HOW THE MOST DANGEROUS VOLCANOES ERUPT
Scientists are peering deep inside Mount St. Helens for insights PAGE 34

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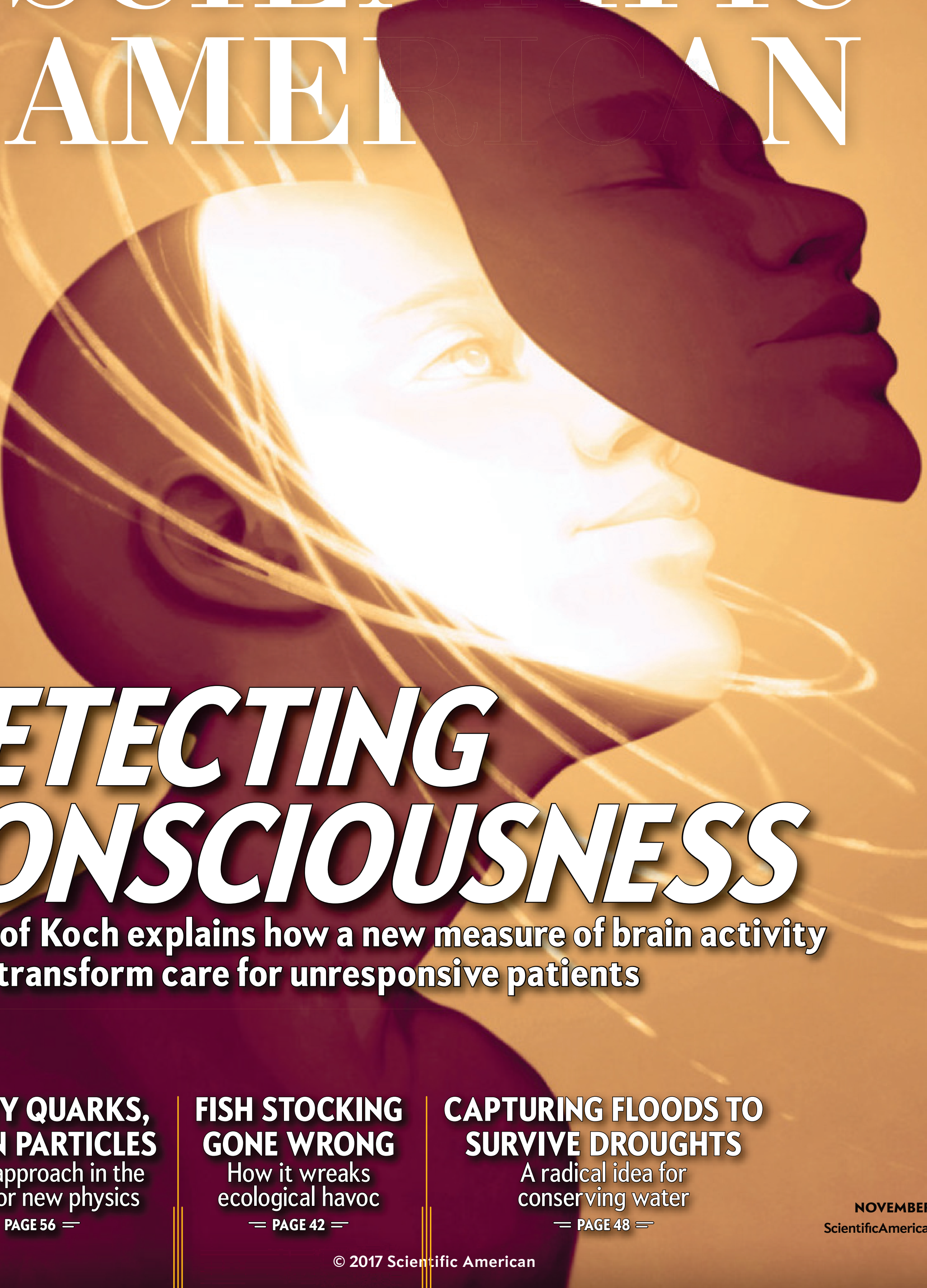

DETECTING CONSCIOUSNESS

Christof Koch explains how a new measure of brain activity could transform care for unresponsive patients

PLUS

BEAUTY QUARKS, HIDDEN PARTICLES
A novel approach in the search for new physics
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NOVEMBER 2017
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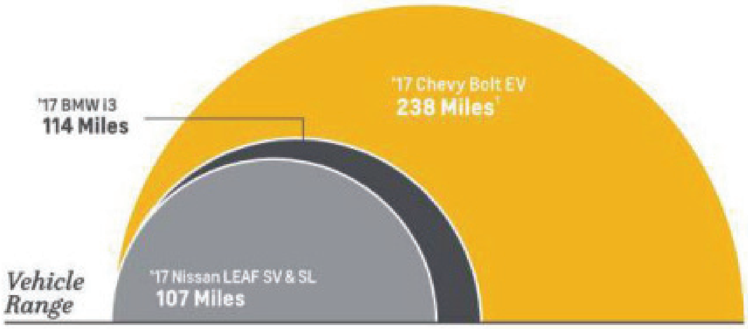

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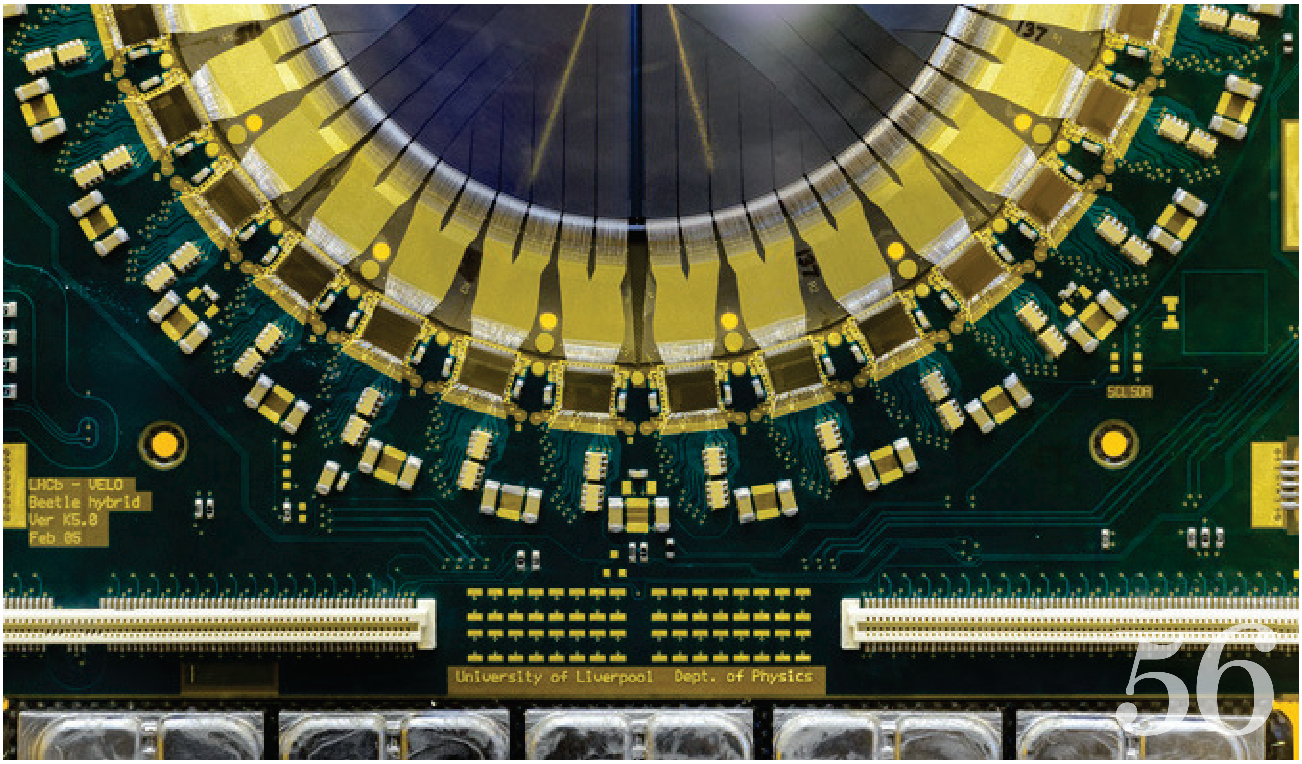
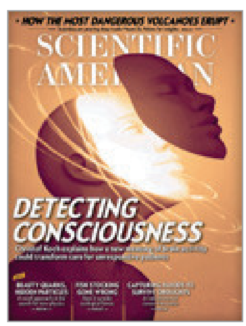
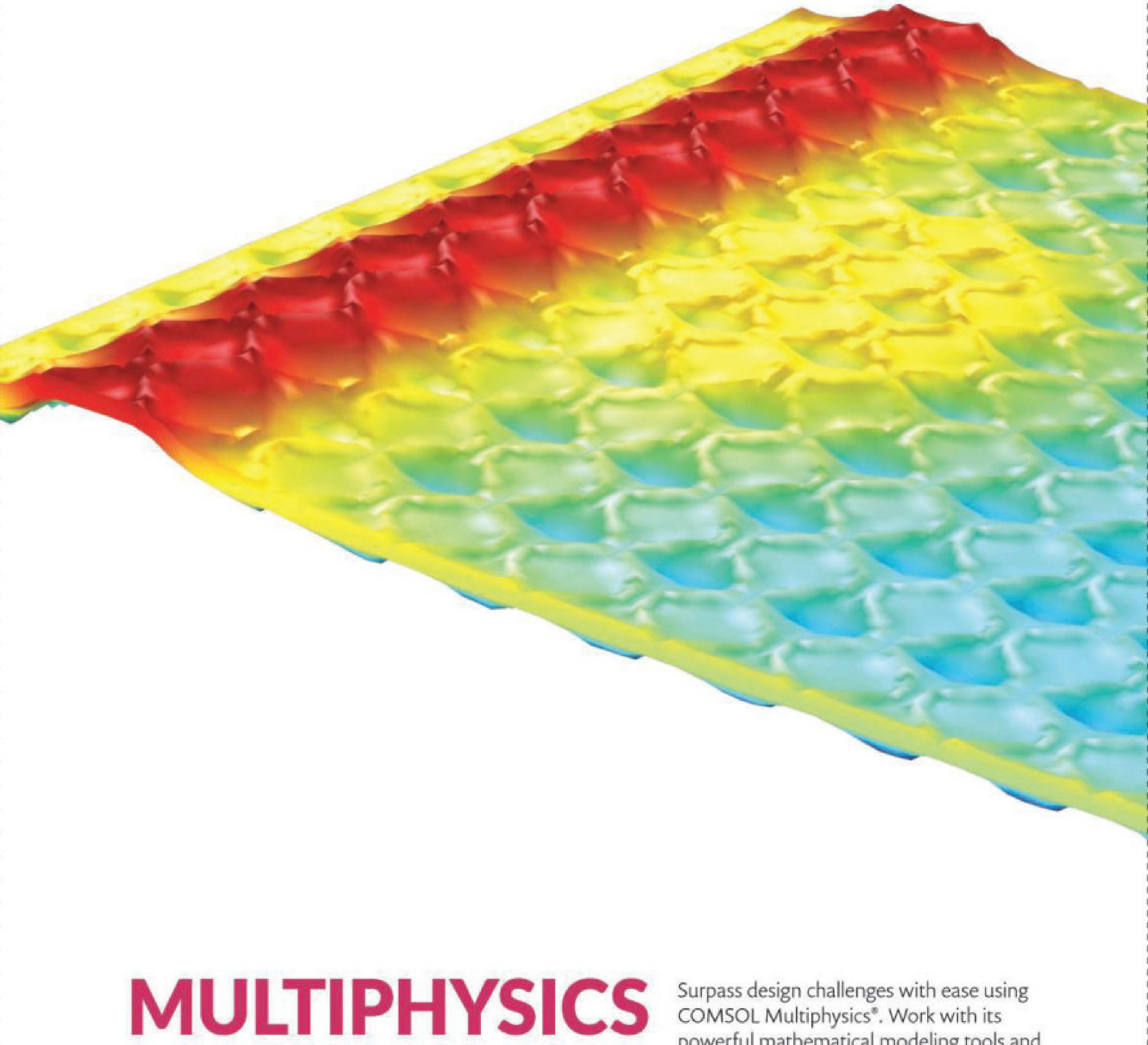




ON THE COVER

Is someone there? That question lingers for physicians and family members who must decide about treatment options for patients who remain unresponsive for long periods. A technique that probes for the presence or absence of conscious activity in the brain promises answers. Image by Ashley Mackenzie.

Photograph by Alastair Philip Wiper



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ON THE WEB

Stormy Weather
This year's Atlantic hurricanes have battered the Caribbean and the U.S.'s southern coasts. What more can we expect? *Go to www.ScientificAmerican.com/nov2017/hurricanes*

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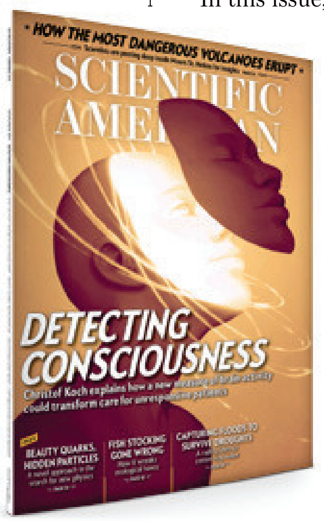
FROM THE EDITOR

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

Peering Within

It's been more than a decade since her death, but the epic, years-long battle around the continued existence of Terri Schiavo so riveted the nation that it still feels recent. After she suffered a cardiac arrest in 1990, Schiavo's brain was damaged by loss of oxygen, and she fell into a persistent vegetative state. Her husband, believing that she would never awaken and would not have wanted to keep living that way, petitioned the courts for her feeding tube be removed. Her parents, who thought their daughter might recover, fought the decision. After multiple appeals, Schiavo ultimately died in 2005 after her feeding tube was disconnected. She was 41 and had been in a vegetative state for nearly half her life. The autopsy later showed the damage was irreversible—her brain weighed half of what it should have because of a massive loss of neurons.



Even with brain-imaging tools, at the time it was impossible to tell definitively whether Schiavo was somehow aware of her surroundings. But as neuroscientist Christof Koch writes in his cover story, scientists are now working on "How to Make a Consciousness Meter." Researchers are using a method called "zap and zip" to probe the brain with magnetic pulses while measuring its electrical activity to be able to detect consciousness. In principle, the technique could make it possible to tell what level of awareness a person with a consciousness disorder has. Someday families and doctors might be able to use such technologies to determine a patient's needs or to make decisions about long-term care. Turn to page 28.

In this issue, you'll find plenty of other examples of how scientists are advancing discovery in ways that are helping to solve some of humanity's greatest challenges. Consider public health. The slime on a bathtub drain, a biofilm, looks innocent enough. On a tub, we simply wipe away these 3-D mats of bacteria. But when they colonize medical equipment or form in the body, they can be deadly. In "The War on Slime," starting on page 64, biologist Karin Sauer explains how understanding the cellular communication of biofilms can save lives.

Elsewhere in the issue, researchers are exploring the mechanisms behind volcanic eruptions ("The Next Big Bang," by Steve Olson, on page 34) and testing a novel idea to use floodwaters to survive droughts ("The Radical Groundwater Storage Test," by Erica Gies, on page 48).

That's not to say we leave no room for the profound. For instance, check out "Measuring Beauty," on page 56, in which particle physicist Guy Wilkinson describes an experiment at CERN's Large Hadron Collider and "the race to discover hidden particles, thereby building a fuller picture of nature at its tiniest scales." Who knows what we'll find?

Illustration by Nick Higgins

July 2017

DANCE DANCE EVOLUTION

Thea Singer's article on "The Evolution of Dance" raises so many questions, not only about entrainment—in which motor neurons align with sensory neurons' detection of auditory signals—and the differences a trained dancer experiences in comparison with one who dances for enjoyment but also about why we dance and why some people and cultures don't dance more.

I dance with my children to feel joyous, connected, energized and relaxed. But I feel uncomfortable studying dance for the way professionals execute movements because I feel that doing so runs the risk of reinforcing inhibitions associated with how dance must look instead of feel in my own culture. It can be highly invalidating when the focus is on who is the leanest and most physically adept for a dance style. Further, taking a look at how different groups and cultures approach dance might open its potential healing aspects, such as for Parkinson's sufferers, to more people.

Cate Andrews *via e-mail*

> **"Taking a look at how different groups and cultures approach dance might open its potential healing aspects, such as for Parkinson's sufferers, to more people."**
>
> CATE ANDREWS *VIA EMAIL*

There appears more to the story of dance than human social evolution. Much of the "sensing" external rhythmic movements and sounds that Singer describes begin in utero. The maternal abdomen and uterus are filled with noises, both maternal and external. After a 45-year career in diagnostic medical sonography and the observations of thousands of fetuses, I am convinced that the ancient human tendency to use ritual rhythm, drumming and dancing is a natural result of these in utero fetal experiences. More research is needed.

Terry J. DuBose *Associate professor emeritus, University of Arkansas for Medical Sciences*

BLACK HOLES, DARK MATTER

"Black Holes from the Beginning of Time," by Juan García-Bellido and Sébastien Clesse, describes the interesting idea that primordial black holes are the constituents of dark matter. But the authors appear to claim credit for a concept that has been in the literature for more than 40 years—see the 1975 paper "Cosmological Effects of Primordial Black Holes" by one of us (Chapline). And in the case of only such black holes of many solar masses making up dark matter, it existed before the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) announced its discovery of gravitational waves in 2016—see a recent preprint paper by one of us (Frampton) at https://arxiv.org/abs/1510.00400.

George F. Chapline *Lawrence Livermore National Laboratory*
Paul H. Frampton *University of Salento, Italy*

Suppose there was a wide distribution of primordial black hole masses. Over time the lower end of the distribution would gradually evaporate by Hawking radiation. If the total mass involved were significant, then the universe's gravitational mass would be gradually reduced, and the slowing of the universe's expansion from gravitational attraction would decrease. In other words, could the long-term evaporation of a mass distribution of primordial black holes be observed as "dark energy"?

Francis X. Hart *University of the South*

THE AUTHORS REPLY: In response to Chapline and Frampton: We note in our article that the idea of primordial black holes (PBHs) dates to the 1970s. This is indeed also the case for PBHs as dark matter, which Chapline was one of the first to propose. But his black holes were smaller than 10^{19} kilograms, which is now ruled out by observations of microlensing events.

We can claim credit for the idea that PBHs (as dark matter) should have both stellar masses and a broad mass distribution, which we proposed in a paper submitted as a preprint in January 2015 (https://arxiv.org/abs/1501.07565) and published in July of that year. And in a preprint paper we submitted immediately after Advanced LIGO's February 2016 announcement of its first gravitational-wave discovery (https://arxiv.org/abs/1603.05234)—published this past March—we noted that it had probably detected the merging of such PBHs and estimated the rate of events expected in our scenario, which seems to agree with more recent observations.

To answer Hart's question: The evaporation rate of black holes via Hawking radiation is very slow, and our PBHs have a significant abundance only in a range of around one solar mass. It would take trillions of trillions of times the age of the universe for one of them to evaporate. In our model, the fraction of evaporating black holes is completely negligible. But even if evaporating black holes were abundant enough in the early universe, the reduction of the dark matter in PBHs could be compensated by an increase of radiation.

In any case, this would give rise to dark radiation, not dark energy, which is very different. In an expanding universe, radiation density redshifts much faster than matter and soon would become inconsequential. On the other hand, dark energy density stays constant, giving rise to the acceleration of the universe.

DIABETES AND SURGERY

In "Operation: Diabetes," Francesco Rubino talks about the role of bile as among the factors in the benefits of using surgery to control type 2 diabetes. But it seems confused on the links among the gallbladder, bile and glucose. For those of us who have had our gallbladders removed, does the lack of the organ tend to increase or decrease the amount of glucose in our blood?

Bill and Mary Stiles *via e-mail*

RUBINO REPLIES: Despite a clear role of bile and bile acids—components of bile that act as signaling molecules—in metabolic regulation, there is no clinical evidence that removing the gallbladder induces substantial effects (positive or negative) on diabetes; in fact, blood glucose levels typically remain about the same. This should not be surprising, because the main function of the gallbladder is to store bile, not produce it (as the liver does), and the loss of such function is usually compensated by the main bile duct and the other bile conduits.

Gastrointestinal surgery can instead change the characteristics of bile and bile acids, which can affect the metabolism of glucose. Indeed, by altering the site and timing of bile-nutrient mix within the intestine, this surgery influences the interaction of bile acids with other components of intestinal content, thereby changing their chemical characteristics. For one, this can influence the ability of bile acids to interact with specific cell receptors in the intestinal lining. Further, changes in bile acids inside the gut can influence their reabsorption from downstream segments of the small intestine, thus affecting their levels in the bloodstream. In turn, this can change the way these molecules signal to other tissues involved in metabolic regulation, including the liver. In that organ, circulating bile acids serve as a feedback mechanism that modulates their own synthesis. As I discussed in my article, however, surgery's effect on diabetes is likely the result of a combination of various changes in GI mechanisms, not of bile acids by themselves.

ERRATUM

"Black Holes from the Beginning of Time," by Juan García-Bellido and Sébastien Clesse, incorrectly states that in the 1970s Bernard Carr and Stephen Hawking proposed primordial black holes only with masses smaller than a mountain's that would have evaporated long ago. They had also investigated the possibility of more massive, nonevaporating black holes.

