes, "entails certain feelings and motivations, such as a desire to help others in need, compassion for those in pain, anger toward the cruel, and guilt and pride about our own shameful and kind actions," which supports what I saw in the video vignette. Society's laws and customs can turn the moral dials up or down, of course, but nature endowed us with the dials in the first place. This is why the constitutions of our nations should be grounded in the constitution of our nature. SA

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Illustration by Izhar Cohen

The ongoing search for fundamental farces

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.

Statistical Significance

There are so many things in heaven and earth that coincidences become certainties

Back in 1980, a woman named Maureen Wilcox played the Rhode Island and the Massachusetts lotteries at the same time. And she hit the correct numbers for both. Unfortunately, she picked all the correct Massachusetts numbers on her Rhode Island ticket and all the right Rhode Island numbers on her Massachusetts ticket. Shirley Jackson couldn't write a more terrifying lottery story.

Wilcox's shenanigans bring to mind a short work by Woody Allen that lampoons numerology, the search for meaning in random numbers. Its last line: "It was reasoning like this that led Rabbi Yitzhok Ben Levi, the great Jewish mystic, to hit the double at Aqueduct fifty-two days running and still wind up on relief."

Anyway, the sad tale of the lottery switcheroo is discussed in the new book *The Improbability Principle: Why Coincidences, Miracles, and Rare Events Happen Every Day,* by mathematician and statistician David J. Hand. (What are the chances that the author of a book that mentions "the probability of being dealt a royal flush in poker is about 1 in 650,000" is named Hand?)

The New England states' mash-up and other oddball lottery cases are in the chapter of the Hand book entitled "The Law of Truly Large Numbers." It opens with a quote, circa 1832, from British writer E. G. Bulwer-Lytton: "Fate laughs at probabilities." By the way, Bulwer-Lytton is the guy who actually started a novel with "It was a dark and stormy night" and who now has a contest named for him that rewards the worst fictional sentence. *The Improbability Principle* is not eligible, because it is a work of nonfiction, and it is good.

"The law," writes the learned Hand, "of truly large numbers … says that, with a large enough number of opportunities, any outrageous thing is likely to happen." Lotteries are wonderful examples of how events that appear virtually impossible actually become inevitable given enough time and trials. Remember, the salient feature of the Wilcox mix-up is not that it happened to her—those odds are crazy small—but that it would eventually happen to somebody. And chance happened to pluck her.

Double lottery winners illustrate the law of truly large numbers in action. For example, on April 7, 2012, a woman matched five of the six Powerball numbers in the lottery in Virginia. Twice. Her two winning tickets were each worth more than $1 million. Plus, her first name is Virginia, which is utterly meaningless but would keep Rabbi Ben Levi up for 52 nights in a row.

Then there are the lotteries themselves. In consecutive games in 2009, the Bulgarian lottery randomly picked the same set of six winning numbers. Naturally, some people suspected fraud. But Hand outs the real culprit: probability. When he works up the math, it takes just 43 years for there to exist a better than even chance for the same sets of numbers to get drawn twice (although the two-in-a-row pick was a bonus).

And that's just in Bulgaria. "When we take into account the number of lotteries around the world," Hand writes, "we see that it would be amazing if draws *did not* occasionally repeat." So it came to pass that in 2010 on September 21 and then on October 16, an Israeli lottery drew the same numbers. "Scores of people flooded Israeli radio station phone-ins," Hand prints in the book, "to complain that the lottery was fixed." Rabbi Ben Levi might have been among them, but chances are he hadn't paid his phone bill.

Which brings us to what comedian Dave Attell calls "God's drive-by shooting," that is, getting hit by lightning. Hand notes the case of one Roy Sullivan, a seven-time loser in the lightning-strike lottery. Sullivan was a park ranger, so he upped his odds by being outdoors a lot. The same went for a sportsman named Major Walter Summerford, struck three times, whose gravestone took a shot four years after his death.