LETTERS TO THE EDITOR

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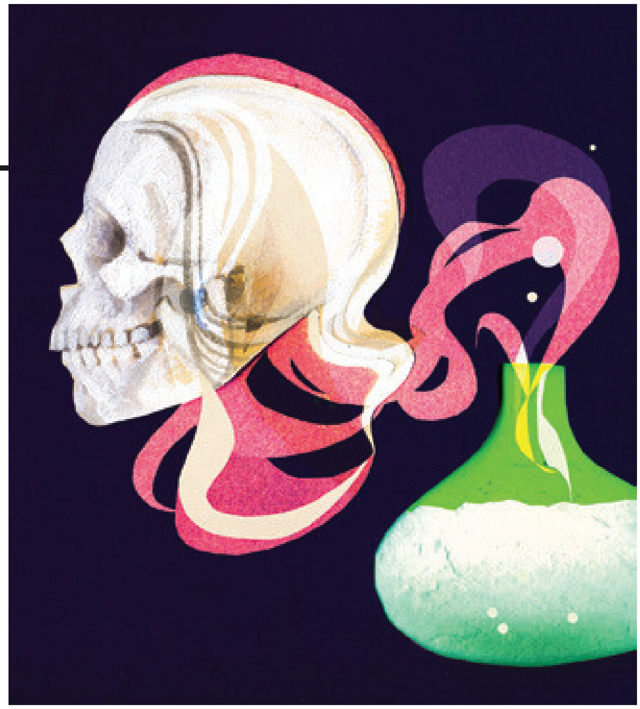
Get Toxic Chemicals Out of Cosmetics

Laws need to change to allow the FDA to protect people

By the Editors



Earlier this year a group of more than a dozen health advocacy groups and individuals petitioned the U.S. Food and Drug Administration to ban lead acetate from hair dyes. The compound, a suspected neurotoxin, is found in many hair products—Grecian Formula, for example. Lead acetate has been outlawed for nearly a decade in Canada and Europe. Studies show it is readily absorbed through the skin and can cause toxic levels of lead to accumulate in the blood.

How is it possible that this chemical is still being sold to U.S. consumers in cosmetic products? The main reason is that petitions such as the one calling out lead acetate are one of the few ways, under current law, that the agency charged with ensuring food, drug and cosmetic safety can even start to limit dangerous chemicals used on our faces and in our bodies. We need to do better.

Under the Federal Food, Drug, and Cosmetic Act and the Fair Packaging and Labeling Act, the FDA can regulate cosmetic chemicals. But it only steps in if it has "reliable information" that there is a problem. In practice, that has often meant that nothing is done before a public outcry. Years can pass while the FDA investigates and deliberates. Aside from these situations, the safety of cosmetics and personal care products is the responsibility of the companies that make them. The law requires no specific tests before a company brings a new product with a new chemical to market, and it does not require companies to release whatever safety data they may collect.

The result is that several chemicals with realistic chances of causing toxic effects can be found in everything from shampoo to toothpaste. One is formaldehyde, a carcinogenic by-product released by the preservatives used in cosmetics. In 2011 the National Toxicology Program at the Department of Health and Human Services declared formaldehyde a known human carcinogen, demonstrated by human and animal studies to cause cancer of the nose, head, neck and lymphatic system. Other research indicates it can be dangerous at the levels found in cosmetics, and nearly one fifth of cosmetic products contained the chemical. Other risky substances include phthalates, parabens (often found in moisturizers, makeup and hair products) and triclosan, which the FDA banned from hand soaps in 2016 yet is still allowed in other cosmetics. At exposures typical of cosmetic users, several of these chemicals have been linked to cancer, impaired reproductive ability and compromised neurodevelopment in children.

A recent study published online by Ami R. Zota of George Washington University and Bhavna Shamasunder of Occidental College in the *American Journal of Obstetrics & Gynecology* showed that women of color are at especially high risk of exposure. In an attempt to adhere to Caucasian beauty ideals, the researchers found, women of color are more likely to use chemical hair straighteners and skin lighteners, which disproportionately expose them to high doses of phthalates, parabens, mercury and other toxic substances.

The U.S. should protect its citizens. One worthwhile approach is to emulate the European Union's directive on cosmetics, which has banned more than 1,300 chemicals from personal health or cosmetic products. In some cases, the E.U. has acted after seeing only preliminary toxicity data. This is a prime example of the "precautionary principle" that has guided U.S. health agencies in setting acceptable levels of exposure to other potentially hazardous substances, such as lead.

Right now the number of studies on cosmetics is limited, and the FDA does not have the resources or directive to initiate broad tests. This past May senators Dianne Feinstein of California and Susan Collins of Maine reintroduced the Personal Care Products Safety Act in Congress. The bill would require, among other things, that all cosmetics makers pay annual fees to the agency to help finance new safety studies and enforcement—totaling approximately $20 million a year. With that money, the FDA must assess the safety of at least five cosmetics chemicals a year. The bill also gives the agency the authority to pull products off the shelves immediately when customers have reported bad reactions, without waiting for a review that can take multiple years.

Consumers should not be forced to scrutinize the ingredient lists in their medicine cabinets and report adverse reactions. That should be the FDA's job. The Feinstein-Collins bill empowers the agency to make efficient determinations from sound science. SA

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Illustration by Julia Breckenreid

Carl L. Hart, chair of the department of psychology at Columbia University, is author of *High Price: A Neuroscientist's Journey of Self-Discovery That Challenges Everything You Know about Drugs and Society* (HarperCollins, 2013).

People Are Not Dying Because of Opioids

They are dying because of ignorance

By Carl L. Hart

Recently, driven largely by opioid-related deaths—predominantly of our white sisters and brothers—President Donald Trump proclaimed that the opioid problem was now a national emergency. He vowed to "spend a lot of time, a lot of effort and a lot of money on the opioid crisis" because "it is a serious problem the likes of which we have never had."

This is false. Beginning in the late 1960s, the heroin crisis played out in a similar fashion, except that the face of the heroin addict then in the media was black, destitute and engaged in repetitive petty crimes to feed his or her habit. One solution was to lock up users, especially after passage of New York State's infamous Rockefeller drug laws in 1973. By the early 2000s more than 90 percent of those convicted under those laws were black or Latino, far out of proportion to the fraction of users they represented.

I am concerned that declaring the opioid crisis a national emergency will serve primarily to increase law-enforcement budgets, precipitating an escalation of this same sort of routine racial discrimination. Recent federal data show that more than 80 percent of those who are convicted for heroin trafficking are either black or Latino, even though whites use opioids at higher rates than other groups and tend to buy drugs from individuals within their racial group.

The president also claimed that the opioid crisis "is a worldwide problem." It isn't. Throughout Europe and other regions where opioids are readily available, people are not dying at comparable rates as those in the U.S., largely because addiction is treated not as a crime but as a public health problem.

It is certainly possible to die from an overdose of an opioid alone, but this accounts for a minority of the thousands of opioid-related deaths. Many are caused when people combine an opioid with another sedative (such as alcohol), an antihistamine (such as promethazine) or a benzodiazepine (such as Xanax or Klonopin). People are not dying because of opioids; they are dying because of ignorance.

There is now one more opioid in the mix—fentanyl, which produces a heroinlike high but is considerably more potent. To make matters worse, according to some media reports, illicit heroin is sometimes adulterated with fentanyl. This, of course, can be problematic—even fatal—for unsuspecting heroin users who ingest too much of the substance thinking that it is heroin alone.

One simple solution is to offer free, anonymous drug-purity testing services. If a sample contains adulterants, users would be informed. These services already exist in places such as Belgium, Portugal, Spain and Switzerland, where the first goal is to keep users safe. Law-enforcement officers should also do such testing whenever they confiscate street drugs, and they should notify the community whenever potentially dangerous adulterants are found. In addition, the opioid overdose antidote naloxone should be made more affordable and readily available not just to first responders but also to opioid users and to their family and friends.

The vast majority of opioid users do not become addicts. Users' chances of becoming addicted increase if they are white, male, young and unemployed and if they have co-occurring psychiatric disorders. That is why it is critical to conduct a thorough assessment of patients entering treatment, paying particular attention to these factors rather than simply focusing on the unrealistic goal of eliminating opioids.

In many countries, including Switzerland, the Netherlands, Germany and Denmark, opioid treatment may include daily injections of heroin, just as a diabetic may receive daily insulin injections, along with treating the patient's medical and psychosocial issues. These patients hold jobs, pay taxes and live long, healthy, productive lives. Yet in the U.S., such programs are not even discussed.

For about 20 years, the number of Americans who have tried heroin for the first time has been relatively stable. Heroin use specifically and opioid use in general are not going anywhere, whether we like it or not. This is not an endorsement of drug use but rather a realistic appraisal of the empirical evidence. Addressing the opioid crisis with ignorant comments from political figures and the inappropriate use of public funds do little to ensure users' safety. Perhaps, for once, we should try interventions that are informed by science and proven to work. SA

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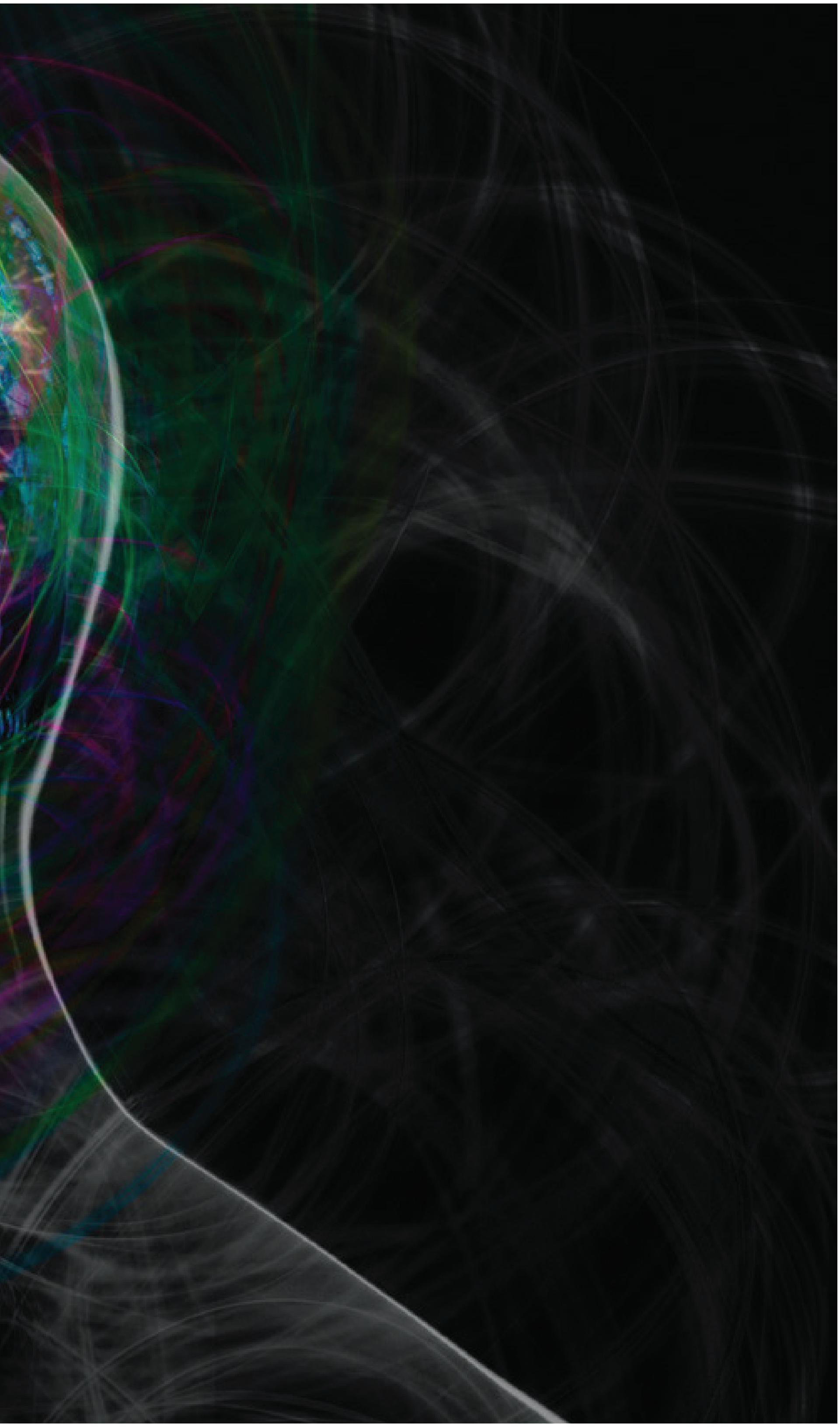
Illustration by Thomas Fuchs

ADVANCES

Panic disorder, schizophrenia and other psychiatric conditions have been tied to increased acidity in the brain.



INSIDE

NEUROSCIENCE

Your Brain on (Actual) Acid

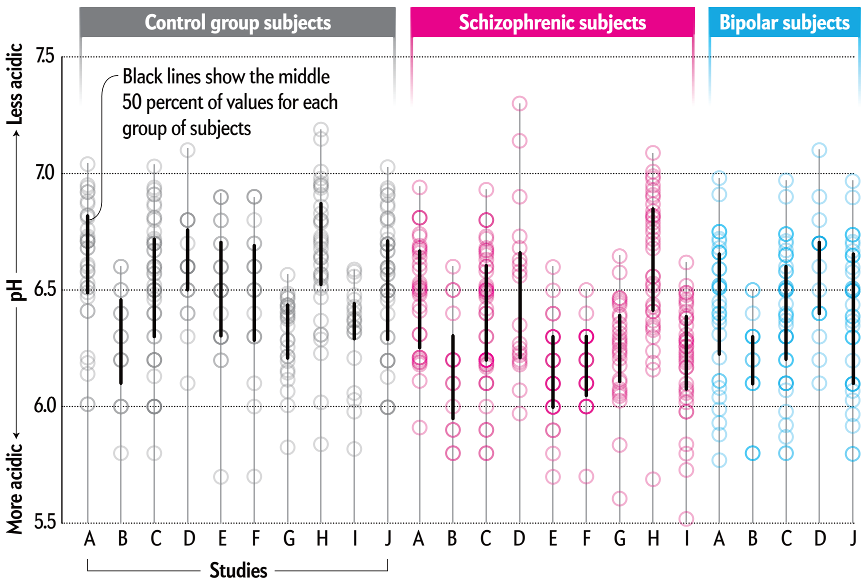
A growing body of evidence links some psychiatric disorders to low brain pH

The human brain frequently undergoes changes in acidity, with spikes from time to time. One main cause of these temporary surges is carbon dioxide gas, which is constantly released as the brain breaks down sugar to generate energy. Yet the overall chemistry in a healthy brain remains relatively neutral because processes such as respiration—which expels carbon dioxide—help to maintain the status quo. As a result, fleeting acid-base fluctuations usually go unnoticed.

But a growing body of research suggests that for some people, even slight changes in this balance may be linked with panic disorder and other psychiatric conditions. Recent findings provide further evidence that such links are real—and suggest they may extend to schizophrenia and bipolar disorder.

There were earlier hints of the acid-disorder link: studies that directly measured pH—a metric of how acidic or basic something is—in dozens of postmortem human brains revealed lower pH (higher acidity) in patients with schizophrenia and bipolar disorder. Multiple studies in the past few decades have found that when people with panic disorder are exposed to air with a higher than normal concentration of carbon dioxide—which can combine with water in the body to form carbonic acid—they are more likely to experience panic attacks than healthy individuals are. Other research has revealed that the brains of

pH Problems



Researchers analyzed results from 10 studies comparing postmortem brain acidity of schizophrenic and bipolar patients with that of control subjects. Overall, the midrange of pH values tended to be lower among those with one of the psychiatric disorders, meaning the chemical composition of their brain was relatively acidic.

people with panic disorder produce elevated levels of lactate, an acidic source of fuel that is constantly generated and consumed in the energy-hungry brain.

Yet researchers have continued to puzzle over whether this acidity is truly disorder-related or stems from other factors, such as antipsychotic drug use or a person's physical condition just before death. For example, "if you're dying slowly, there would be a longer period where there's a greater chance that you would have low oxygen levels, and that's going to change your metabolism," explains William Regenold, a psychiatrist and professor at the University of Maryland. In this situation, he says, the body and brain begin to rely more heavily on an oxygen-independent pathway to produce energy. This can lead to higher than normal lactate levels that subsequently decrease pH.

Such questions prompted Tsuyoshi Miyakawa, a neuroscientist at Fujita Health University in Japan, and his colleagues to scour 10 existing data sets from the postmortem brains of more than 400 patients with either schizophrenia or bipolar disorder. Their aim was to test each of the leading theories about the acid-disorder connection.

These findings provide convincing evidence that the link between brain acidity and psychiatric disorders is real.

First, the researchers controlled for potential confounding factors such as a history of antipsychotic medication use and age at death. As they had suspected, brain pH levels in people with schizophrenia and bipolar disorder were significantly lower than in healthy individuals. The team also examined five mouse models—rodents with mutations in genes associated with these conditions—and found similar results: The pH levels in the brains of about two dozen drug-free mice were consistently lower, and their lactate levels higher, than those in comparable healthy animals. What is more, the researchers had euthanized all the mice in the same way—which suggests the pH differences cannot all be explained by how long it takes to die.

These findings, published this fall in *Neuropsychopharmacology,* collectively provide the most convincing evidence to date that the link between brain acidity and psychiatric disorders is real, Miyakawa says. Regenold, who was not involved in the new work, agrees. "When you combine all these [data sets] and you find strong statistical significance, that's when it becomes more convincing that [lower pH] would be inherent to the disorders," he says. "I think what is novel about this [study] is that they are singling out lower pH and saying that this is something that—in and of itself—could well be part of the pathophysiology of these disorders, irrespective of what's causing it."

But John Wemmie, a neuroscientist at the University of Iowa, says that although the postmortem findings are intriguing, it is hard to know if they are related to the pH changes in the living brain. Live brain-imaging studies of people with bipolar disorder, schizophrenia and panic disorder provide much more direct evidence for the acidity hypothesis, he notes. Using magnetic resonance spectroscopy, a method that can detect biochemical changes in tissue, scientists have consistently found elevated levels of lactate in these individuals' brains.

Even as it becomes clearer that brain acidity may be a key characteristic of schizophrenia and bipolar disorder, whether this could be a cause or effect remains an open question. According to Miyakawa, one possibility is that the increased acidity results from higher than normal neuronal activity in the brains of people with these disorders. Another popular theory is that the greater acidity could be the result of impairments in mitochondria, the powerhouses of cells, Regenold says. These two hypotheses may not be mutually exclusive.

The next big question will be whether low pH in the brain can lead to the cognitive or behavioral changes associated with these disorders, Miyakawa says. There are suggestions that this is the case. "We know that receptors [that are activated by acid] have prominent effects on behavior in animals," Wemmie says. "That implies that there may be changes in brain pH in the awake and functioning brain that people haven't appreciated all that well."

—Diana Kwon

PRECEDING PAGES: ANDREW BRET WALLIS *Getty Images;* THIS PAGE: SOURCE: "DECREASED BRAIN PH AS A SHARED ENDOPHENOTYPE OF PSYCHIATRIC DISORDERS," BY HIDEO HAGIHARA ET AL., IN *NEUROPSYCHOPHARMACOLOGY.* PUBLISHED ONLINE SEPTEMBER 6, 2017

Graphic by Amanda Montañez

Less revolting than racism?

PSYCHOLOGY

Bad Reputation

People are willing to sacrifice life and limb to be viewed as moral

Psychologist Abraham Maslow's famed "hierarchy of needs" says people seek food, shelter and safety before esteem and self-actualization. So what explains foolish dares and violent sports, in which people risk grave injury to pursue respect? New research suggests the hierarchy may be more fluid than we think—many individuals will undergo disgusting or painful ordeals to save their reputations.

Andy Vonasch, a psychologist at the University of North Carolina at Chapel Hill, and his colleagues conducted an online survey of 111 Americans about the value of reputation. Of the respondents, 40 percent said they would choose a year in jail and a clean reputation over no jail and a criminal reputation. Incarceration is directly harmful, but "reputation is what helps you gain access to all of the things you want in society," Vonasch says. In similarly sized surveys, 70 percent of respondents told Vonasch's team they would give up their dominant hand to avoid a swastika face tattoo; 53 percent would choose immediate death over a long life as a suspected child molester; and 30 percent would take immediate death over a long and happy life followed by postmortem rumors of child molestation. This study was released online in July by *Social Psychological and Personality Science.*

But what about the real world? As part of the new study, white college students took a test of implicit racism. Then they chose between having their scores e-mailed widely and putting one hand in a bowl of "superworms" (*photograph*). People given (falsely) high scores of implicit racism were more likely to choose the superworms (30 versus 4 percent) and were more likely to hold their hands in near-freezing water (63 versus 9 percent)—even though many said they doubted the e-mail threat.

People make all kinds of sacrifices to preserve their honor, from ritual suicide to settling out of court to ceding subway seats. In an age of social media public shaming, this paper helps explain why sticks and stones may break your bones, but tweets can hurt much worse. *—Matthew Hutson*

ALAMY

HEALTH

Cancer Vaccine

A Lasker Award winner talks about how to expand the reach of HPV immunization

Douglas Lowy (*left*) and John Schiller (*right*), both at the National Cancer Institute, paved the way for the HPV vaccine.

The human papillomavirus (HPV) vaccine can prevent almost all cervical cancers and protects against cancers of the mouth, throat and anus. In September two researchers who completed fundamental work on these vaccines, Douglas Lowy and John Schiller, both at the U.S. National Cancer Institute, received one of this year's prestigious Lasker Awards—prizes that are sometimes called America's Nobels. Yet despite overwhelming evidence of the vaccine's safety and effectiveness, it still faces barriers to widespread use and acceptance. SCIENTIFIC AMERICAN spoke with Schiller, a virologist, about his and Lowy's award-winning HPV research, their future plans and ways to combat antivaccine attitudes. Edited excerpts of the interview follow. *—Dina Fine Maron*

What's the biggest hurdle to getting more coverage with the HPV vaccine?

JOHN SCHILLER: The biggest problem is actually not in the West or most developed countries; it is in the lower- and middle-income countries because of low availability and steep vaccine prices. In those settings, vaccine acceptance is actually very high. But these countries present the biggest problem because some 85 percent of cervical cancers occur there. In the more developed countries, there are many different factors involved [in vaccine hesitancy], and they differ by country. In the U.S., it is more about fear of vaccines in general. And there are some issues with HPV vaccines specifically related to this being about a sexually transmitted disease.

How can the science community help combat HPV vaccine hesitancy in the U.S.?

Quite a few studies show one of the biggest issues is that the vaccine is not being promoted sufficiently by pediatricians and general practitioners. If you look at other vaccines, for instance, for meningitis and hepatitis B—which are also administered to adolescents and could be given in the same visit as HPV—they are given at greater rates than HPV. So there is some disconnect in communication between pediatricians and parents there. Part of the problem here is that the HPV vaccine is a prophylactic vaccine to prevent a disease—cervical cancer—that those providers never see. Obstetrician-gynecologists see it, but pediatricians don't, which is the opposite of most other childhood or pediatric vaccines.

What led you to work on HPV?

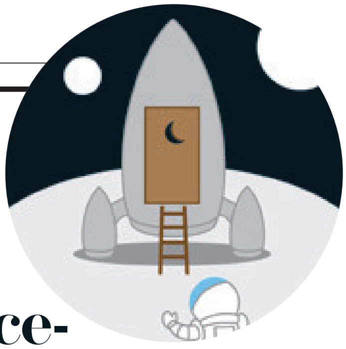
I had joined Doug Lowy's lab at the National Cancer Institute as a postdoc back in 1983, and the second lecture I went to there was by Harald zur Hausen—who later won the Nobel Prize—and his lecture was saying, "Eureka! We found a virus that seems to cause 50 percent of cervical cancers." And that virus turned out to be a human papillomavirus strain, HPV-16. So basically we went from looking at a model about how a normal cell transforms to become carcinogenic to something probably involved in causing human cancer. It was somewhat serendipitous.

What are you working on now?

One thing we are doing at the institute—co-sponsored by the Bill & Melinda Gates Foundation—is testing if one dose of HPV vaccine is enough to provide long-term protection. It would be transformative, especially in the setting of developing countries, if you could just have one dose at a younger age. We are also looking into cancer immunotherapy work. It turns out that these viruslike particles we work with for the HPV vaccine—these are typically the outer shell of a virus, say, from the HPV-16 strain or other animal or human papillomavirus particles—have a unique ability to infect tumor cells and bind to them specifically. So we are using that knowledge to develop cancer therapies that are broad-spectrum.

To read more of the conversation with John Schiller—which includes his advice for aspiring scientists and more—visit www.scientificamerican.com/hpvvax

COURTESY OF NATIONAL CANCER INSTITUTE



BIOLOGY

Space-Saving Yeast

Microbes could turn astronauts' waste into nutrients or plastic

Astronauts need to travel light. Every extra ounce of provisions can hinder a rocket, and certain crucial foods may not survive journeys as long as NASA's proposed mission to Mars. But scientists are devising creative ways to maximize storage efficiency—including recycling astronauts' urine and breath.

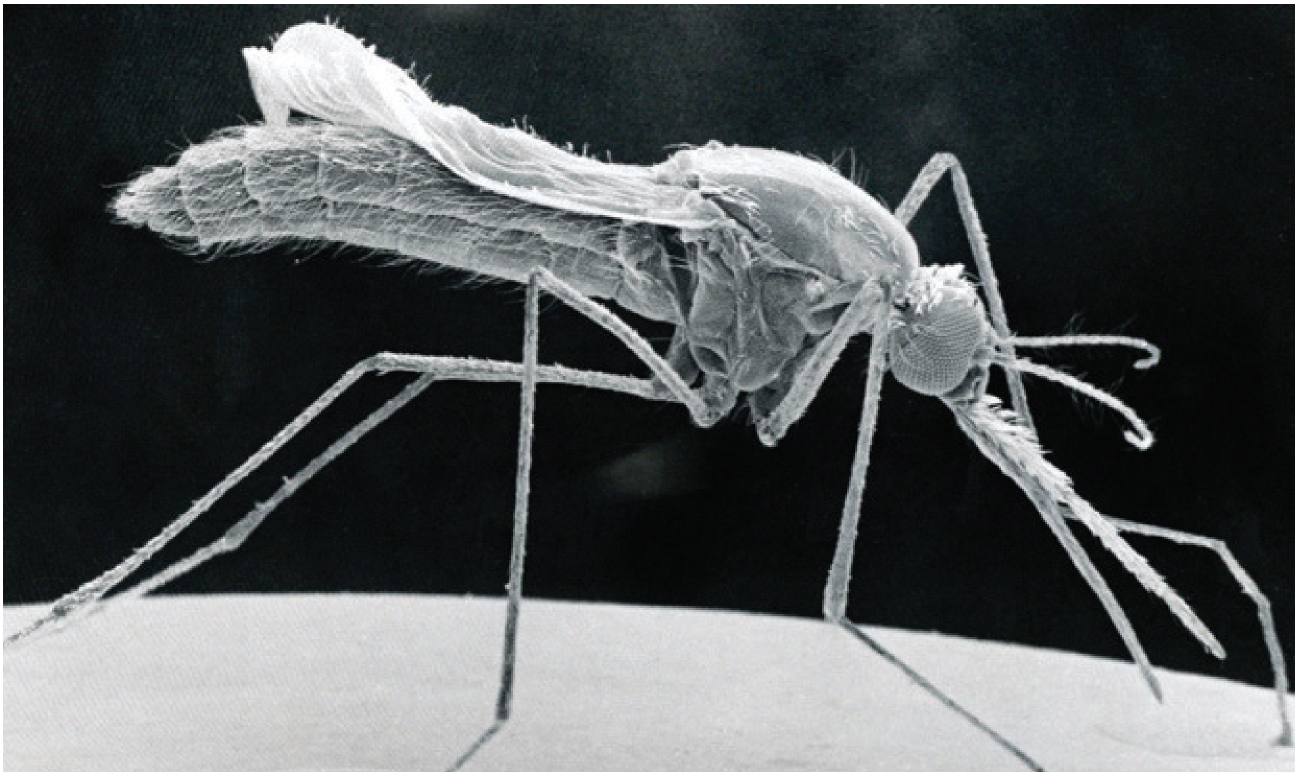
"As missions become longer in duration, astronauts will be generating more waste. So the question is, What do we do with all that waste?" asks Mark Blenner, a chemical engineer and synthetic biologist at Clemson University. Rather than bringing it back to Earth, Blenner and his colleagues have shown that yeast can convert waste products into essential nutrients—and even plastics that could be used to make tools.

The researchers found that *Yarrowia lipolytica,* a relative of baker's yeast, could survive by feeding on a component of human urine. Separately, they grew algae that converted carbon dioxide from exhaled air into carbon-rich nutrients, which the yeast then used to produce fatty acids. By splicing a few genes from algae and phytoplankton into the yeast's genome, Blenner's team got the microbes to "upgrade" these fatty acids to omega-3s, which are vital for human heart, eye and brain health. In another strain of *Y. lipolytica,* Blenner and his group altered the fatty acid production pathway to produce plastic polyesters that could be used to 3-D print tools in space. The researchers presented their findings at the American Chemical Society's biannual meeting in August.

"Yeast is a great organism to use for this kind of innovative research," says Jitendra Joshi, technology integration lead for Advanced Exploration Systems at NASA, who was not involved in the work.

The researchers still need to demonstrate that the microorganisms can thrive and produce the useful products at the same rates in the low-gravity, high-radiation environment of space. But Blenner is hopeful that future astronauts will be "using yeast as their own flexible manufacturing platforms." —*Knvul Sheikh*

Illustrations by Thomas Fuchs



PUBLIC HEALTH

Mosquito Death Traps

New chemical innovations lure in and kill the disease-carrying insects

Mosquitoes are not just a nuisance—they spread devastating diseases, including malaria and Zika virus, which have triggered global health crises. In 2015 alone, malaria struck about 212 million people and killed an estimated 429,000, most of them in sub-Saharan Africa.

Wealthy nations such as the U.S. have effective mosquito-control measures in place, but many developing countries cannot afford them. "Right now we're limited in the number of ways we have to control mosquitoes," says Edmund Norris, an entomologist at Iowa State University. "We need to be developing new methods."

ISCA Technologies in Riverside, Calif., is aiming to do just that. The company says it has created three simple, inexpensive ways to target malaria-carrying mosquitoes with compounds called semiochemicals—pheromones or other substances that organisms secrete to influence others' behavior. ISCA's cocktails of plant- and animal-derived semiochemicals lure in the pests, then kill them with insecticides. This method targets mosquitoes more efficiently while reducing the need to spray large amounts of insecticide into the environment, ISCA CEO Agenor Mafra-Neto says.

Others agree. "This sort of technique of using odors is an exciting technology and is really quite promising," says Chelci Squires, a research entomologist at the London School of Hygiene & Tropical Medicine. (Like Norris, Squires is unaffiliated with ISCA.) "There are lots of issues we still need to consider, though," she notes—such as the possibility of mosquitoes adapting their behavior to avoid these semiochemicals.

ISCA has been conducting lab tests and field trials in Tanzania, Brazil and the U.S. It hopes these methods can one day help to combat diseases such as dengue, West Nile virus and Zika. *—Annie Sneed*

TROJAN COW

ISCA's "signature blend" of semiochemicals mimics human odor—which, unsurprisingly, mosquitoes adore. The faux human perfume can be poured onto cattle or other livestock, hence the reason ISCA named it "Trojan Cow." Mosquitoes, enticed by the scent, feed on the animal decoys instead of people. When the livestock are also dosed with chemicals toxic to mosquitoes—such as a typical deworming medication—the bloodsuckers die.

AN INTOXICATING SCENT

This mix of compounds includes a pheromone that draws in adult females, as well as an attractant that ensnares their larvae. It is sprayed on potential breeding sites before a rainfall. When it comes in contact with water, it releases the alluring pheromones, duping females into laying their eggs in the treated areas. The larvae hatch and eat the attractant, which includes a live bacterium called *Bacillus thuringiensis israelensis*. These microbes kill mosquito larvae but leave other insects such as bees or butterflies unharmed.

A SWEET ENDING

Disease-carrying mosquitoes may relish blood, but they also need sugar to survive. ISCA's scientists searched a collection of semiochemicals derived from plant and floral sources to develop a mixture that smells like nectar. The company envisions this concoction being sprayed around the eaves of houses or near a community's walls or fences, along with a pesticide. Mosquitoes would visit these sweet-smelling traps for a meal—and meet a sugary death. *—A.S.*

GETTY IMAGES

ENVIRONMENTAL SCIENCE

Poison-Eating Poplars

Specialized bacteria help trees clean up a Superfund site

1

2

Black poplars (*Populus nigra*) (*1*) and their leaves and catkins (*2*).

Groundwater pollution might have a new nemesis: trees with a boosted microbiome. Scientists recently harvested a particularly effective strain of toxin-degrading bacteria from a specific poplar tree and transferred it to others. This improved the trees' natural ability to break down the carcinogen trichloroethylene (TCE)—an industrial solvent that has leached into underground sources near waste sites across the U.S. Study results, published in September in *Environmental Science & Technology,* suggest such trees could be planted over areas of heavily tainted groundwater as an efficient and affordable cleanup method.

Ordinary poplars are sometimes planted to help remove TCE from lightly contaminated groundwater. But that does not always degrade the chemical fully, and heavier cleanups may require bioremediation machines that involve often prohibitive sums between $700,000 and $3 million for installation alone. In earlier research, Sharon Doty, a plant microbiologist at the University of Washington, and her colleagues had genetically modified a poplar to cope with high TCE levels. Like all GM plants, however, it required lengthy environmental impact testing that deterred potential planters.

This time around, no such testing would be necessary. Doty and her team first crossbred two poplar species. One of Doty's students collected the microbe, an *Enterobacter* strain dubbed PDN3, from a Wisconsin poplar cutting. The researchers soaked their hybrid saplings in the bacteria, then planted them alongside untreated trees at three heavily TCE-contaminated Superfund sites—hazardous waste sites targeted for cleanup by the U.S. government—near San Francisco.

Three years later the benefits were obvious. Soil surrounding the inoculated poplars had 50 percent more chlorine ions—the harmless remnants of degraded TCE molecules—than the dirt around their untreated counterparts. The microbe-enriched trees also had about 30 percent wider trunks, indicating healthier growth. Jerry Schnoor, an environmental engineer at the University of Iowa, who was not involved in the study, says the team's methods are impressive. He notes that the trees lowered the surrounding TCE concentration below the EPA-mandated drinking-water limit. "I think that is a big story," he says.

Doty and her colleagues are now sleuthing out the gene that enables PDN3 to accomplish this feat. They are also measuring other benefits the bacterium may convey to the plants. Doty says she has high hopes for the trees' future: "Turn Superfund sites into parks?" *—Leslie Nemo*

GETTY IMAGES (*1* and *2*)

1

Researchers surveyed Volcán de Pacaya (*1*) and Volcán de Fuego (*2*) using remotely operated aircraft.

2

GEOLOGY

Flying into Volcanoes

Drones offer an intimate look at a crater's fiery inner workings

Volcán de Fuego lives up to its name. Not only does Guatemala's "Volcano of Fire" blast columns of ash skyward several times every hour, it also becomes a true inferno about once a month, when larger eruptions hurl menacing lava and debris down its slopes. This cyclic behavior is intensifying, making scientists wonder if a more explosive eruption is imminent. In a massive 1974 outburst the mountain shot an ash cloud four miles into the sky and sent a huge amount of debris racing down its sides. Another such eruption would be a nightmare scenario for the 100,000 people now living in the volcano's shadow.

But without the ability to peek into its dangerous and inaccessible crater, scientists have struggled to predict what is next. So earlier this year a team of volcanologists and engineers dispatched drones to capture unprecedented images of the crater's activity. "From a volcanology point of view, we never imagined we'd see explosions this close," says team member Emma Liu, a volcanologist at the University of Cambridge. "It's spectacular."

The pilotless flights revealed a gigantic cone that had formed within the crater days before one of Volcán de Fuego's monthly eruptions. Liu and her colleagues suspect the cone kept growing higher until—much like a precarious Jenga tower—it became unstable and partially collapsed, triggering the larger lava and debris flows as part of a pattern that repeats semiregularly.

By building on this idea, volcanologists could help predict more precisely when those cyclic eruptions will come. Einat Lev, a volcanologist at the Lamont-Doherty Earth Observatory, who was not involved in the research, calls the work "a superb demonstration of new knowledge about volcanoes in general, and Guatemalan volcanoes specifically, that [drones] have been providing." The findings have not yet been published.

The team members plan to return to Guatemala this November to test their hypothesis by observing the crater throughout an entire cycle. This time their drones will be equipped with new instruments that will also let them sample the ash column directly—which may help them determine whether Volcán de Fuego is about to have another catastrophic eruption.

—Shannon Hall

JEREMY WOODHOUSE *Getty Images* (*1*); COURTESY OF UNIVERSITY OF CAMBRIDGE, UNIVERSITY OF BRISTOL, AND NATIONAL INSTITUTE OF SEISMOLOGY, VOLCANOLOGY, METEOROLOGY AND HYDROLOGY (*2*)

IN THE NEWS

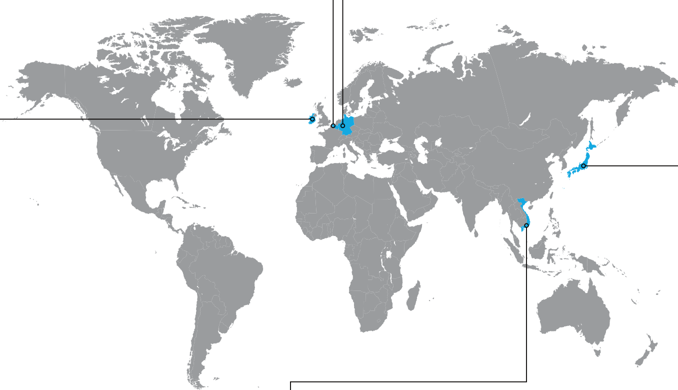
Quick Hits

BELGIUM

Researchers debuted a robotic arm that can form Flemish sign-language letters translated from simple typed words. Their next goal is to develop a second arm so the robot can sign entire phrases.

GERMANY

A wave of pesticide contamination of eggs across Europe has prompted German health officials to study how much of the involved chemical, fipronil, can safely be consumed.



IRELAND

Local scientists and politicians have called for the nation to join CERN, the European laboratory for particle physics near Geneva. They claim the investment will be profitable and will encourage citizens to pursue science careers.

JAPAN

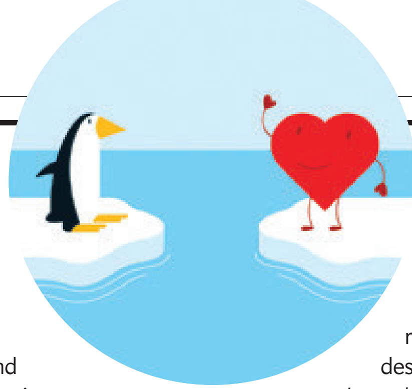
The nation recently launched its third of seven planned GPS satellites, intended to form a network independent of the U.S. system. The government plans to have all seven in orbit by 2023.

VIETNAM

British and Thai researchers are searching for Vietnam's native Edwards's Pheasant, which has not been spotted for years and is designated as critically endangered. They hope to make the point that rare, understudied species are worth saving.

—Leslie Nemo

For more details, visit www.ScientificAmerican.com/nov2017/advances



BIOCHEMISTRY

Antifreeze for Your Heart

Chemicals inspired by Arctic animals could keep transplant organs viable for longer

Exposing living tissue to subfreezing temperatures for long can cause irreparable damage. Microscopic ice crystals shred cells and seize moisture, making donor organs unsuitable for transplantation. Thus, organs can be chilled for only a few hours ahead of a procedure. But a set of durable new antifreeze compounds—similar to those found in particularly hardy animals—could lengthen organs' shelf life.

Scientists at the University of Warwick in England were inspired by proteins in some species of Arctic fish, wood frogs and other organisms that prevent blood from freezing, allowing them to flourish in extreme cold. Previous research had shown these natural antifreeze molecules could preserve rat hearts at −1.3 degrees Celsius for up to 24 hours. But these proteins are expensive to extract and highly toxic to some species. "For a long time everyone assumed you had to make synthetic alternatives that looked exactly like antifreeze proteins to solve this problem," says Matthew Gibson, a chemist at Warwick who co-authored the new research. "But we found that you can design new molecules that function like antifreeze proteins but do not necessarily look like them."

Most natural antifreeze molecules have a patchwork of regions that either attract or repel water. Scientists do not know exactly how this process stymies ice crystal formation, but Gibson thinks it might throw water molecules into push-pull chaos that prevents them from clumping into ice. To replicate this mechanism, he and his colleagues synthesized spiral-shaped molecules that were mostly water-repellent—but had iron atoms at their centers that made them hydrophilic, or water-loving. The resulting compounds, described in July in the *Journal of the American Chemical Society,* were surprisingly potent at stopping ice crystals from forming. Some were also nontoxic to the roundworm *Caenorhabditis elegans,* indicating they might be safe for other animals.

"These mimics are really cool because they are not proteins—they are other types of molecules that nonetheless can do at least part of what natural antifreeze proteins do," says Clara do Amaral, a biologist at Mount St. Joseph University, who was not involved in the research. Gibson's antifreeze compounds will still need to be tested in humans, however, and may be only part of a solution. "We don't have the whole picture yet," do Amaral adds. "It's not just one magical compound that helps freeze-tolerant organisms survive. It's a whole suite of adaptations." —*Knvul Sheikh*

Claudia Wallis is an award-winning science writer and former managing editor of *Scientific American Mind.*

Health by the Numbers?

Doctors shift toward personalized goals for glucose, cholesterol, and more

By Claudia Wallis

In an era when everyone seems to be tracking their daily 10,000 steps with a Fitbit, measuring calories with MyFitnessPal and monitoring fertility with apps like Glow, it's easy to get hung up on numbers. Is my body mass index sitting nicely below 25? Is my blood pressure normal for my age? Is my blood level of that nasty LDL cholesterol in check—say, below 100 mg/dL? But this health-by-the-numbers approach has its limits and might even lead you astray. Newer research suggests we should embrace more personalized goals instead of one-size-fits-all targets.

Take blood sugar—an issue for the roughly half of American adults who either have diabetes or are prediabetic. For decades doctors have told such patients to aim below one specific target: a 7 percent blood level of hemoglobin A_{1C}—a sugar-coated protein that reflects blood glucose levels for the previous two to three months. The magic number was based on a classic 1993 study that showed multiple, long-term benefits to staying below seven—through diet, drugs or exercise, or all three.

JoAnn Manson has seen patients drive themselves crazy chasing the perfect seven during her 25 years in clinical practice and as chief of preventive medicine at Boston's Brigham and Women's Hospital. That goal tends to grow more elusive over time as the body's insulin production drops, leading patients to pile on the medications. Side effects multiply. So do the medical bills. And, crucially, newer research shows that not all drugs that lower A_{1C} levels are equally good at protecting diabetics from heart disease, kidney failure, blindness and other dreaded complications.

Increasingly, experts are recommending a more individualized approach to managing the disease. One consideration is that the benefits of "tight control" over blood sugar accrue slowly over many years, whereas the harms of overtreatment—such as a drop in glucose that can make you pass out—happen fast. That means "an older or frailer patient might not live long enough to see the benefits," says endocrinologist Judith Fradkin of the National Institute of Diabetes and Digestive and Kidney Diseases. Such a patient might be more concerned about breaking bones if he or she falls because of low blood sugar. Bottom line: treatment becomes a discussion.

The same may be said for managing cholesterol levels. Fifteen years ago doctors told patients they should keep their LDL cholesterol below 100 mg/dL and, if they had already had a heart attack or stroke, aim for 70 mg/dL, with help from diet, exercise and statin drugs. Although these ideas linger, the guidelines changed in 2013 after a panel of experts found insufficient evidence for such specific goals and replaced them with a more individualized approach. "We took a big step toward getting people to think about what kind of risk group they were in, as opposed to saying that below some number, your risk disappears and that above the number, all the risk is present," says cardiologist Neil J. Stone of Northwestern University, who chaired the panel.