Yet consider that about 100 lightning bolts reach the earth's surface every second—statistically, hundreds of thousands of people are going to get hit annually, with somebody bound to take multiple zaps. And if there were really such a thing as bad luck, that somebody would be Maureen Wilcox. SA

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Illustration by Matt Collins

U.S. GOV'T GOLD

U.S. GOLD COINS AUTHORIZED FOR IMMEDIATE RELEASE

The United States Gold & Silver Reserve Vault Facility today announces what could be the final release of U.S. government-issued gold coins previously held in The West Point Depository/U.S. Mint. For a limited time, U.S. citizens will have the opportunity to purchase these $5 government-issued gold coins for the incredible at-cost price of only $147.00 per coin. An amazing price because these U.S. government-issued gold coins are completely free of dealer markup. That's correct—our cost. This may be your final opportunity to buy U.S. government-issued gold coins at this price. Gold, which is currently around $1,375 per ounce, is predicted by experts to have the explosive upside potential of reaching up to $5,000 per ounce in the future. Please be advised: Our U.S. government gold inventory will be priced at $147.00 per coin while supplies last or for up to 30 days. These coins may sell out. Call today! United States Gold & Silver Reserve will release these U.S. government-issued gold coins at cost on a first-come, first-served basis. Orders that are not immediately received or reserved with the order center could be subject to cancellation and your checks returned uncashed. Good luck. We hope that everyone will have a chance to purchase this special U.S. government-issued gold at this price because it could be going to $5,000 per ounce. Order immediately before our vault sells out completely! Special arrangements can be made for gold purchases over $50,000.


U.S. Government-Issued American Eagle Gold Coins

Coins enlarged to show detail.

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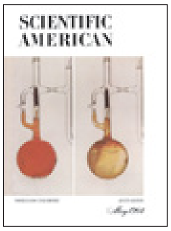
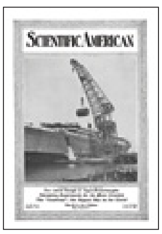


May 1964

Earlier Man

"The British paleontologist L.S.B. Leakey has discovered in Africa the bones of creatures he regards as the earliest men, for whom he has proposed the name *Homo habilis.* Previously the first true man had been thought to be *Pithecanthropus,* a creature that lived about 500,000 years ago. The bones Leakey and his colleagues have found appear to date as far back as 1.8 million years. Leakey describes the creatures as walking erect on feet almost identical with modern man's and as having hands of considerable dexterity. Leakey also announced that he has abandoned his earlier opinion that *Zinjanthropus,* a manlike creature whose bones he found in Africa in 1959, was on the line of evolution to man."



May 1914

Noted Futurist

"*The World Set Free.* By H. G. Wells. New York: E. P. Dutton & Co., 1914. This latest of Mr. Wells' books is at once one of those magnificent flights of imagination which gave us *The Time Machine* and *The War of the Worlds,* and the keen sociological perception which gave us *The New Machiavelli* and its successors. The atomic bomb which plays so great a part in this story, although a creation of Mr. Wells, may be regarded as inspired by Frederick Soddy's *The Interpretation of Radium* (1909). Wells argues that inasmuch as radio-active substances are constantly decaying and giving off energy as they do so, tremendous results could be obtained if the decay could occur with explosive rapidity. Trained scientist as he is, he presents his atomic bomb with an air of definiteness and conclusiveness that almost convinces one it exists."

Preparing for War

"No less reliable an authority than Dr. Hugo Eckener [of Luftschiffbau Zeppelin in Germany] is responsible for startling revelations about a different kind of aerial marksmanship, dropping bombs to the ground, as practised by modern Zeppelins. From a safe altitude of 5,000 feet heavy bombs were dropped within circles marked by buoys on the water of the lower Elbe, of only 15 feet in diameter, showing that they could be dropped as well into the funnels of warships. Tests made on land showed that from an equal elevation a railroad station could be completely wrecked by four of these bombs."

Three months later World War I broke out; shortly after, Zeppelins dropped bombs on Liège and Antwerp in Belgium.

Ships for Leisure

"With the launching of each 'largest' steamship it was customary, a few years ago, to say of her that the limit of size had been reached. To-day we hear no such prognostications. It was less than one year ago that there steamed into the port of New York the 'Imperator' of the Hamburg-American Line—the first ship to exceed a length of 900 feet and her displacement 52,000 tons. This week sees the advent of the 'Vaterland,' which exceeds the 'Imperator' in length by 41 feet."

View a slide show on cruise ships and leisure boats at www.ScientificAmerican.com/may2014/pleasure-boating

WHEN ANIMALS ACT: A scene from the earliest days of the "movies," 1914

SCIENTIFIC AMERICAN, VOL. CX, NO. 22; MAY 30, 1914

Animal Actors

"Strong, ambitious wild animals, which until now have hoped for fame only in the circus or on the vaudeville stage, have found a new field for exercising their talent. A private dramatic school has been established for them near Fort Lee, New Jersey. Paul Bourgeois, a young French animal tamer, first thought of teaching jungle inhabitants to appear before the camera for the 'movies' [*see photograph*]."