That panel's report concluded that there was good evidence for using statins—along with lifestyle changes—to lower cholesterol in high-risk patients, such as those with a history of heart attack or stroke or people between ages 40 and 75 with diabetes. But for the "worried well," a careful assessment and decision making together with the patient was the best way to go. The panel published a risk-estimation tool to guide the conversation.

Mind you, there are still some bright lines. An LDL level above 190 mg/dL should be treated, no matter what. And a hemoglobin A_{1C} count at nine or above means danger for anyone. But overall, medicine has embraced the mantra of shared decision making. One reason is a greater understanding of the harms of both undertreating and overtreating. Another is respect for patient preferences. "People tend to know themselves pretty well," Manson says. Some are sensitive to drug side effects; some are terrified by a family history of heart attacks or strokes.

Third, there is growing recognition that the perfect must not become the enemy of the good. Take body weight: in one major study, prediabetic adults, many of them obese, halved their risk of developing diabetes over the next three years just by dropping an average of 15 pounds—still far from a svelte ideal.

Personalized goals and shared decision making put a greater burden on all of us to be informed. Luckily, this is one way those health-related apps can help. Fradkin, Manson and others are excited about a new generation of truly smart apps that are less about counting and more about guiding healthy decisions. SA

Illustration by Celia Krampien

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

Fighting Format Rot

The Library of Congress has your back

By David Pogue

I'm not the first techno writer to raise the alarm about data rot, which can be described as "the tendency of computer files to become inaccessible as their storage media go to the great CompUSA in the sky." Over the years we've entrusted our writing, business documents, music and art to such now defunct formats as punch cards, magnetic tape, floppy disks and Zip disks. And if you think CD-ROM and DVD-ROM will be with us much longer, you're crazy.

I come before you today, though, with something much more sinister to keep you awake at night: *file-format rot.*

That's where you worry not about the storage media but about the document formats of your files.

The problem struck me like a sledgehammer when I tried to open some old Microsoft Word documents earlier this year. They wouldn't open! Microsoft Word, circa 2017, could not open its own documents, circa 1989. Doesn't that seem to violate some fundamental law? Some implied guarantee? It's like waking up one morning to find out that today's screwdrivers don't fit the trillions of screws that are holding our structures together.

For the first decade of my career, right out of college, I worked as an arranger and conductor of Broadway musicals in New York City. I spent years of my life creating musical scores with early sheet-music software such as Professional Composer, Deluxe Music Construction Set and HB Engraver. Each one took hours and hours and *hours.* And now? I can't look at those scores. Apart from the ones I have as printouts, I'll never see them again. The parent software programs are long gone—and with them, all of the notes and chords locked forever in their documents.

So how can we expect future generations to be able to open our screenplays, novels, photographs, videos and other works of creation?

You know who spends a lot of time worrying about this question? The Library of Congress. It's in the process of a multimillion-dollar effort to digitize its 70 million manuscripts, 14 million photos and 800,000 rare books. The idea is both to preserve them and to make them available to the public on the Internet.

A couple of years ago I had the chance to interview Helena Zinkham, the library's chief of prints and photos. She pointed out that not only has paper turned out to be one of the best document formats but that *older* paper is the best of all. "Paper was actually much sturdier in the 1400s, 1500s, 1600s, because they made it from cloth, rag content, linen-based paper and cotton-based papers," she told me. "But in the 19th century, to mass-produce paper, they began to introduce chemicals into the process." Those chemicals led to faster deterioration.

So if you're the Library of Congress, and you're well aware of file-format rot, and you're hoping to preserve your collection for future generations, what's your scan plan? What computer-file format could you possibly expect to be around in 200 years?

Well, first, you choose as open a format as possible, one that's not jealously guarded by one software company. The library has chosen TIFF files as it digitizes its photos, books and documents. "That seems to give us the best hope of being able to migrate [these files] over many years," Zinkham says.

And that, it turns out, is the key: *re*conversion is baked into the library's plans. When the library began its scanning program in the mid-1990s, the resolution was very low—420 by 560 pixels for an entire image. Today each scan is several thousand pixels tall and wide.

What this means, of course, is that the job of converting file formats never actually ends. Already the Library of Congress is *re*scanning its most important documents and pictures, to take advantage of advances in bit depths and resolution—and plans to do so, periodically, forever.

That, it turns out, should be our strategy, too. Had I opened those Word 1.0 documents and resaved them every few years, with successive versions of Word, I'd still have them. I wasn't diligent about reconverting my files because I didn't even recognize the problem. Now you, at least, don't have that excuse.

SCIENTIFIC AMERICAN ONLINE
LEARN HOW TO READ OLD MICROSOFT WORD DOCUMENTS:
scientificamerican.com/nov2017/pogue

Illustration by Jay Bendt

NEUROSCIENCE

HOW TO MAKE A CONSCIOUSNESS METER

Zapping the brain with magnetic pulses while measuring its electrical activity is proving to be a reliable way to detect consciousness

By Christof Koch

Illustration by Ashley Mackenzie

IN BRIEF

Even with access to brain-imaging tools, a physician can have difficulty establishing whether a severely brain-injured patient is conscious of his or her surroundings.

A technology to address this gap in care would, in principle, determine whether a patient is deeply asleep or anesthetized or has lost consciousness because of damage to the brain.

Over the past few years development of what might be called "consciousness meters" opens the possibility of reliable detection devices that can be used in medical settings.

Physicians and family members might use such technologies to help them make decisions about care for the tens of thousands of patients unable to communicate their needs.

Christof Koch is chief scientist and president of the Allen Institute for Brain Science in Seattle. He serves on *Scientific American*'s board of advisers.

I HAVE DIED MANY TIMES OVER. EVERY NIGHT WHEN I LAY DOWN MY WEARY SELF TO REST, my consciousness is extinguished. I experience nothing until I wake up inside my sleeping body—in a dream disconnected from the external world. Or later consciousness resurfaces in the morning on return to the wakening world.

Daily life contains many such experiences. In my childhood, I had an appendectomy and was anesthetized—my consciousness was switched off and, following the surgery, was restored. A fading memory from my teenage years places me in the back seat of a Renault that is driving down a tree-lined avenue in North Africa. Suddenly, the scenery changes abruptly. I'm on the same street, seeing things now from the ground up. The car had hit a tree, ejecting me onto the cobblestones, and I lost consciousness.

Many readers will have had similar recollections of consciousness lost and regained. We are used to the diurnal cycle of waking, sleeping and dreaming. But that experience is not the same for everyone. For some patients with brain trauma, consciousness flees for days, weeks or longer.

In practice, a clinician may have difficulty establishing whether someone is quietly sleeping, anesthetized or severely brain-injured. Is a person lying with eyes open experiencing anything, no matter the content, or has the conscious mind fled the body and no one is home?

Ideally, a technology could be devised to serve as a form of consciousness meter to answer these questions. At first, the idea of the equivalent of a blood pressure cuff for consciousness might seem absurd. But the development of several technologies in recent years has raised real prospects for detectors that meet the criteria for consciousness meters—devices useful in medical or research settings to determine whether a person is experiencing anything at all. This ability to detect consciousness could also help physicians and family members make decisions about how to care for tens of thousands of uncommunicative patients.

RECORDING BRAIN WAVES

CONTEMPLATING THE possibility of a consciousness meter requires consideration of the internal dynamics of our mental life, activity that waxes and wanes within fractions of a second, dictating the measuring of those fluctuating brain signals at a similar timescale. The most important physiological tool to infer consciousness from probing the brain has been, and continues to be, the electroencephalogram (EEG).

The EEG was developed by German psychiatrist Hans Berger, whose lifelong quest was to uncover the link between objective brain activity and subjective phenomena. He recorded the first ever brain waves of a patient in 1924 but, filled with doubt, did not publish his findings until 1929. The rest is history, as the EEG became the foundational tool of an entire field of medicine called clinical neurophysiology, although Berger was never accorded any significant recognition in Nazi Germany and hanged himself in 1941, despite being nominated for the Nobel Prize several times.

There are, of course, other ways to record brain activity besides the venerable EEG. The most common tools measure the dynamics of blood flowing inside the brain with magnetic scanners or track the magnetic field around the brain with magnetoencephalography (MEG). Yet these instruments, as well as more recently emerging techniques such as near-infrared spectroscopy, come with methodological and practical issues that preclude their routine clinical use for the time being.

The EEG measures the tiny voltage fluctuations (10 to 100 microvolts) generated by electrical activity across the neocortex, the brain's outer surface, which is responsible for perception, action, memory and thought. The main actors whose collective electrical activity is thought to be responsible for the EEG signals, via a mechanism known as volume conduction, are cortical pyramidal neurons, named because of their tetrahedral shape. Contributions from deeper structures, such as the thalamus, have to be inferred indirectly, through their action on cortical cells. The technology functions by placing electrodes directly on the scalp—that is, without the need for invasive surgery to penetrate the skull. With the move toward high-density EEG setups—with up to 256 electrodes—maps showing the distribution of electrical activity across the brain have become commonplace.

Still, placing the electrodes with their wet, conductive gel onto the scrubbed skin of the head is cumbersome, time-consuming, and prone to produce errors if the electrodes move, all of which limits the technology. With today's more sensitive dry electrodes, the EEG has morphed from a clinical tool into a consumer device that can be used for hours at a time for biofeedback—allowing athletes or do-it-yourself "brain hackers" to focus their thoughts or insomniacs to track, deepen and extend their naturally occurring sleep.

From the late 1940s onward, detection of an "activated EEG" signal was the surest sign of a conscious subject. This state is characterized by low-voltage, rapid up-and-down fluctuating waves that are desynchronized rather than in lockstep across the skull. In general, as the EEG shifts to lower frequencies, consciousness is less likely to be present. Yet there are enough exceptions to this rule that it cannot serve as a general basis to diagnose absence or presence of consciousness in a given individual. Thus, scientists and clinicians alike have cast about for more reliable measures and have now found one based on a fundamental property of any conscious experience.

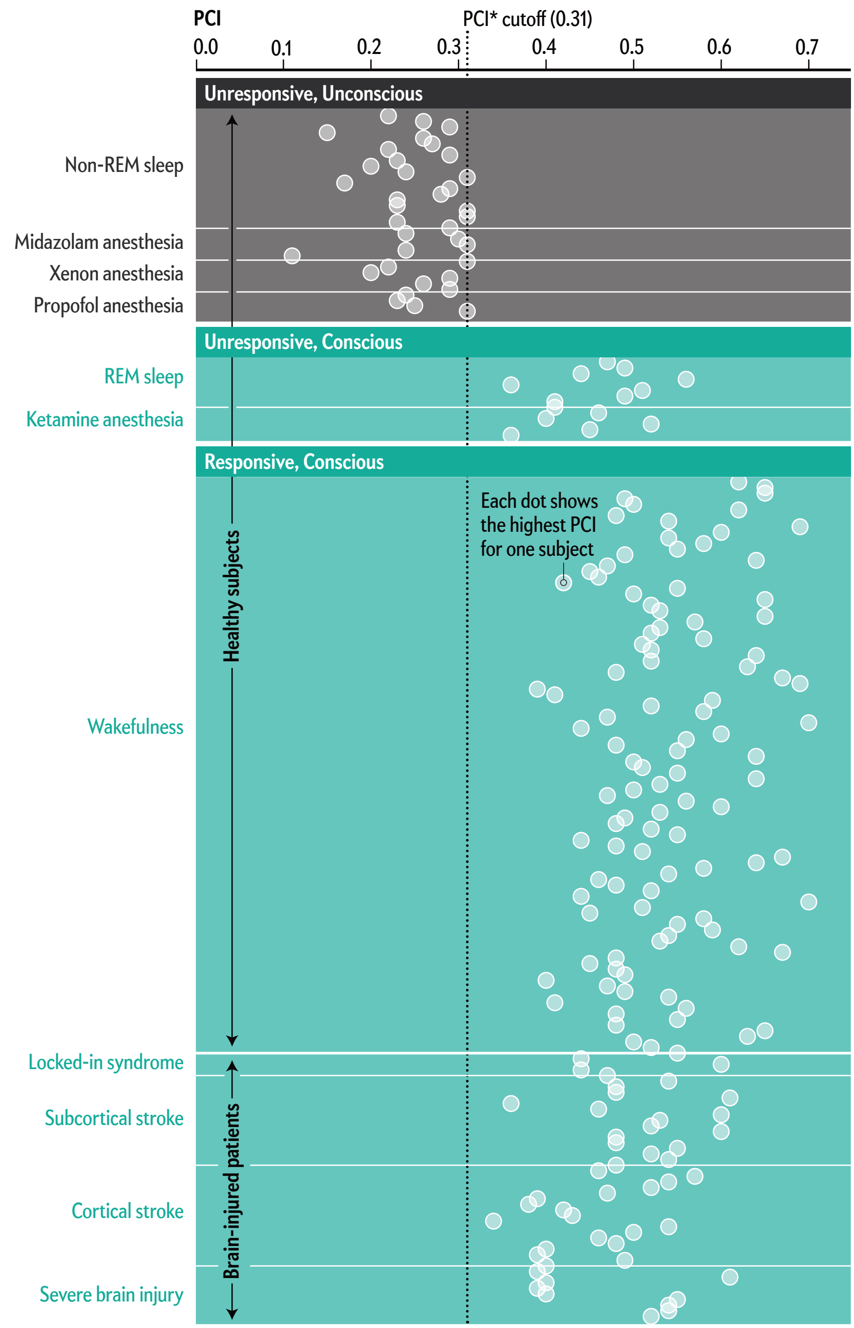
INTO THE NETHERWORLD

BEFORE WE COME to that, we should consider why clinicians care about detecting consciousness in two distinct groups of patients (pediatric patients represent a different challenge that will not be addressed here). The first consists of adults with severe disorders of consciousness following traumatic brain injury, infections of the brain (encephalitis) or its surrounding protective layers (meningitis), stroke, or drug or alcohol intoxication. After surviving the initial insult, patients are stable but disabled and bedridden, unable to speak or signal their thoughts and intentions. With proper nursing care to avoid bedsores and infections, these patients can live for years.

In this first group, clinicians distinguish several subcategories. Patients in a vegetative state, which is better described by the less pejorative term "unresponsive wakefulness syndrome" (UWS), cycle in and out of sleep. Yet setting up a bedside communication channel—"if you hear me, squeeze my hand or move your eyes"—meets with failure. UWS patients do swallow, yawn, and open and move their eyes or head but not in a seemingly intentional manner. No willed actions are left—only brain stem reflexes, activity that controls basic processes such as breathing, sleep-wake transitions, heart rate, eye movements and pupillary responses. Terri Schiavo is a name many remember, a patient in Florida who, following cardiac arrest, was resuscitated and lingered for 15 years in UWS until her medically induced death in 2005. UWS patients are a modern phenomenon depending for

Zapping and Zipping

In pursuit of a consciousness test, Silvia Casarotto of the University of Milan and her colleagues recruited 102 healthy subjects and 48 still responsive and awake brain-injured patients. Their brains were "zapped" with magnetic pulses (transcranial magnetic stimulation) in both conscious and unconscious states, and brain activity was detected with an EEG and analyzed with a data-compression algorithm—and so it was said to be "zipped." A value known as a perturbational complexity index (PCI) was calculated for the EEGs—and participants were also interviewed about their state of mind. It was determined that a conscious person exhibited at least one value above 0.31 (PCI*), whereas unconscious subjects all had lower scores. Using this value, the zap-and-zip testing was then performed on patients with severe disorders of consciousness (*results not shown*), finding some individuals who appeared to be conscious.



SOURCE: "STRATIFICATION OF UNRESPONSIVE PATIENTS BY AN INDEPENDENTLY VALIDATED INDEX OF BRAIN COMPLEXITY," BY SILVIA CASAROTTO ET AL., IN *ANNALS OF NEUROLOGY*, VOL. 80, NO. 5; NOVEMBER 2016

Graphic by Amanda Montañez

their survival on the infrastructure of 911, emergency helicopters and advanced medical care. There are more than 10,000 such individuals in the U.S. alone, living in hospices or nursing homes or at home.

Whereas behavioral evidence is compatible with the notion that UWS patients do not experience anything, it is important to recall that "absence of evidence is not evidence of absence" and to give the patients the benefit of doubt. There is a diagnostic gray zone into which UWS patients fall as to the question of whether their injured brains are capable of experiencing pain, distress, anxiety, isolation, quiet resignation, a full-blown stream of thought—or perhaps just nothing. Some studies have suggested that 20 percent of UWS patients are conscious and are therefore misdiagnosed. To family and friends who may care for their loved one for years, knowing whether anybody is mentally there can make a dramatic difference.

The situation is less ambiguous for minimally conscious state (MCS) patients. Unable to speak, they can signal but often only in a sparse, minimal and erratic fashion, smiling or crying in appropriate emotional situations, vocalizing or gesturing on occasion, or tracking salient objects with their eyes. Here the assumption is that these patients do experience something, however minimal, at least some of the time.

The need to monitor consciousness also arises in a second, totally different set of patients who have a normal functioning brain—people like you and me who undergo invasive surgery for the usual host of ills, such as injuries, removing a cancerous growth, or fixing knees, hips and other body parts. Anesthesia eliminates pain and other conscious experiences, prevents mobility and stabilizes the autonomic nervous system, which controls breathing and other functions, for hours at a time.

Patients "go under" in the expectation that they will not wake up during surgery and that they will not have to contend with traumatic memories of intraoperative experiences that could haunt them for the rest of their lives. Unfortunately, this goal is not always met. Intraoperative recall, or "awareness under anesthesia," can occur in a small number of operations, estimated to be in the one per 1,000 range, in particular when patients are paralyzed during a procedure by an anesthesiologist to facilitate intubation and to prevent gross muscle movements. Given that millions of Americans undergo surgical-level anesthesia every year, this tiny fraction translates into thousands of awakenings under anesthesia.

Existing EEG measures monitor depth of anesthesia during an operation. Yet none of the vast diversity of anesthetic agents work in a consistent manner across all patients, who range from neonates to the very elderly. What is needed is a tool that can reliably track the presence of consciousness in individual subjects across a large spectrum of normal and pathological conditions under both acute (anesthesia) and chronic conditions (the plight of neurologically impaired patients).

THE NATURE OF CONSCIOUS EXPERIENCE

TO DETECT consciousness, it is necessary to consider two essential characters of any subjective experience, no matter how mundane or exalted. First, by definition, any experience is different from all other experiences. It is specific to the moment and place it occurs. Each one is highly informative—take the unique visual richness associated with a mountain hike in the Rockies or another in the Cascade Range. Now combine these recollections with other sensory modalities, such as sounds and smells, emotions and memories. Each one is distinct in its own way. The second point is that each experience is seamless, integrated and holistic. You cannot separate the iconic percept of black smoke arising from the burning Twin Towers on a backdrop of blue sky into a half experience of the North Tower and another half experience of the South Tower.

The current most promising scientific theory of consciousness, which encompasses both of these ideas, is Integrated Information Theory (IIT). Devised by Giulio Tononi, a psychiatrist and neuroscientist at the University of Wisconsin–Madison, IIT emphasizes the differentiated and integrated aspect of any subjective experience and postulates that the mechanism supporting conscious experience in the human brain's neocortex must likewise incorporate these two attributes. To probe the extent to which these mechanisms are intact, Tononi, together with a team that included neurologist and neuroscientist Marcello Massimini, now at the University of Milan in Italy, devised an EEG-based method back in the early 2000s. It provides a very crude approximation of IIT's formal calculus. The team verified its basic soundness by correctly discriminating between when six healthy volunteers were conscious but quietly resting with eyes closed and when they were deeply asleep and therefore unconscious.

The brain of a deep sleeper acts like a stunted, badly tuned bell. Whereas the initial amplitude of the EEG is larger than when the subject is awake, its duration is much shorter, and it does not reverberate across the cortex to connected regions. While neurons remain active in deep sleep, as evidenced by the strong response in a local brain region, integration has broken down. Little of the electrical activity found in an awake brain is present.

Although distinguishing the brain's response during a restful state from its response while sleeping may seem trivial, the method can be extended to the more difficult task of discriminating among a variety of brain states. Indeed, in the intervening years, Tononi, Massimini and 17 additional doctors and brain scientists tested the procedure in many more subjects. A paper summarizing this landmark study appeared last year in the peer-reviewed literature.

The method zaps the brain by sending a single pulse of magnetic energy via an enclosed coil of wire held against the scalp, a method called transcranial magnetic stimulation, or TMS. This technique induces a brief electric current in the underlying cortical neurons, which, in turn, engage other neurons in a cascade that reverberates inside the head before the electrical surge dies out in a fraction of a second. Think of the brain as a large church bell and the TMS device as the clapper. Once struck, a well-cast bell will ring at its characteristic pitch for a considerable time, as does the brain. Its electrical activity is monitored by a high-density EEG cap worn by the patient. The EEG is averaged and displayed during the course of 200 TMS pulses, as if it were a movie unfolding in time.

In an awake brain, with intact connectivity, this monitoring of different areas in response to the probe shows a highly complex pattern over much of the cortex, activity that is neither totally predictable nor completely random—and is emblematic of what is meant by "complex."

The researchers estimate its complexity, the extent to which this response differs across the cortex and across time, using a mathematical measure capturing its diversity. The technique itself is borrowed from computer science and is the basis of the popular "zip" compression algorithm for reducing the storage demand of images or movies, which is why the entire procedure of measuring consciousness is known in the trade as zap and zip. Ultimately each person's EEG response is mapped onto a single number, the perturbational complexity index, or PCI. If the brain does not react to the magnetic response—say because the cortical activity is suppressed or only wiggles minimally—PCI will be close to zero while maximal complexity yields a PCI of one. The larger the PCI, the more diverse the brain's response to the magnetic pulse.

A measurement value derived by researchers enabled them to establish a critical threshold—the minimum degree of complex brain activity supporting consciousness.

ZAP AND ZIP IN PATIENTS

THE LOGIC OF the 2016 study, which involved patients from specialized clinics in Belgium and Italy, is straightforward. In a first step, zap and zip is applied to a control population to infer a cutoff value—tagged PCI*—above which consciousness is thought to be present. In every case in which consciousness can be reliably established in any one subject, the person's PCI values should be bigger than PCI*, and in every case in which the subject is unconscious, PCI values should be below this threshold. This procedure establishes PCI* as a critical threshold—the minimum measure of complex brain activity—supporting consciousness. Then, in a second step, this threshold is used to infer whether consciousness is present in patients living in the gray zone, where more conventional measurements are insufficient.

In the study, the benchmark population used to calibrate the procedure encompassed two groups. One consisted of 102 healthy volunteers who experienced various conscious or unconscious states: quietly awake with eyes closed or dreaming during REM sleep (the latter also a conscious state assessed by randomly awakening the sleepers during REM sleep and only including their EEGs in the final results if they reported any dream experience immediately prior to awakening). The EEGs were also assessed under anesthesia using ketamine, a pharmacological agent that disconnects the mind from the external world but does not extinguish consciousness. (At a lower dose, ketamine is abused as a hallucinogenic drug, known as vitamin K.) The unconscious conditions for which EEG was measured during the study were deep sleep (reporting no experiences immediately prior to being awakened) and surgical-level anesthesia using three different agents (midazolam, xenon and propofol). The study also included 48 brain-injured but responsive and awake patients who were assessed while awake as controls.

The investigators found that consciousness could be inferred with complete accuracy in every single subject using the same PCI* value of 0.31. That is, in every one of the 540 conditions tested across the 150 subjects, if the electrical response was at or below this threshold, the subject was unconscious. If above PCI*, the subject was conscious. Everyone in the study, whether healthy volunteer or brain-injured patient, received a correct classification. This achievement is remarkable given the variability in gender, age, brain locations where the TMS pulses were applied, and medical and behavioral conditions in the study cohort.

The team then applied zap and zip with this threshold value (of 0.31) to a distinct set of patients with severe disorders of consciousness—those either in a minimally conscious state or in an unresponsive wakeful one. In the MCS group, patients with at least some signs of behavior beyond reflexive functions such as breathing, the method correctly assigned consciousness to 36 out of 38 patients, misdiagnosing the other two as unconscious. Of the 43 UWS patients, in which communication failed, 34 had a brain response whose complexity was less than that of anyone of the benchmark population when conscious, an expected result. That is, the complexity of their EEG responses was comparable to that of the benchmark group when not detecting consciousness.

Much more troubling, however, were the other nine patients who responded to the TMS pulse with a complex pattern of electrical activity that lies above the threshold. That is, the perturbational complexity of their brain's response was as high as in many conscious benchmark controls. These patients with high-complexity cortical responses may experience something yet are unable to communicate with the world and their loved ones.

As any successful experiment does, this one opens up new avenues of thought. How can the zap-and-zip method be improved to achieve 100 percent accuracy in minimally conscious patients? Could other groups of patients, such as those in catatonia, late-stage dementia, infants or young children, also be tested? Another question is whether other physiological or behavioral measures can be developed to corroborate the inference that some UWS patients are conscious. Can the method be turned into a prognostic tool, inferring to what extent UWS patients are on the road to recovery? Those questions need to be tackled moving forward. But in the interim, let us celebrate a milestone in untangling the ancient mind-body problem. SA

MORE TO EXPLORE

Breakdown of Cortical Effective Connectivity during Sleep. Marcello Massimini et al. in *Science*, Vol. 309, pages 2228–2232; September 30, 2005.

A Theoretically Based Index of Consciousness Independent of Sensory Processing and Behavior. Adenauer G. Casali et al. in *Science Translational Medicine*, Vol. 5, No. 198, Article No. 198ra105; August 14, 2013.

Stratification of Unresponsive Patients by an Independently Validated Index of Brain Complexity. Silvia Casarotto et al. in *Annals of Neurology*, Vol. 80, No. 5, pages 718–729; November 2016.

FROM OUR ARCHIVES

Testing for Consciousness in Machines. Christof Koch and Giulio Tononi; Consciousness Redux, *Scientific American Mind*, September/October 2011.

scientificamerican.com/magazine/sa

BLASTOFF: In May 1980 the giant Mount St. Helens eruption blew off the upper 1,300 feet of the mountain, leaving a gaping crater; 57 people were killed.

GEOLOGY

THE NEXT BIG BA

N G

FROM UNDERNEATH MOUNT ST. HELENS, A NEW PICTURE OF VOLCANIC "PLUMBING" IS EMERGING, WITH IMPORTANT CLUES FOR PREDICTING DEADLY ERUPTIONS

By Steve Olson

Steve Olson is a writer based in Seattle and author of *Eruption: The Untold Story of Mount St. Helens* (W. W. Norton, 2016).

EARLY ON THE MORNING OF MAY 18, 1980, ARLENE EDWARDS, a freelance photographer from Portland, Ore., and her 19-year-old daughter, Jolene, drove across the Columbia River to a high outcropping of rock in southwestern Washington State. There they set up Arlene's camera and began to watch the Mount St. Helens volcano 10 miles to their southeast. For the previous two months the volcano had been spitting out ash and steam, and the Edwardses were among dozens of observers on surrounding ridges who thought they were a safe distance away. It was a gorgeous Sunday morning, the air warm and still beneath a cloudless sky, the volcano grand and terrible under its ash-streaked glaciers.

Suddenly, the entire north side of Mount St. Helens began to slide into the adjacent valley. An angry, gray cloud of pulverized rock and hot gas leaped from the void that had been a mountainside seconds before. The cloud grew explosively, filling the eastern sky and rushing toward Arlene and her daughter. When the cloud hit the viewpoint on which they stood, it blew Arlene 1,000 feet away; her body was later found tangled in the branches of a hemlock tree below the ridge. Jolene, dead of ash asphyxiation, was found near her mother's pickup. Around the mountain, 55 other people lay dead or mortally wounded, victims of an eruption much larger than geologists anticipated.

More than three and a half decades later and just a few hundred yards down the ridge from where the Edwardses were standing, University of Washington seismology graduate student Carl Ulberg kneels amid the greenery of the regrowing forest. A large plastic cooler is half-buried in the ground in front of him, its dirt-speckled lid like a hatch into the underground. He reaches into a tangle of electronics and wires and pulls out a flash memory card. In the distance, Mount St. Helens glistens in the sun, cooled magma from the volcano's most recent 2004–2008 eruptions partly filling its crater. Ulberg slips the flash card, which contains six months of data on vibrations under the mountain, into a plastic carrying case and inserts a fresh card into the recorder. "This is how we're going to figure out what's going on down there," Ulberg says, looking across to the volcano.

For the past three years this seismic station and 69 others scattered around Mount St. Helens have been recording the jolts of buried explosives, the trembling of earthquakes and even the faint susurration of oceanic waves on distant shorelines. They are part of a project known as Imaging Magma Under St. Helens, or iMUSH, an initiative to trace the movement of molten rock from the earth's interior to its surface. It is one of the most ambitious and comprehensive efforts ever undertaken to image the plumbing system under a volcano, and it has revealed a subterranean world hitherto not seen. The traditional view of volcanoes has been simple: a magma-containing chamber deep underground, with a strawlike duct leading to the surface. But under Mount St. Helens, molten rock is traveling through several interconnected reservoirs, where it undergoes chemical changes that can lead to more forceful eruptions. The magma feeding the volcano is moving horizontally as well as vertically, making its way around obstacles and taking advantage of preexisting faults in the earth. As it moves around, the magma causes both deep and shallow earthquakes, presaging future eruptions as the magma chamber under the volcano recharges.

These and other findings from iMUSH have implications not just for the millions of people living near this and other volcanoes in the Cascade Range—including areas near Vancouver, Seattle, Portland, Reno and Sacramento—but other volcanoes worldwide. More than 25,000 people have died from eruptions around the planet since 1980, so the need for better hazard forecasts is acute. Like Mount St. Helens, most land volcanoes rise above colliding plates of the earth's crust that enable heat from the interior to reach the surface. One goal of the project is to extend the findings from iMUSH to other volcanoes, even ones that appear to be quite different. "All volcanoes are individuals," says Michael Clynne, a geologist at the U.S. Geological Survey's location in Menlo Park, Calif. "But we need to thoroughly understand this one to know what's going on at others."

SEEING THROUGH ROCK

THE DEEPEST HOLES ever drilled into our planet go down only about eight miles, but the roots of a volcano extend much farther. Say you had a rig that could go down as far as you wanted and started drilling next to Mount St. Helens. You would encounter typical

PRECEDING PAGES: DIANE COOK AND LEN JENSHEL *National Geographic Stock*

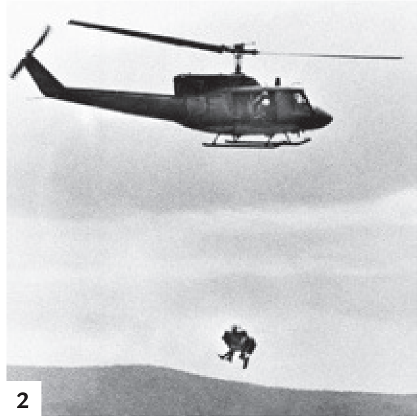
IN BRIEF

A chain of volcanoes running up America's West Coast imperils millions of people. Mount St. Helens is the most infamous and deadly.

New methods of probing inside the mountain show surprising ways that molten rock moves from the deep earth through intricate networks of conduits.

Signals of these movements and of chemical changes in magmas may help forecast the timing and danger of coming eruptions here and at similar volcanoes.

1



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3

CATASTROPHE: The major 1980 eruption of Mount St. Helens sent a towering ash cloud 15 miles into the air (*1*). People had to be rescued by helicopter (*2*). The blast mowed down forests, and fallout blanketed towns (*3*).

continental rocks for the first 45 miles or so—but then something astonishing would happen. The drill would hit oceanic rocks, waterlogged, still carrying fossilized sea life.

This is a small tectonic plate, a piece of the northern Pacific seafloor that is angling into the earth under the edge of North America. This process, known as subduction, is the major driver of volcanism worldwide. When slabs of oceanic crust descend under continental plates, they heat up and create magmas in the overlying crust that percolate toward the surface. The plate diving under North America has made not only the line of volcanoes extending from Mount Garibaldi in British Columbia to Lassen Peak in northern California but also thousands of lava fields and spatter cones that speckle the Cascade Range.

But Mount St. Helens has some odd differences from other volcanoes in this roughly north-south line. One is that it is about 30 miles to the west. Another is that seismic studies suggest that the rock directly beneath Mount St. Helens is too cold to produce magmas, so where does the volcano get its molten fuel? Despite its out-of-the-way location, Mount St. Helens has been the most active volcano in the Cascades in recent centuries. In the early 1800s it erupted almost continuously for decades and a blast around 1480 was several times the size of the 1980 behemoth.

The iMUSH project has sought to explain this strange behavior by tracing the path of the volcano's magmas "from slab to surface," the project's organizers say. "We're using all the tools we have available to try to figure out what's going on," says Ken Creager, a geophysicist at the University of Washington and one of the project's leaders. "No one technique will get us where we want to go. But by putting them together, we hope to come up with a coherent story about how magma is moving."

Last December a few dozen iMUSH researchers gathered around a long, rectangular table in San Francisco. All the people in the room would call themselves geologists, but geology has many branches, and most of these researchers knew relatively little about the detailed work others were doing. Ulberg, for example, is a seismologist who gathers and analyzes seismic signals, but the people around the table included chemists, traditional hard-rock geologists and experts on the earth's magnetic field. They were meeting for what Cornell University geophysicist Geoffrey Abers called the "stare and compare" phase of iMUSH: looking at one another's results to see how they fit together.

The seismologists at the table had the most accessible story to tell—which is ironic, given that seismology is somewhat akin to tapping on a multilayered ball with a hammer and deducing its composition by the sounds it makes. Since the 1980 eruption, permanently installed seismometers around Mount St. Helens have been listening for earthquakes that occur anywhere near the volcano. The waves from earthquakes travel faster through dense, hard rock and slower through hot, partly liquid rock. By comparing earthquake vibrations at different seismometers around the volcano, geophysicists had been able to piece together a rough picture of where magma resides under the mountain.

The iMUSH researchers temporarily gave this seismic network a huge upgrade by adding more and better instruments, including the seismometer Ulberg was servicing. "The instrumentation used in iMUSH was an order of magnitude better, and the resolu-

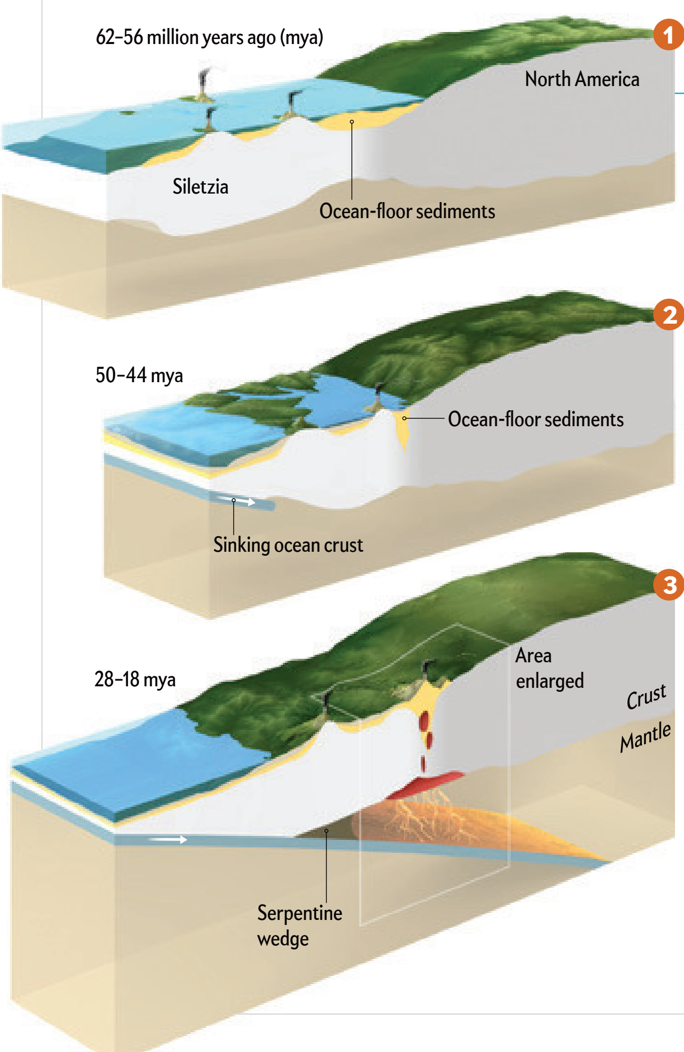
GETTY IMAGES (*1*); AP PHOTO (*2*); JOHN BARR *Getty Images* (*3*)

Inside Mount St. Helens

The volcano's May 1980 eruption killed 57 people, and the mountain has a history of blowups going back thousands of years. Today a blast can endanger millions. Volcanologists recently have probed the mountain's interior and revealed several surprises about how it formed and flares up. The information can improve hazard forecasts not only for Mount St. Helens but other volcanoes around the planet.

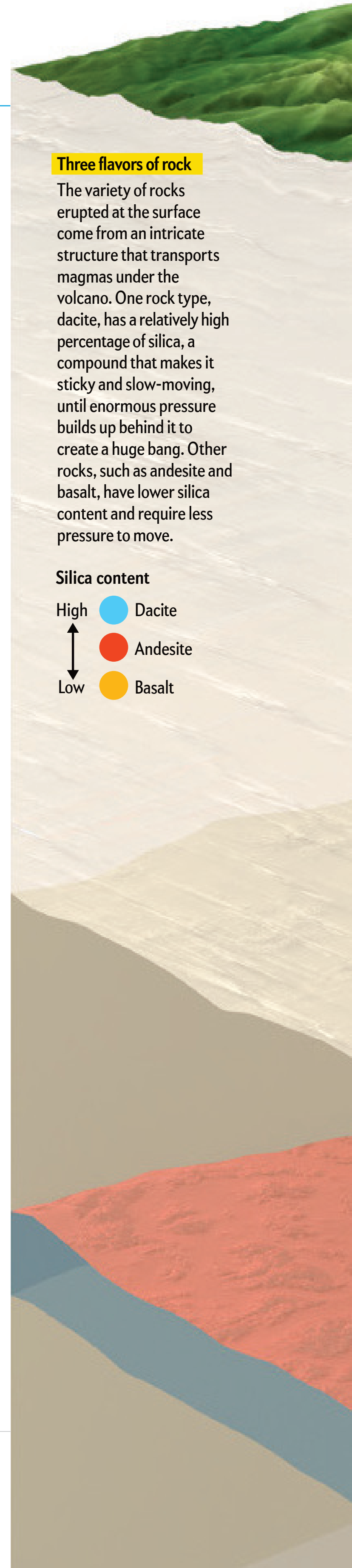
How the Mountain Works Today

Scientists have sent seismic waves under Mount St. Helens from many directions. Their speed and echoes reveal the varying density and components of a complex plumbing system reaching more than 45 miles below the surface—a system quite unlike the simple vision of a magma chamber with a strawlike channel to the mountaintop. Other lines of evidence, such as different types of magma erupted on Mount St. Helens's surface, support this idea.



Building a Volcano

Mount St. Helens formed many miles to the west of other volcanoes in the region. One theory about its unusual location rests on a "ghost plate" of crust that seems to lie under the mountain. That plate is a piece of an ancient region called Siletzia that rode east with the Pacific seafloor, colliding with the North American plate 1. During tens of millions of years, the slow-motion collision forced the former Siletzia, and seafloor sediments, into the edge of North America 2. This geologic "fender bender" formed a zone of fractured rock in the crust. It has numerous cracks through which hot magma can rise. A wedge of cold serpentine rock formed as water from the sinking seafloor combined with hotter mantle rock. This wedge may mark the western limit of magma ascent 3.



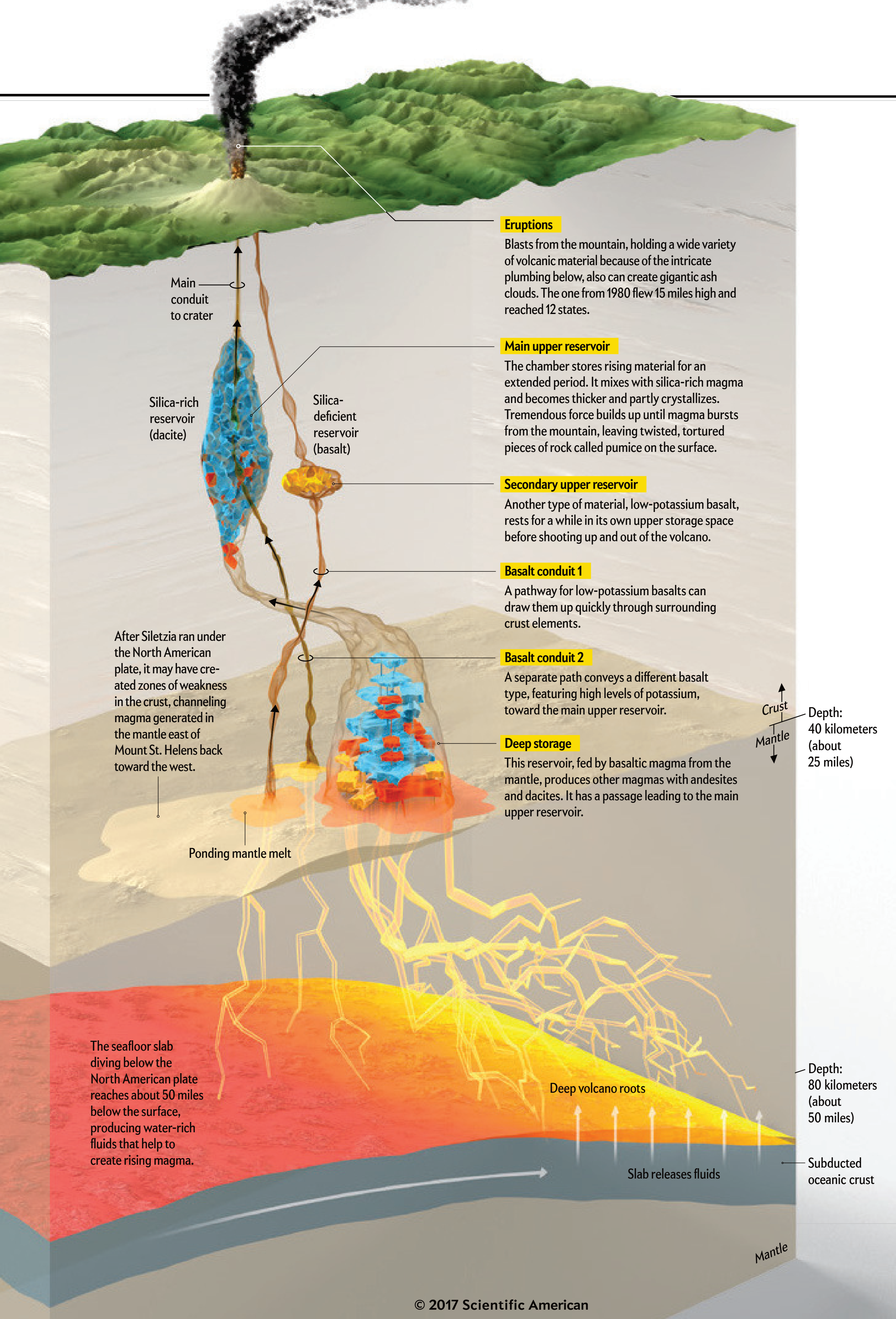
Three flavors of rock

The variety of rocks erupted at the surface come from an intricate structure that transports magmas under the volcano. One rock type, dacite, has a relatively high percentage of silica, a compound that makes it sticky and slow-moving, until enormous pressure builds up behind it to create a huge bang. Other rocks, such as andesite and basalt, have lower silica content and require less pressure to move.