May 1864

Dark Side of Fame

"The great English poet Alfred, Lord Tennyson, is exposed to great annoyance from the curiosity of intruders. Strangers are found from time to time seated in his garden, peering in at his windows, wandering freely through his grounds. From the lawn in front, when conversing with his family in assumed privacy, he has, on casually looking up, discovered an enterprising British tourist taking mental notes of his conversation from the branches of a tree above. Mr. Tennyson has been compelled to make fences, raise embankments, train foliage, and in fact half-fortify his house."

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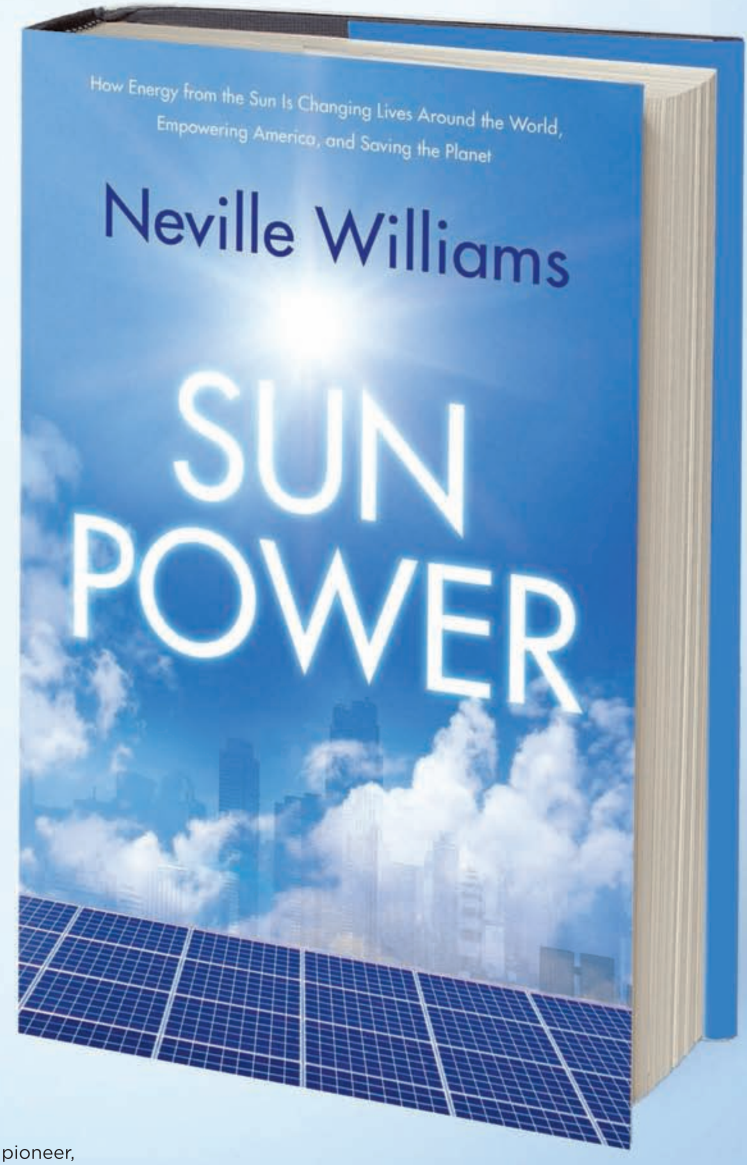

Hardcover and eBook

Jason Easterly

NEVILLE WILLIAMS is a solar power pioneer, advocate, and entrepreneur. He founded a highly successful non-profit organization to bring sun power to unelectrified peoples in developing countries and has launched companies all over the world to sell and install solarelectric systems. Williams first became involved with solar power during the Carter Administration as a consultant to the US Department of Energy. Williams lives in Naples, Florida.