Silica content

High — Dacite
Andesite
Low — Basalt

Illustration by Bryan Christie Design



SOURCES: CARL ULBERG AND KEN CREAGER *University of Washington;* PAUL BEDROSIAN *U.S. Geological Survey (historic panels);* MAREN WANKE AND OLIVIER BACHMANN *Swiss Federal Institute of Technology Zurich (reservoir schematic)* tion was also an order of magnitude better," says Seth Moran, a geophysicist at the USGS's Cascades Volcano Observatory. The seismometers gathered data from natural vibrations and from shaking caused by two dozen 1,000- and 2,000-pound explosives detonated in boreholes. The result has been a much more accurate and detailed picture of hotspots and conduits below the mountain.

CONNECTED CHAMBERS

THE FIRST SURPRISE lay directly beneath the crater's lava dome. Earlier results had pointed to a shallow reservoir of magma just a mile or two under the crater. New findings suggest that this area actually consists of a complex network of fractures that channel magma from deeper in the earth.

Beneath this fracture zone, both older and newer data reveal a sizable reservoir of magma extending from about five to 11 miles under the crater. But here, too, the new images from iMUSH are more nuanced. The traditional picture of a volcano focused on large "chambers" of magma connected to the surface by narrow tubes. But "the more we have investigated, the more we have come to realize that it's quite rare for there to be a high fraction of liquid in the upper crust," notes Brandon Schmandt, a seismologist at the University of New Mexico. "Maybe 1 to 10 percent of the pore space in a rock might be filled with melt, but that's a very different image than a chamber." In keeping with this idea, the magma reservoir under Mount St. Helens seems to be more of a mush than a melt. Chemical reactions can transform the magma into distinct compounds held in different parts of the reservoir.

Farther below this magma storage area, another surprise: the seismic data have revealed a large mass of rock that is too cold and dense for magma to get through. Seismic waves sweep through the region at high velocity, an indication of exceptionally dense material. Blocked by this mass, rising magma appears to be detouring around the rock to the southeast. "Magma will come up the easiest way it can," says seismologist Alan Levander of Rice University. "What we think is that rock is moving up the sides of these high-velocity regions, collecting at the top and then moving into the upper magma reservoirs."

Knowing the complete pathway for the movement of magma could help predict future eruptions. After the 1980 eruption of Mount St. Helens, seismologists detected deep and unusually protracted earthquakes along presumed magma conduits, and comparable earthquakes have occurred before and after eruptions elsewhere in the world. "The general concept is that magma is moving on the way to an eruption or to refill a reservoir after an eruption," observes John Vidale, a seismologist at the University of Washington. These so-called deep, long-period earthquakes do not always presage an eruption, and sometimes they occur only after a magma reservoir has emptied. But "when they're firing off, something is moving, and a volcano may be more dangerous than usual," he says.

GHOST PLATE

SEISMIC WAVES are not the only way to see inside the earth. High above our heads, charged particles from the sun batter the world's magnetic field and create electric currents within the planet. With arrays of electromagnetic detectors on the earth's surface, geophysicists can measure changes in these currents over time—and these changes reflect the presence of liquids. The method is called magnetotellurics. "Once you start to melt a rock, it lights up like a Christmas tree," says Paul Bedrosian of the USGS.

MOUNT DOOM: Before the 1980 outburst blew off its top, Mount St. Helens towered nearly 10,000 feet in the air.

GETTY IMAGES

The magnetotelluric data from iMUSH have been eagerly anticipated because of the hope that they will resolve a long-standing controversy. Previous and sketchier data hinted at the presence of a huge reservoir of liquid underneath Mount St. Helens, Mount Adams to the east and Mount Rainier to the north. Some geologists proposed that all three volcanoes might be sitting atop a vast, interconnected sea of magma.

The much more detailed iMUSH data have not shown any such sea, but they point to another intriguing possibility. The high conductivity under the volcanoes appears to be coming from a large region of water-bearing sedimentary rocks buried by plate tectonics. These rocks appear to mark the edge of the last major piece of North America to be tectonically plastered onto the Pacific Northwest: a ghost plate, once part of a region known as Siletzia that now lies buried, mostly to the west of Interstate 5, in Washington and Oregon. The suture zone between Siletzia and the rest of North America could be an area of weakness through which fluids from below can travel. Sure enough, Mount St. Helens appears to sit above or very near to that zone.

A preexisting weakness in the crust also could explain the blobs of dense rock underlying Mount St. Helens. Continual injections of magma into the suture zone could gradually cool, requiring future injections to make their way around these solidified intrusions. Like the seismic data, the magnetotelluric data reveal dense rock beneath Mount St. Helens around which magmas must be migrating, although the two methods place the rock in slightly different places. Reconciling these differences to create more detailed subterranean maps "is the juiciest part of the process," says Adam Schultz, who does magnetotelluric research at Oregon State University.

MANY MAKES OF MAGMA

THE MOST COMPLEX DATA, however, are neither seismic nor magnetotelluric. They are the data generated by walking around, picking up rocks on the mountain and analyzing their components. A great variety of lavas have erupted from Mount St. Helens, which seems counterintuitive given that they all came from the same volcano. But even a glance at the multihued and multitextured walls of the volcano's crater suggests how hard it will be to explain the petrology—the origins, composition and distribution—of all the rocks it has emitted. As magma ascends, it "differentiates, ascends again, crystallizes, picks up some stuff, assimilates and finally reaches the surface," notes Olivier Bachmann, a petrologist now working in Switzerland, who was instrumental in getting iMUSH up and running. The movement of rock inside the earth "is like a big washing machine," he says.

One kind of rock is both ubiquitous and telling. All around the volcano, hikers can reach down and pick up pieces of pumice, a light-colored, frothy rock so filled with bubbles that it floats. Under a hand lens, the rock looks tortured. The air bubbles are stretched into long tendrils, as if the lava were being torn apart as it solidified.

That rock provides a clue to the ferocity of the 1980 eruption. It consists of a substance known as dacite, which contains a relatively high percentage of silica. Silica makes magma viscous, so that it clogs up the vents of volcanoes and traps the gases it contains. That is one reason why the 1980 eruption was so powerful: the sticky dacite remained trapped under the mountain, building up pressure, until the collapse of the volcano's north flank gave the pressure a way to escape.

But Mount St. Helens has erupted many other kinds of lava over its history. On its south side, lava caves burrow through runny basalts like those seen in Hawaiian volcanoes. The pre-1980 cone, which took shape in just the past 2,500 years, consisted in part of mountain-building andesite rocks. How can a single volcano produce such different kinds of lava?

A home run for iMUSH would be accounting for the dacitic magmas that made the 1980 eruption so deadly while explaining the origins of the volcano's other magma types. Dawnika L. Blatter, Thomas W. Sisson and W. Ben Hankins, who are all USGS scientists, recently published a new explanation, drawing both on the iMUSH results and on previous findings. Their hypothesis hinges on earlier work done by a joint Vanderbilt University–USGS team on the dating of zircons, which are crystals that tend to form in high-silica magmas. Zircons in lava from Mount St. Helens have undergone repeated cycles of heating and cooling, "like kneading a dough," Sisson says. Over many thousands of years injections of molten rock from below appear to have repeatedly heated areas of mush. As it thermally cycles, the magma picks up silica from the surrounding crustal rocks, giving Mount St. Helens' lavas their characteristic stickiness. When enough energy enters the system, the transformed magma forces its way to the surface.

But sometimes the injections of magma from below are powerful enough to shoot right through the middle of the storage region with little modification. As geophysicist Weston Thelen of Cascades Volcano Observatory says, fresh magma from deep in the earth can "race out of the mantle, largely skip storage and be erupted immediately," accounting for the runny basalts that Mount St. Helens sometimes emits.

If this model bears out, it could have implications around the world. Many infamously violent volcanoes erupt mostly dacitic magmas, including Mount Pinatubo in the Philippines, Thíra in Greece and Krakatau in Indonesia. If earthquakes, gas emissions or other signals could be linked to the processing of magmas underground, volcanologists could have another way of predicting dangerous eruptions. "One of our shortcomings in studying hazardous volcanoes," Sisson says, "is we generally don't know they're getting ready to erupt until magma makes it to the upper crust, where it generates earthquakes and ground deformation." Understanding how magma is being cooked deep underground—how it is separating chemically, how it is interacting with the surrounding rock—could indicate what it is getting ready to do.

PREPARING FOR THE INEVITABLE

TODAY MOUNT ST. HELENS is quiet. Tourists viewing the crater and scientists working on its flanks have no need to worry about an unexpected eruption. But the mountain's repose will not last. Several times since the 1980 eruption—most recently in 2016—flurries of relatively shallow earthquakes beneath the crater have pointed to the movement of magma. The earthquakes do not mean that an eruption is imminent, but "the system is recharging," says the University of Washington's Creager. "The volcano has begun building up to its next eruption."

Geologists and emergency planners in the Pacific Northwest learned a hard lesson from the 1980 eruption. When a dangerously unpredictable volcano is rumbling, they will never again let people within just a few miles. But volcanoes pose many dangers other than explosive eruptions. If ashfalls like those from previous Cascades eruptions were to occur today, they would devastate large downwind communities. Volcanic mudflows can roar down river valleys with little warning. At present, Mount Rainier, which looms just to the southeast of Seattle and Tacoma, is considered much more dangerous than Mount St. Helens because of its size and the number of people living nearby. More than 150,000 Washingtonians live and work on top of mudflows from Rainier that have occurred within the past few thousand years.

The iMUSH results have given geologists a more detailed, though more complicated, picture of what is happening under Mount St. Helens. That picture is producing a new perspective on subterranean signals that mean something is happening, signals that not been well understood. When the next eruption occurs—either at Mount St. Helens or elsewhere—a better grasp of those details could mean the difference between life and death.

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FROM OUR ARCHIVES

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ECOLOGY

gone

Stocking rivers and lakes with game fish is good for anglers. But it is wreaking ecological havoc

By Richard Conniff

fishing

Richard Conniff is an award-winning science writer for magazines and a contributing opinion writer for the *New York Times*. His books include *House of Lost Worlds* (Yale University Press, 2016) and *The Species Seekers* (W. W. Norton, 2010).

IT'S ONE OF THE FEW GOVERNMENT PROGRAMS MOST TAXPAYERS love. Stocking America's waterways with fish for anglers has a persistent Norman Rockwell kind of appeal, based on the idea that, with a little help, any lake or stream can be a place where your average kid (or grown-up) can toss out a line and just maybe reel in dinner.

Fish stocking is also the basis for a recreational fishing economy worth $25.7 billion a year, according to a 2011 survey by federal agencies. Hence, it has been government policy since the late 1800s to haul juvenile fish from hatcheries to local lakes and since the 1950s to airlift and release them by the thousands into remote lakes everywhere.

But indiscriminate fish stocking is increasingly looking as if it might just be one of the dumber things people have ever done to the environment, because the introduced fish tend to displace native species. "Think about it," says Julian D. Olden, a University of Washington ecologist working on nonnative fish issues. "The fish we stock are those that grow rapidly, are highly fecund and are great on the end of the hook," he says, referring to the trout, bass, northern pike and other game fish that are commonly introduced to U.S. lakes and rivers. That is, we select for aggressive predators. "It shouldn't be too surprising that the same attributes we love as anglers are also responsible for the high impacts we are witnessing on native species and ecosystems," Olden says.

Fish stocking has, of course, sometimes helped rebuild threatened native species—for instance, lake trout in the Great Lakes and brook trout in Great Smoky Mountains National Park. But until recently, hatcheries and fish stocking also made it easier to sacrifice rivers and lakes to development, observes Rick Williams, a fisheries biologist who advises Fly Fishers International. "[Development proponents] would say, 'We're going to put this dam into this rivershed, and it's going to create all these benefits,'" he explains. The proponents would admit that there might be some negative effects on native salmon or steelhead trout, for example, but then they would gloss over those consequences, saying, "Don't worry, we're going to put in a hatchery." Eventually, after the habitat was damaged beyond repair, people gradually realized that "hatchery fish are not wild fish." The adaptations that let fish thrive in crowded hatchery conditions do not easily translate into survival or reproductive success in the wild. After just a single generation in captivity, hatchery steelhead already differed from their wild counterparts in the expression of hundreds of genes, according to a 2016 study.

State and federal officials, together with some anglers, have thus begun to rethink our long infatuation with fish stocking, and in some cases they are working to unwind its destructive effects. In August 2016 the National Park Service approved a plan to remove stocked fish from 85 high-elevation lakes in California's Sequoia and Kings Canyon National Parks. Also last year, Oregon removed limits on how many bass, walleye and other introduced game fish anglers can take in three rivers where those fish interfere with native species. In addition, a proposed nationwide network of native fish refuges moved toward becoming reality in 2015, when North Carolina, Georgia and Tennessee designated the Little Tennessee River basin the nation's first Native Fish Conservation Area.

TROUBLED WATERS

CONCERNS ABOUT the inadvertent effects of fish stocking have been around almost from the start. In Europe, people began to experiment with rearing fish fry in captivity to restock streams in the

PRECEDING PAGES: MIKE POWELL *Getty Images*

IN BRIEF

Stocking waterways with trout, northern pike, bass and other species for sport fishing is a popular and time-honored tradition.

But introducing these game fish in places where they do not occur naturally can have devastating consequences for native species and ecosystems.

Recently officials and conservation-minded anglers have begun work to mitigate the damage. Not everyone supports such efforts, however.

1

2

3

4

COMMONLY STOCKED SPECIES such as brook trout (*1*), lake trout (*2*) and northern pike (*3*) are aggressive predators. The fish are raised in hatcheries and then released into lakes and rivers (*4*), where they may displace native species.

JOHN KUCZALA *Getty Images* (1); GETTY IMAGES (2 and 3); STEPHEN OSMAN *Getty Images* (4)

17th century, and the practice spread to North America as waterways became fished out a century or so later. Olden likes to show his students an article from an 1893 Oregon newspaper arguing that introduction of largemouth bass would be either a blessing on the Columbia River ("the best friend not only of our salmon and trout, but of our water fowl") or a curse ("the natural enemy of all young fish").

But even those who should have known better seem not to have taken the potential hazards seriously. More than a century ago Robert Roosevelt, a New York State congressman who was an early conservationist (and uncle of Theodore), was largely responsible for instigating government stocking programs in the U.S. In 1871 he pushed Congress to establish the U.S. Fish Commission to investigate declining fisheries and the potential of aquaculture to replenish depleted waterways. Within a few years the new transcontinental railroad was shipping brook trout from east to west and rainbow trout from west to east, often stopping repeatedly en route to seed local bodies of water.

Enthusiasm for fish stocking blossomed from there, sometimes with devastating consequences. As early as 1910, the yellowfin cutthroat trout, a favorite of local anglers and known to weigh 11 pounds or more, disappeared from Colorado's Twin Lakes through hybridization with rainbow trout and competition with other introduced game fish. The same factors, together with overexploitation, killed off New Hampshire's silver trout, first described as a new species in 1885 and considered extinct by 1939. In one of the most egregious "improvements," the state of Oregon deliberately poisoned the Miller Lake lamprey in the 1950s because it preyed on introduced trout. A 1989 study implicated the introduction of nonnative fish as a factor in more than two dozen North American fish extinctions over the previous century—and the rate of extinction appears to have increased by 25 percent since then.

"It's not only occurring in one place—it's all over the world," says Vance T. Vredenburg, a herpetologist at San Francisco State University who has studied the effects of fish stocking on native species. "The California golden trout is a really beautiful fish, and because of that you can find them introduced in Mexico and in the Andes. You can find them in New Zealand. You can find them on Mount Kilimanjaro," rarely with any consideration of the effect on native species. And yet invasive species and disease ranked among the top three culprits when the

WWF reported in 2016 a stunning 81 percent decline in freshwater fish and amphibians worldwide since 1970.

In 2004 Vredenburg provided experimental evidence of the damage fish stocking does to mountain yellow-legged frogs, a species native to the Sierra Nevada. Working in Kings Canyon National Park, he began to suspect that brook trout and rainbow trout, introduced into high mountain lakes there that had never seen any fish before, were gobbling up all the native tadpoles before they could become frogs. To test his hypothesis, Vredenburg removed the introduced fish from five lakes in the park. Then, over a six-year period, he watched as the yellow-legged frog population rapidly recovered in those lakes, while tadpoles continued to vanish from eight nearby lakes that still contained introduced trout.

NATIVE SPECIES displaced by fish stocking can bounce back after the stocking of nonnative fish has stopped. Such remediation efforts may explain the recent recovery of the mountain yellow-legged frog in Yosemite National Park.

Other studies suggested that stocked fish were disturbing entire ecosystems in Kings Canyon National Park. Unexpected links tie one species to another, "and when fish are introduced, they sever those connections," explains Danny Boiano, the park's aquatic ecologist. Yellow-legged frogs, for instance, were the main prey of mountain garter snakes in the park. When fish stocking made the frogs scarce, Boiano says, garter snake populations also declined. Gray-crowned rosy finches, birds that are partial to rocky alpine habitats, used to cruise the high mountain lakes to feed on mayflies. When introduced fish beat them to the mayflies, the finches became scarce. The fish also dramatically altered populations of *Daphnia* and other zooplankton that are the base of the food chain.

Vredenburg recalls that his initial study on yellow-legged frogs got no traction with policy makers at first, perhaps in part because the belief in the goodness of fish stocking is so strong. The U.S. Forest Service acknowledged that he had found a problem in that park, he notes, but it maintained that other habitats are different, saying, "We know places where frogs and fish coexist." The experiment would have to be repeated to "show it was not just one place, not just one person's data," Vredenburg says.

The California Department of Fish and Wildlife (then operating under the old name "California Department of Fish and Game") also resisted any change to its fish-stocking practices. It was not so much a matter of economics as of "power, authority and mission," says Kierán Suckling, executive director of the Center for Biological Diversity in Tucson, Ariz. Stocking fish was simply what fish and game departments, largely funded by fishing and hunting license fees, had always done. Suckling points out the contradiction: with one hand, the department was spending money to protect rare native fish, amphibians and other freshwater species, while the other hand was spending even more money stocking nonnative trout in waters where this practice was putting at least 39 such species at risk. But it took legal action from conservationists, together with the 2012 state (and 2014 federal) listing of the yellow-legged frog as an endangered species, to bring about change.

ON THE HOOK

CALIFORNIA has since made major changes in its stocking practices, according to Roger Bloom, who manages inland fisheries for the California Department of Fish and Wildlife. For one thing, it has stopped stocking hundreds of lakes. And for those lakes it continues to stock, the state legislature has ordered a shift to stocking with native species, starting at a minimum of 25 percent of all stocked fish. In a few areas, the state now stocks only native species, notably Lahontan cutthroat trout in the Truckee and Carson rivers, where they are endemic.

"Our mantra," Bloom says, "is to use the right fish in the right place at the right time and in the right numbers and to make sure we consider the benefits and effects at the ecosystem level." The state now performs an environmental review of any new area proposed for stocking and periodic environmental impact statements on all stocked waters. Bloom says that when fishery officials in other states hear about this, their eyes widen in disbelief. "I think we're ahead of the others because of the complexity and the endangered species we've got," he says.

Other states may have to catch up. "All states are supposed to look for sensitive species" before stocking, Suckling notes. "But they don't always do it unless you sue them." A mix of what he describes as "weak and overly procedural" federal and state laws complicate the process. But in California, "the Endangered Species Act comes into play, and that's the big dog in the room," Suckling says. "It's clear, it's strong, it's enforceable and that's when things tend to change more rapidly."

It is also an outrage, to some anglers. When California announced a plan to protect native species by ending fish stocking in 175 lakes and streams, a headline on the outdoors column in the *San Francisco Chronicle* declared, "It's a Load of Bullfrogs!" "Every lake is somebody's favorite lake, so no matter

JOEL SARTORE *Getty Images*

which lake you stop stocking, it's going to make somebody angry," observes Jessica Strickland, a fisheries biologist at Trout Unlimited, an organization of conservation-minded anglers based in Arlington, Va. "The local angler perspective is that they want to continue fishing where they want to fish. The conservation-minded angler who is more open to change says, 'Maybe I can just go fish one of the other 9,000 lakes'" that continue to be stocked. For Trout Unlimited, she says, the important thing is for government agencies to operate in the open, giving anglers a chance to provide input and understand changes in stocking policy.

"At most, I would say we've only got significant conflicts [with endangered species] in 2 to 5 percent of stocked areas," Suckling says of California's waterways. "And that's because the endangered species have retreated to small pristine areas. There's very little hope of bringing them back to the mainstream rivers. They're too full of exotic species and pollution."

In some areas where agencies have stopped stocking and actually removed introduced fish before it was too late, native habitats have bounced back.

Elsewhere the move away from fish stocking goes slowly. Stocking with nonnative fish continues, for example, in the Little Tennessee River Native Fish Conservation Area, according to Fred Harris, an angler and retired fisheries biologist involved with the project. "Those rainbow and brown trout fisheries are very popular," he says, "and the last thing you want to do, if you want to start a conservation process, is piss off a lot of anglers."

Instead, he says, the project aims to work around the continued stocking. Removing river barriers is a priority, for instance, to open upstream areas to brook trout and other native species and to recover former habitat. At the same time, the project also maintains certain other barriers to keep the introduced rainbow and brown trout safely downstream.