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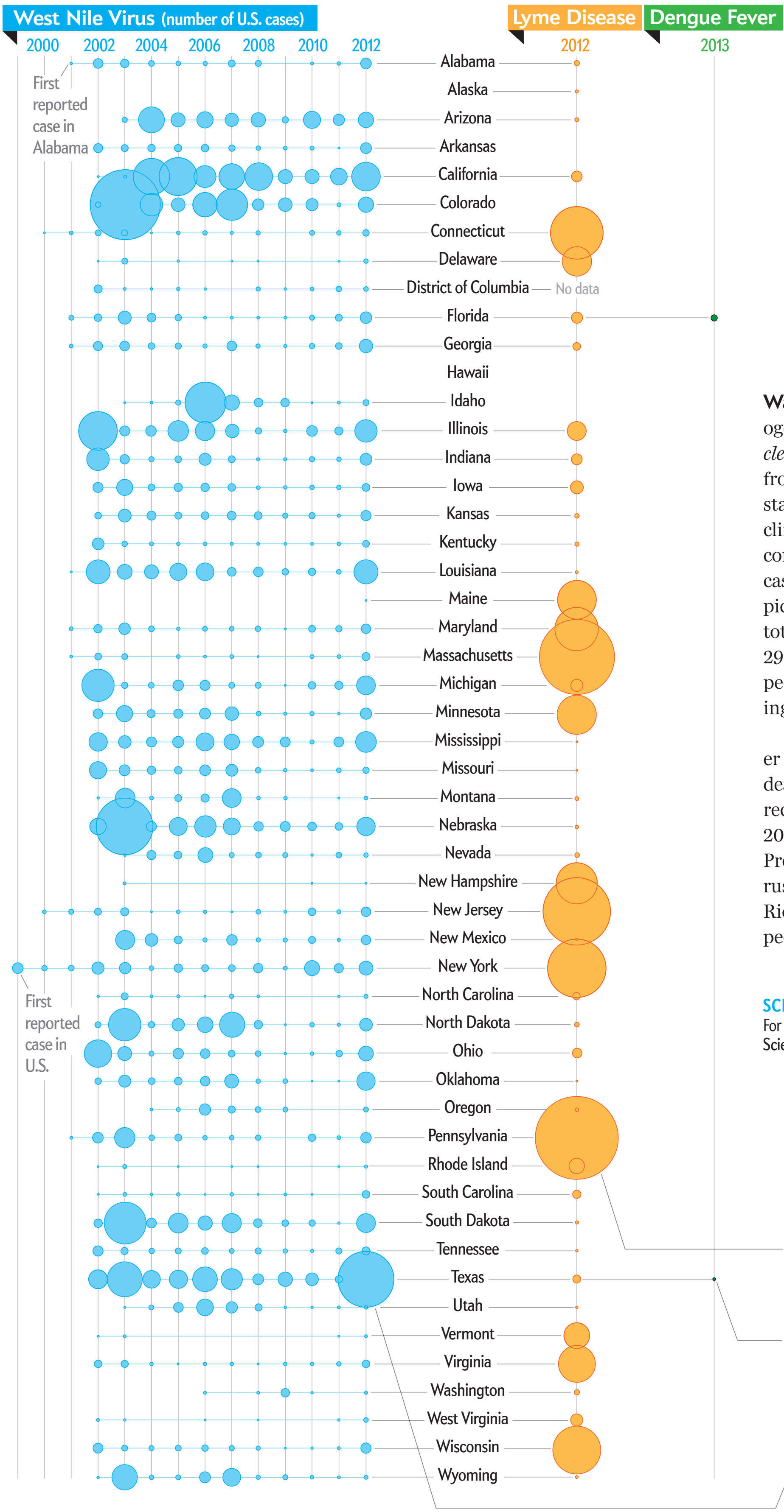
Spring Fever

A new season of West Nile, Lyme and dengue has begun

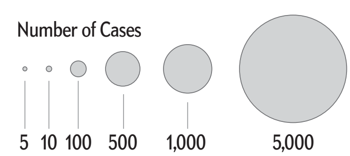
Warm weather brings bugs—and the pathogens they carry. West Nile virus (*blue circles*), transmitted by mosquitoes, has spread from only three U.S. states in 2000 to 48 states in 2012, and human cases have climbed from 21 to 5,674. Lyme disease was concentrated in the Northeast in 2000, but cases of the bacterial infection have also picked up across the country (*orange*). The total U.S. number has fallen from a peak of 29,959 in 2009, however, in part because people have gotten into the habit of checking themselves and their pets for ticks.

Those illnesses can cause fever and other serious symptoms. But another, more deadly mosquito-borne disease, dengue, has recently begun to rise in the U.S. (*green*). In 2013 the Centers for Disease Control and Prevention recorded three cases of the virus in Texas and 20 cases in Florida. Puerto Rico, which is not listed, is a hotspot: 8,148 people there tested positive last year.

—Mark Fischetti



SCIENTIFIC AMERICAN ONLINE
For more on dengue fever in the U.S., see ScientificAmerican.com/may2014/graphic-science



SOURCES: U.S. CENTERS FOR DISEASE CONTROL AND PREVENTION; U.S. GEOLOGICAL SURVEY

Graphic by Jen Christiansen

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