That go-slow strategy may appease anglers, but it also poses risks of its own. The Little Tennessee River basin is an important site in one of the nation's great unheralded biodiversity stories: more than a third of the world's 840 freshwater mussel species live in North America, mostly in the Southeast. They have co-evolved with native fish species, developing ingenious adaptations to lure a fish close enough to blast their larvae into the fish's gills. The fish then becomes a traveling nursery for the mussel larvae and eventually disperses the young bivalves around the habitat. That dispersal maximizes the distribution of animals that spend most of their lives buried in the mud. It also benefits the habitat because the mussels filter bacteria and algae from the water.

But Suckling, whose Center for Biological Diversity has recently opened a Southeastern office, worries that continued stocking with nonnative game fish may displace native fish and throw the mussels' co-evolutionary strategies into the waste bin. Together with water pollution, dams, wetland destruction and other habitat changes, such displacement could push native freshwater mussels—already among America's most endangered species—into extinction.

CATCH AND RELEASE

THE FIGHT over fish stocking thus seems poised to become more widespread and perhaps uglier. But there is also promising news: in some areas where agencies have stopped stocking and actually removed introduced fish before it was too late, native habitats have bounced back. When researchers in the Italian Alps recently removed stocked brook trout from lakes in Gran Paradiso National Park, "recovery was very, very rapid," says Rocco Tiberti of the University of Pavia. *Daphnia* and other native invertebrates that had been decimated suddenly blossomed. Dormant "resting eggs," produced in periods of environmental stress years or even decades earlier, shed their protective envelopes and repopulated the lake. "Many populations can recover even after local extinction," Tiberti observes.

Likewise, a study published in the *Proceedings of the National Academy of Sciences USA* in October 2016 announced a dramatic recovery of yellow-legged frogs in Yosemite National Park. Most news reports on the recovery emphasized the tantalizing possibility that long-term exposure to the deadly chytrid fungus, which has contributed to more than 100 amphibian extinctions since the 1970s, may have allowed the frogs there to evolve some form of resistance. But there was a hitch: yellow-legged frog recovery is so far happening only in Yosemite. A much simpler explanation, the authors of the study proposed, is that the frogs are recovering because in 1991 the National Park Service ended the practice of stocking high-elevation lakes with nonnative game fish. Although these lakes still harbor nonnative fish from earlier stocking efforts, discontinuation of that practice has given the frogs a reprieve, even in the absence of total elimination of those introduced species.

Back in the Sierra Nevada, watching his yellow-legged frogs leaving the threat of extinction behind, Vredenburg, a coauthor of the new *PNAS* study, notes that humans have inflicted many ills on freshwater species, from pesticides to climate change. "It's death by a thousand cuts," he remarks. "But amphibians have been around for 360 million years. They are survivors. If we can just remove some of these obstacles—such as introduced fish—we can give these species the opportunity to survive." SA

MORE TO EXPLORE

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FROM OUR ARCHIVES

Exchanging Fish Fry with Europe. October 14, 1899.

scientificamerican.com/magazine/sa

SUSTAINABILITY

THE RADICAL GROUNDWATER STORAGE TEST

New tactics for capturing floods and surviving droughts could help communities across California and the world

By *Erica Gies*

Illustration by Bomboland

Erica Gies, a fifth-generation Californian, writes about science and the environment from Victoria, British Columbia, and San Francisco. Her work appears in the *New York Times,* the *Guardian,* the *Economist,* and elsewhere.

"Seventeen is closed, Skyline is closed, nine is closed, 152 is closed,"

my mom tells me at a restaurant in San Jose, Calif., rattling off highways between the San Francisco Bay Area and the Pacific coast, where I'm scheduled to drive the next morning. Last winter's torrential storms turned California's hillsides so sodden that they slid down over roads, cutting off communities. Between October 2016 and February 2017, the state saw about double the seasonal average annual precipitation. North of Sacramento, more than 188,000 people were forced to evacuate their homes as the Oroville Dam overflowed, eroding a giant crater into its spillway and threatening to release one of the state's biggest reservoirs. "I can't remember ever seeing it like this," my mom says, echoing the amazement of millions of longtime Californians.

It was a head-spinning reversal from the previous five years, when, at times, 100 percent of the state was in a drought. Empty reservoirs and brown lawns created a subconscious drumbeat: scarcity, scarcity, scarcity. The fear was palpable: Can we continue to live here? Can we support new residents? Should we continue to grow food for the world? The deluges first brought relief, then growing unease. But California water managers, still traumatized by the years of want, saw opportunity. They wondered: Can we capture all this extra water and save it for the next drought?

That question reflects a new reality. Although California has historically cycled between droughts and floods, scientists say climate change is making both phases more intense. Also, warmer temperatures are already reducing the Sierra Nevada's snowpack, predicted to shrink by up to 90 percent, which spells trouble. Most of the state's precipitation falls in the winter; summers are usually dry. On average, snow supplies 30 percent of California's human water consumption, melting slowly through the spring and summer, just when it is needed the most. And in the future, snow is expected to fall as rain, creating even more flooding in the winter and even less water supply in summer. Rapid population growth complicates these wilder swings: more people are living in the paths of floods and are demanding water during droughts. Water managers know they must alter their strategies.

Worldwide, changing precipitation patterns and rising population are impelling adaptation. Millions of people who have relied on snowpack and trickling glaciers—Asians living around the Himalayas, Europeans alongside the Alps, South Americans by the Andes—will also need new ways to capture floods to protect infrastructure and to store water for later.

In California, like other places, new reservoirs cannot solve the problem. "We've already dammed most rivers," says State Water Resources Control Board chair Felicia Marcus. But there is plenty of room underground. Aquifers—large water deposits—that have been depleted by farmers' pumping from progressively deeper wells, have 10 times the capacity of California's 1,400 reservoirs. And storing water underground is a comparative bargain, about one-fifth the cost of building reservoirs. A constellation of forward-thinking people in science, agriculture, conservation and public policy are designing ways to actively store water underground on an unprecedented scale, to reduce flood damage while increasing reserves.

Winter floods and spring melts once spread out across the Central Valley, gently percolating down into aquifers and feeding riparian forests and vernal pools that supported dense salm-

IN BRIEF

California could better survive flood years and drought years by capturing floodwaters and using them to recharge underground aquifers that farmers and municipalities now pump from when rains are scarce.

To do so, water users and managers have to regard surface water and groundwater as one connected resource.

A variety of test projects are proving that this approach can work. For example, farm fields can be flooded even when crops are growing so the water can percolate down into aquifers. Revising water rights and paying landowners to allow flooding can help the techniques work across California and the world.

THIS PAGE AND OPPOSITE PAGE: COURTESY OF JUDAH GROSSMAN *The Nature Conservancy*

PROLONGED DROUGHT had left California's Cosumnes River Preserve floodplain exceedingly dry. But when winter rains this year raised the river (*on horizon*), a gap cut in the levee there augmented flooding so more water could percolate through the ground to recharge the aquifer below.

on runs, elk, grizzlies and clouds of birds. That all changed in the 20th century, when California became arguably the apex of water engineering hubris. Massive dams, reservoirs, aqueducts, canals, levees and pumps changed the plumbing of the entire state and caused countless unintended consequences. This intensive infrastructure made possible modern California, but the recent drought and floods exposed how ill prepared this system is to handle current realities. One key weakness is that by cutting off rivers from their floodplains to protect cities and farms, engineers have greatly cut the recharging of aquifers.

Now managers and engineers are seeking to return, somewhat, to nature's way, by letting land flood in a controlled manner. Implementing this vision would require a shift in the dysfunctional "mine! mine!" culture that has long characterized water use in California. There are signs of motion. A groundbreaking state law passed in 2014 puts more responsibility for careful management on local water users, establishing a statewide vision while allowing local flexibility. Similarly, in an about-face from large waterworks, the new approach would be a patchwork of thousands of grassroots recharge projects across individual water basins.

To that end, scientists and local managers are running pilot projects to study how to exploit each site's unique hydrology, land use and financial accounting. They are searching for solutions that can serve multiple masters—for example, flooding farm fields to recharge aquifers at times that do not harm crops and that benefit wildlife.

Dry places around the world watch one another's water innovations closely: drip irrigation developed in Israel, Australia's overhaul of water rights and trading. This is California's move.

THE PUMPING MIRAGE

SUCCESSFUL PROJECTS START WITH correcting long-term misunderstandings about basic hydrology. This past April, after four months of big storms, California's drought had retreated to just 9 percent of the state, and Governor Jerry Brown declared it over. But "that's a surface-water-centric way of looking at it," says Sandi Matsumoto, associate director of the California water program at The Nature Conservancy (TNC). An aquifer and the lakes, rivers and streams on the surface above it are actually the same water, intricately linked by gravity and hydraulic pressure. The truth, Matsumoto says, is that even though California surface waters may look replenished this year, aquifers are still extremely depleted from decades of farmers and municipalities aggressively pumping up water. "It will take us decades, if not half a century, to recover from what we've done," she says.

Underground water, called groundwater, supplies about 60 percent of the state's demand during dry years and 30 percent in average years. Neither of those rates is sustainable because surface water percolating down to restore groundwater cannot keep up. More than half of the earth's largest aquifers have exceeded tipping points, according to a 2015 study of NASA satellite data.

That is worrisome because most of the pumped water helps farmers fill the world's food baskets. If these lands fall fallow because of groundwater depletion, it would be catastrophic, given that the United Nations Food and Agriculture Organization estimates we need to *increase* global food production by 70 percent to feed a projected 9.1 billion people in 2050.

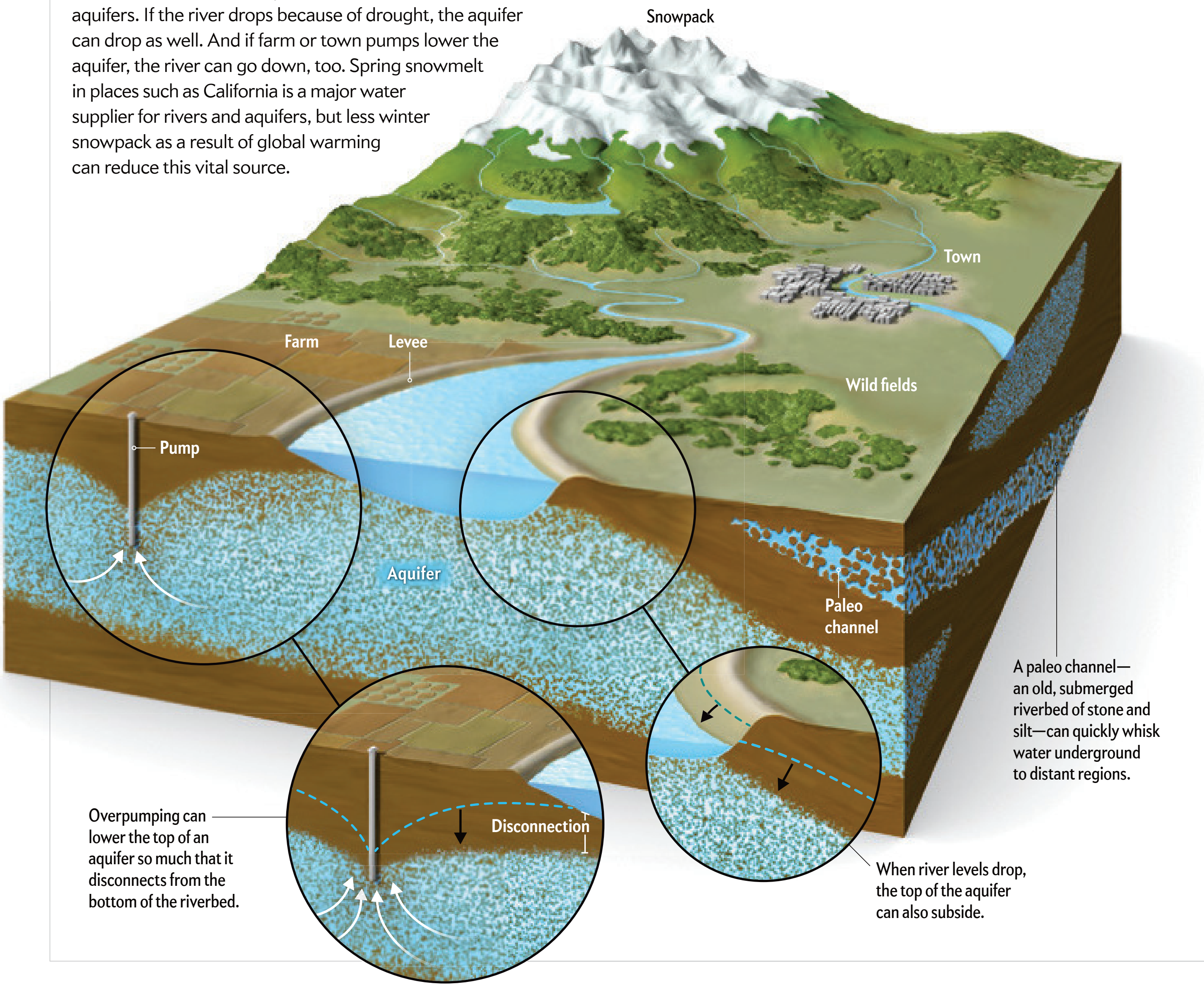
For more than a century California managed only its surface water. Groundwater, in contrast, was a property right: you could dig a well on your land and pump all the water you needed, regardless of how that affected your neighbor's supply. This management schism treated surface water and groundwater as two separate resources, even though a full aquifer can help feed a river's flow during the dry season, and when groundwater sinks, river water can filter down to replenish it.

Pumping a sunken aquifer can therefore deplete surface water, the very problem that spurs farmers and cities to pump in the first place. In the San Joaquin Valley, water tables have fallen so far belowground in some places that they have become functionally disconnected from the streams they once exchanged water with, says Helen E. Dahlke, professor of integrated hydrologic sciences at the University of California, Davis. The disconnect also harms aquatic species by drying up wetlands, seeps and springs. Groundwater recharge could reconnect some aquifers with their rivers, making the whole hydrologic system more resilient. These multiple benefits are "the way we make it in the future," Marcus says, "as opposed to us each fighting for our molecule of water."

This ethos sets California's new test projects apart from earlier storage approaches that treated aquifers as a water bank: if you made a deposit, you would get an equal withdrawal. The problem is that water does not necessarily stay in a tidy underground basin waiting to be pumped out when needed. For the state's new vision to become reality, people will have to shift their notion of water ownership to something more communal. Spain, for example, has demonstrated that kind of thinking, says Alvar

One Big Water Supply

Surface water and groundwater are intimately connected. Water in rivers and creeks often percolates down into groundwater aquifers. If the river drops because of drought, the aquifer can drop as well. And if farm or town pumps lower the aquifer, the river can go down, too. Spring snowmelt in places such as California is a major water supplier for rivers and aquifers, but less winter snowpack as a result of global warming can reduce this vital source.



Escriva-Bou, a Spanish-born research fellow at the Public Policy Institute of California (PPIC) Water Policy Center.

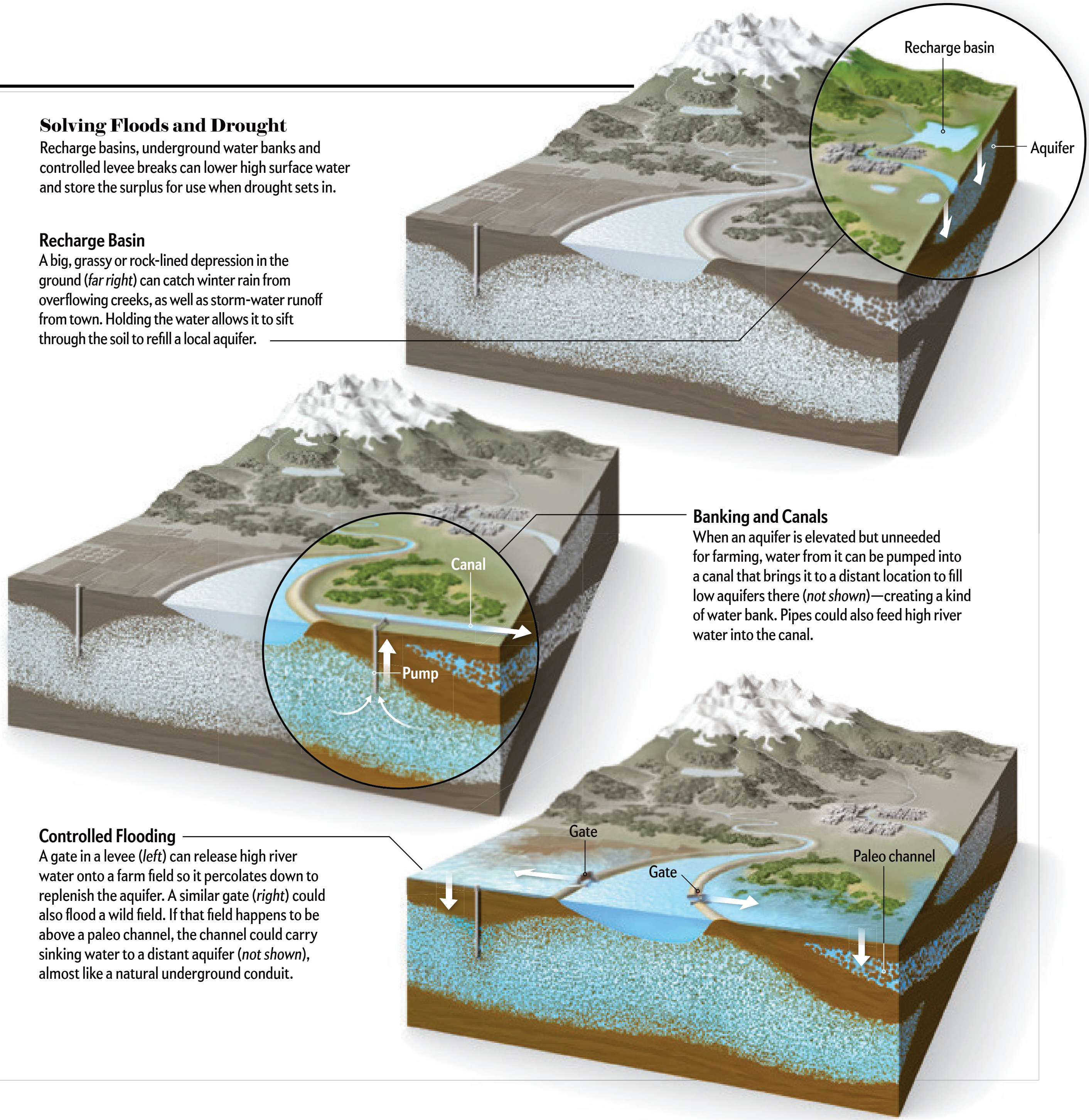
THE REVOLUTIONARY COMPROMISE

CALIFORNIA'S WATER RIGHTS were considered politically inviolable until the recent drought, when the panicked pumping it induced cracked open a door. After decades of trying, the state legislature passed the most significant water reform in a century: the 2014 Sustainable Groundwater Management Act (SGMA), pronounced "SIG-ma." The act prescribes management at the level of groundwater basins—three-dimensional areas that include surface water and the permeable aquifer below. California has 515 basins, but just 127 of those account for 96 percent of groundwater pumping, so the state has prioritized them for better management. Each basin must form a groundwater sustainability agency, craft a groundwater sustainability plan by 2022 and manage groundwater sustainably by 2040. That target is challenging because most basins lack robust data collection, says Tara Moran, who oversees sustainable groundwater work at Stanford University's Water in the West program.

The SGMA rules encourage recharge by requiring cities and irrigation districts to stop depleting groundwater. "Most groundwater sustainability agencies would prefer to do groundwater recharge rather than restrict pumping," says Esther Conrad, a postdoctoral researcher at Water in the West who has been attending local water meetings across the state.

For inspiration, the agencies can look to communities that had to reckon with troubled basins decades ago. One of those is

Illustration by Emily Cooper



Solving Floods and Drought

Recharge basins, underground water banks and controlled levee breaks can lower high surface water and store the surplus for use when drought sets in.

Recharge Basin

A big, grassy or rock-lined depression in the ground (*far right*) can catch winter rain from overflowing creeks, as well as storm-water runoff from town. Holding the water allows it to sift through the soil to refill a local aquifer.

Banking and Canals

When an aquifer is elevated but unneeded for farming, water from it can be pumped into a canal that brings it to a distant location to fill low aquifers there (*not shown*)—creating a kind of water bank. Pipes could also feed high river water into the canal.

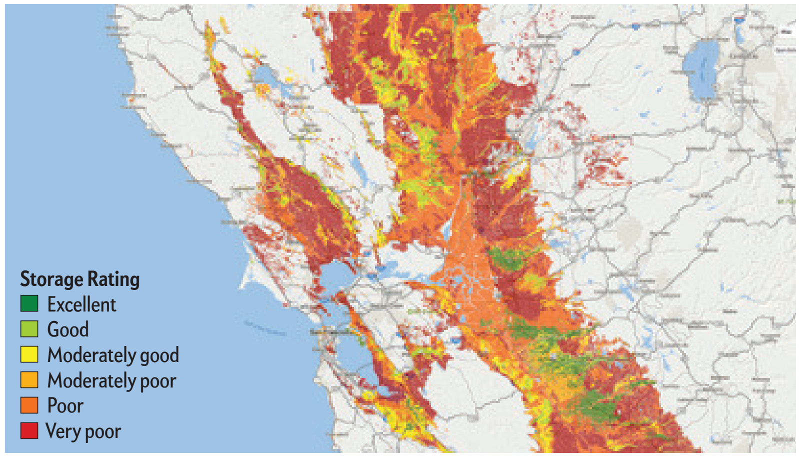
Controlled Flooding

A gate in a levee (*left*) can release high river water onto a farm field so it percolates down to replenish the aquifer. A similar gate (*right*) could also flood a wild field. If that field happens to be above a paleo channel, the channel could carry sinking water to a distant aquifer (*not shown*), almost like a natural underground conduit.

Santa Clara Valley, known today as Silicon Valley. In the 19th and 20th centuries it was called the Valley of Heart's Delight, a nod to its stone fruit orchards—Blenheim apricots, Bing cherries, Burbank plums. To keep the crops viable during dry summers, farmers pumped groundwater enthusiastically. The hurrah was short-lived. Between 1890 and 1920 water levels plummeted and the land surface sagged. Downtown San Jose dropped 13 feet.

Local leaders decided to try to refill aquifers by capturing heavy water flows that would otherwise rush through creeks and rivers to the ocean. Just as beavers dam a stream to create a pool, human engineers built partial walls across Page Creek in Los Gatos, using burlap sacks filled with dirt. The structures created ponds alongside the creek that gave the water time to percolate underground. Earthen dams followed, such as the 34-foot-tall Vasona Percolation Dam across Los Gatos Creek. Heavy rains might flood the town park surrounding the dam, allowing extra recharge without threatening homes or businesses. The water projects halted land subsidence and receding groundwater levels. But the valley's population boomed after World War II and beyond, and the district needed more water than the ecosystem naturally offered. It built pipes to the massive canals constructed by the state and federal government to route northern California water southward, securing an extra share.

Today the Santa Clara Valley Water District benefits from recharge basins—barriers people built alongside more than 90 miles of local creeks that will slow rushing water so it swells the banks and sinks into the ground. The district has an additional 300 acres of freestanding percolation ponds, which fill with water piped in from nearby creeks when they are high. Recharge really showed its value during the recent drought; groundwater provided 51 percent of the county's water in 2014, even though the state water shortage was acute.



BEST WATER STORAGE: Allowing floods in certain California areas would maximize the water that seeps down into underground aquifers for storage. The best sites (*green* and *yellow*) are flat and have permeable soil that drains quickly and will not become compact.

SOURCE: SOIL AGRICULTURAL GROUNDWATER BANKING INDEX, UNIVERSITY OF CALIFORNIA DIVISION OF AGRICULTURE AND NATURAL RESOURCES; COURTESY OF ANTHONY O'GEEN AND HTTPS://CASOILRESOURCE.LAWR.UCDAVIS.EDU/SAGBI/

GO WITH THE FLOW

AN OBVIOUS QUESTION ABOUT widespread groundwater recharge is, Where will the water come from? "Most people's [water-rights] permits are for planting and growing season," Marcus explains. "There's plenty of excess water in winter." A study published by Dahlke this past July confirms that there is enough to resupply Central Valley aquifers.

The challenge is to move the water, when it pours, to where it can be absorbed underground. In California, more water falls in the winter in the north, and more water is used in the summer in the south. Yet the big engineered canals and aqueducts that start up north and fill irrigation systems in the south are underused in winter when fewer growers need to irrigate. The infrastructure could send excess winter water to southern farm fields for recharge rather than allowing it to flow out to the ocean.

Another possibility is reverse banking. Comparatively water-rich areas such as farms around the Sacramento River would pump groundwater when it is plentiful during wet years to irrigate crops and send their surface water southward via the infrastructure to recharge the needy aquifers there, says Ellen Hanak, director of the PPIC Water Policy Center. The accounting would be tricky, though. Managers still need to work out compensation techniques before that practice would become widespread.

Capturing excess winter water is also difficult "because everything is saturated and every reservoir is full," Hanak says. But some stretches of land are already set up to function as flood-relief valves, and increasing their area could allow recharge right there or serve as short-term storage until pipes or other structures could move the water to refill storage sites farther away. To get a sense of what that might look like, I traveled in February to the Sacramento–San Joaquin Delta, where those two mighty northern and southern rivers meet, meander and ultimately empty into San Francisco Bay. For more than a century individual farmers remade this marsh-scape by pushing up earthen levees, creating farmland protected from river floods.

When I arrive, I meet Josh Viers, a watershed scientist at the University of California, Merced, at the Oneto-Denier restoration site in the Cosumnes River Preserve. Two experts join us from TNC, including Judah Grossman, director of this project. We walk atop an earthen levee, flanked on either side by floodwater three to six feet deep. Valley oaks, cottonwoods and bushes rise out of the water close to us. Beyond lie flooded fields that TNC is restoring to native habitat. This flood was augmented because engineers in 2014 removed 750 feet of levee to help the Cosumnes River fill this part of its floodplain when waters run high.

Last winter was the first real test of the removal. Hydrogeologist Graham Fogg of the U.C. Davis Center for Watershed Sciences set up instruments to measure the groundwater recharge. When the floodwater receded, Fogg's students calculated that the flooding had recharged groundwater three times more than typical from rain and irrigation. The area that flooded is relatively small, only about 285 acres, yet this past winter's storms resupplied more than 2,000 acre-feet of water. Upstream, the work has already inspired people to begin similar projects. And at a nearby site Viers is also studying how native fish are benefiting from this type of floodplain habitat.

FARMING WATER

BECAUSE MUCH OF THE CENTRAL VALLEY is now farmed, scientists are studying how to safely flood farm fields. A good agricultural recharge site has various qualities, including a fairly flat surface so water can infiltrate evenly; permeable soil that moves water underground quickly; and soil relatively free of salt, pesticides or nutrients that could taint groundwater. And before growers get onboard, they need assurance that water applied to fields at carefully orchestrated times will not harm their land or crops.

U.C. Davis's Dahlke is conducting test floods that measure plant and root health, water infiltration rates, and salt and nitrate levels. On an alfalfa field in northern California's Scott Valley, she applied water across three- to four-acre test patches at different frequencies: one to two days a week, three to four days a week, or continuously from February through April. Over the course of the winter's trials on the entire 15-acre field, she recharged about 135 acre-feet. "More than 90 percent of applied water went to deep percolation," she says. And the alfalfa yield was not affected. An unexpected side benefit: the flooding flushed out gophers, who "really like to eat alfalfa," Dahlke laughs.

She is testing other crops on working farms, including almonds, even though conventional wisdom says they are sensitive to water sitting on their roots. After deliberate flooding in winter and early spring the onset of blooms, as well as the timing of leaf out, was consistent with adjacent nonflooded groves. "This is already a good sign," Dahlke says.

Keeping nutrients and pesticides out of recharged groundwater is another challenge. That will require timing fertilizer applications away from flooding "so you're not creating a monster in the process," says Thomas Harter, another hydrologist at U.C.

Davis, who co-authored a seminal report to the state on groundwater pollution.

One grower has been way ahead of the scientists, inspired when he noticed that a neighboring vineyard, flooded for months after heavy rains in 1983, still reaped a good harvest. Don Cameron manages Terranova Ranch, a 7,000-acre farm southwest of Fresno in the San Joaquin Valley that grows 25 different conventional and organic crops, almost entirely with groundwater. In 2011 and again this past winter, the local Kings River Water Association allowed Cameron to take high water that its members were not using. He funneled it via canals to fallow fields and to those full of alfalfa, wine grapes, walnuts, almonds and pistachios. It worked: crops were unharmed, and sensors installed by an engineering firm showed that at least 70 percent of the water passed below plants' root zones, en route to the aquifer. State and federal grants are allowing Terranova Ranch to add canals and pumps so it can flood its entire acreage in the future.

Farmers wishing to follow Cameron's lead could face more difficulty in taking winter water. In most places, farmers will need a permit, and getting one is a lengthy process. Part of the delay is antiquated data. "Information about water rights is contained in 10 million paper files stored at the State Water Resources Control Board and scattered among 58 county courthouses around the state," says Michael Kiparsky, director of the Wheeler Water Institute at the University of California, Berkeley, School of Law. It is not an accident that water rights languish on paper in an epicenter of digital culture. Rights holders tend to think the less others know about their water usage, the better. Kiparsky and Richard Roos-Collins of the Water and Power Law Group in Berkeley, Calif., are now working with the state to develop a database that would make it easier for regional water boards to look up water rights for a given stream and to understand which water is already spoken for—or not—when considering new permits.

PAY DIRT

OTHER INNOVATORS ARE GREASING the wheels by paying farmers to participate in groundwater storage. On a sunny, clear day last September, I visited a submerged fallow field on Knaggs Ranch northwest of Sacramento with Matsumoto and Mark Reynolds, lead scientist for TNC's California migratory bird program. Water burbling from an irrigation pipe tapped into the nearby Sacramento River creates something of an "instant habitat: just add water" effect across 129 acres, attracting birds, insects and frogs. A flock of dowitchers swoops in for a landing. Fat, orange-brown dragonflies buzz by, and a dramatic V of sandhill cranes sweeps overhead.

Migratory water birds depend on flooded agricultural land for 60 percent of their needs. But because they are just passing through, the birds need the water for only a few weeks. The Knaggs Ranch flooding is part of a TNC program called BirdReturns that rents flyway habitat from farmers and floods them for two-week periods during the fall and spring migration seasons. "It's an Airbnb idea," Reynolds says.

TNC is expanding its program, now partnering with farmers over severely depleted aquifers. For example, a 206-acre flooding of a rice farm last fall, postharvest, helped Merced Irrigation District recharge an estimated 180 to 250 acre-feet of groundwater, using permits it already held for winter water. Over four years TNC conservatively estimates that BirdReturns has recharged about 20,000 acre-feet of water.

Along the coast, U.C. Santa Cruz hydrogeologist Andrew Fisher came up with another creative solution to pay farmers for recharge. Later in February, I drove to his pilot project in Pajaro Valley, south of Santa Cruz, taking my mom's advice by detouring around the area's washouts via Highway 129. The rolling hills and farmland here supply artichokes, berries and leafy greens around the world. But there is little surface water; growers rely almost exclusively on pumped groundwater. In the 1980s overpumping was already a big problem, so the state created the Pajaro Valley Water Management Agency and empowered managers to charge water users to pump groundwater. The money is used to build and manage infrastructure that improves water supply and quality and to meet environmental and legal rules.

Fisher's project diverts excess rainwater from fields and surrounding foothills into a four-acre recharge basin. Last winter his team recorded about 140 acre-feet of infiltration. The storage earns farmers credit against their future groundwater pumping charges, much as utilities credit customers with rooftop solar panels for surplus power that they send to the grid.

On Fisher's advice, the Pajaro Valley Water Management Agency credits growers 50 percent of the infiltration rate, a cautious figure to account for water that would have seeped down without their efforts and for infiltrated water that is "lost" underground to the wider hydrologic system. "Instead of arguing about who owns water, why don't we claim the win based on the hydrologic benefit?" Fisher asks. "It's everybody's water because it goes into the basin that everyone is pumping from. Everybody wins."

Because that collective spirit has been the exception in California's fractious water scene, people running these pilot projects expected resistance. But they were wrong. "There's way more interest than we can handle," Fisher says. With BirdReturns, initial hesitance gave way after word from early adopters got out in the community. After four years, Matsumoto says, the project has gotten twice as many bids as it can use.

These successful early projects show that groundwater recharge can have multiple benefits, and their success encourages others to follow. They also illustrate that if anything can change dysfunctional water culture, it is community empowerment. "Hydrology is as much about understanding people as it is about science," Harter says. "Communities are much more open if they can take ownership of the idea." Along with the pressures of SGMA to actually manage groundwater, these innovators are revealing that the culture of scarcity can evolve into something more holistic, where cities, farms and nature have enough. SA

MORE TO EXPLORE

Sustainable Groundwater Management: What We Can Learn from California's Central Valley Streams. The Nature Conservancy, February 2016. http://scienceforconservation.org/dl/TNCSGMWhatwecanlearn_2016.pdf

Availability of High-Magnitude Streamflow for Groundwater Banking in the Central Valley, California. Tiffany N. Kocis and Helen E. Dahlke in *Environmental Research Letters,* Vol. 0012, No. 8, Article No. 084009; August 2017. http://iopscience.iop.org/article/10.1088/1748-9326/aa7b1b/meta

Soil Agricultural Groundwater Banking Index: https://casoilresource.lawr.ucdavis.edu/sagbi/

FROM OUR ARCHIVES

Saving the Ogallala Aquifer. Jane Braxton Little; *Scientific American Earth 3.0,* March 2009.

scientificamerican.com/magazine/sa

VIEW INTO THE CAVERN housing the LHCb experiment, where protons collide to produce particles containing beauty quarks.

PARTICLE PHYSICS

The Large Hadron Collider beauty experiment has seen hints of new particles that may point the way toward a higher theory of physics

MEASURING *Beauty*

By Guy Wilkinson

IN BRIEF

The LHCb experiment at CERN's Large Hadron Collider is searching for undiscovered particles that may illuminate new truths about how nature operates at its tiniest scales.

Instead of aiming to produce these new particles directly, LHCb scientists are hoping to detect the influence of "virtual" particles that pop briefly in and out of existence and influence conventional matter.

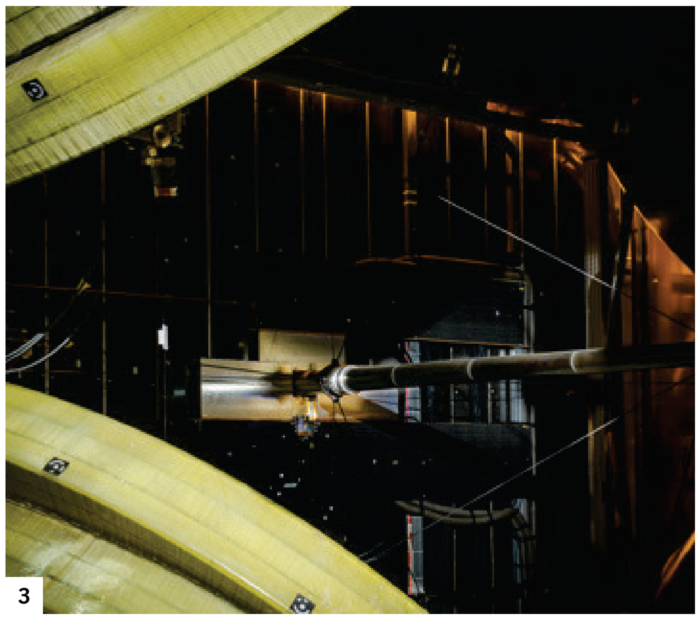
Already the experiment has shown hints of odd particle behavior that cannot easily be explained by current laws of physics. More research will determine if these are the first glimpses of new lands on the particle map.

Photographs by Alastair Philip Wiper

Guy Wilkinson is a particle physicist at the University of Oxford and a former spokesperson for the Large Hadron Collider beauty experiment at CERN.

1

IT IS UNUSUAL FOR TV NEWS to open with a story about physics, but it happened on July 4, 2012, when all around the world stations chose to devote prime time to breaking news from Geneva: a search of almost 50 years had ended with the discovery of the Higgs boson particle by the Large Hadron Collider (LHC) at the CERN physics laboratory. For experimentalists, the Higgs was the last and most important missing piece in the trophy cabinet of the Standard Model of particle physics—the theory describing all the known particles in the universe and the forces between them. Yet physicists believe there may be more elementary particles than those in the Standard Model, and a new and even more challenging hunt is on to find them.



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Like the quest for the Higgs, the race to discover hidden particles, thereby building a fuller picture of nature at its tiniest scales, is taking place at the LHC. The experiments that discovered the Higgs—ATLAS and CMS—will play an important role, but LHCb, a smaller and less well-known project operating at the same accelerator, brings guile and stealth to the chase. There is a real chance that this third experiment may be the first to bring home the prize.

LHCb follows a different game plan than most pursuits of new particles. Whereas ATLAS, CMS and many other efforts try to create undiscovered particles directly, the LHCb experiment on which I work uses so-called beauty hadrons to look for the signatures of unseen particles that we cannot directly produce

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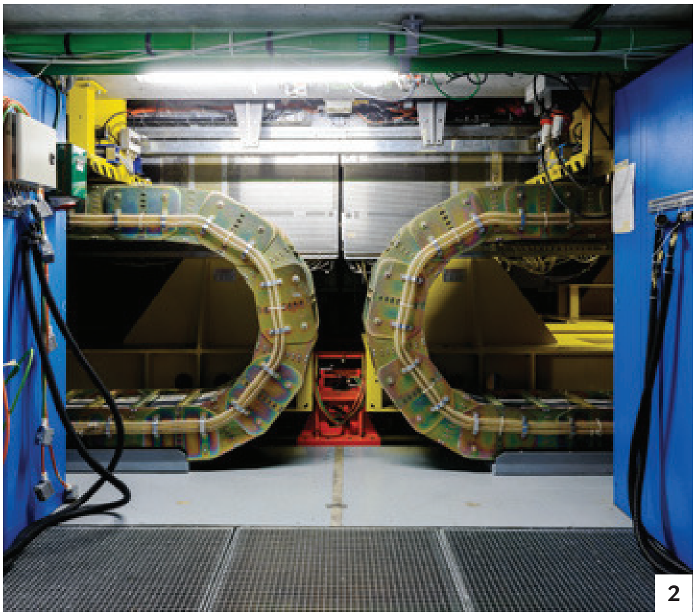

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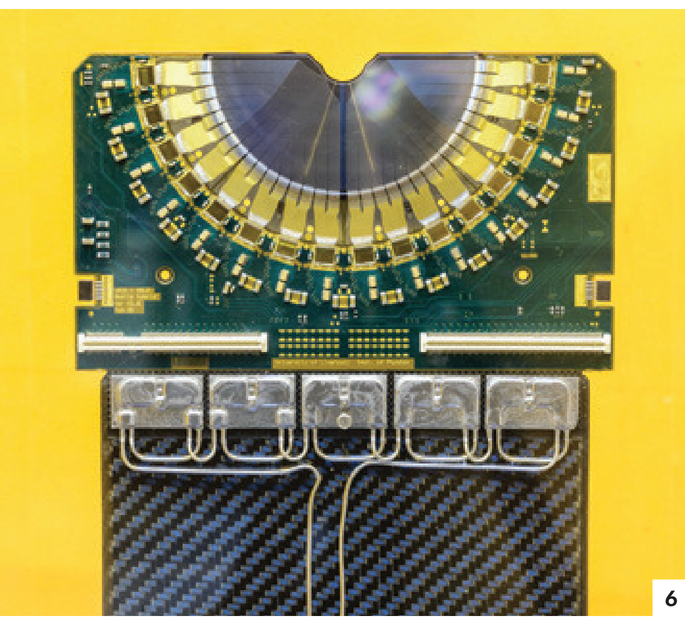

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LHCb, seen from the side (*1*) and underneath (*2*), studies collisions of protons that travel through a beam pipe (*3*) into the experiment. Inside the control room (*4*), physicists monitor operations. Computer processors (*5*) determine which reactions to record for analysis. The collisions occur inside the delicate Vertex Locator (VELO), which uses silicon sensors (*6*) to detect beauty particles.

but that affect reactions behind the scenes. LHCb (the "b" stands for "beauty") studies what happens when beauty hadrons are created in the Large Hadron Collider and then decay into other particles. Beauty hadrons make excellent test subjects because they decay in a huge variety of ways, and physicists have very precise predictions about how these reactions should proceed. Any deviation from those predictions is a clue that we might be seeing interference from unknown particles.

This type of search is complex and requires great precision, but it has the potential to uncover particle species that are impossible for ATLAS and CMS to access. Already it has turned up several intriguing hints of phenomena that threaten to defy the laws of physics as they are currently written. We may be witnessing the actions of particles or forces in nature that physicists have never before observed and possibly never even imagined. If so, our investigations at LHCb could reveal the workings of the cosmos on a more fundamental level than humans have ever glimpsed before.

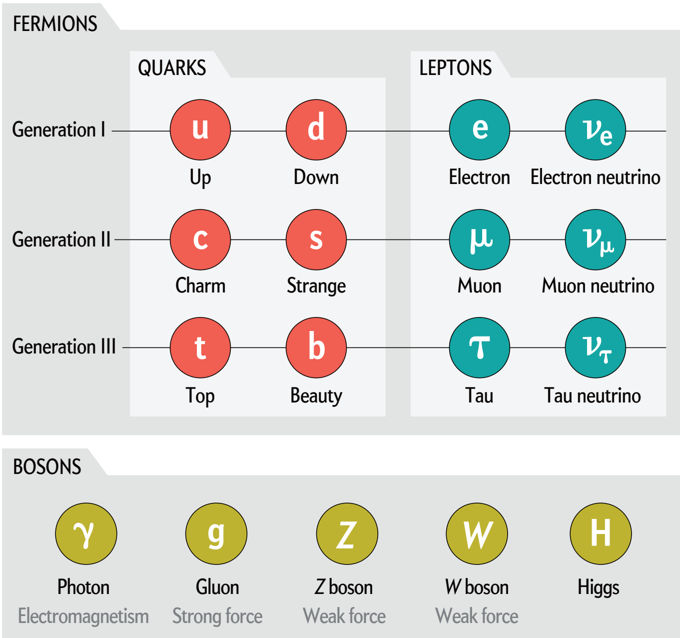
AN INCOMPLETE THEORY

THE STANDARD MODEL has been highly successful at describing the behavior of the elementary particles of nature and the forces that act on these particles. It divides the elementary particles into quarks and leptons. There are six quarks arranged in three groups, called generations: up and down, charm and strange, and beauty (also called bottom) and top. We never see these quarks in isolation; rather they cluster together in so-called hadrons—beauty hadrons, therefore, are particles containing beauty quarks. Likewise, there are three families of leptons: the electron and electron neutrino, the muon and muon neutrino, and the tau and tau neutrino. The up and down quark and the electron—all from the first generation—make up the atoms of everyday matter. The particles belonging to the other two generations tend to be more elusive; we must use particle accelerators to coax them into existence. The forces that act on these particles—excluding gravity, which is unimportant at the subatomic level—are electromagnetism, the weak force and the strong force. Each force is transferred by an additional particle: for example, the photon carries electromagnetism, and the *W* and *Z* bosons deliver the weak force. Alongside all of these, the Higgs boson sits alone, the manifestation of an underlying field that gives some particles mass.

And yet physicists know that the Standard Model must be wrong. "Wrong," though, is an extreme word; rather we prefer to say that the theory is incomplete. It succeeds very well in answering certain questions but has nothing to say about others. At the cosmic level, it cannot explain why the universe is overwhelmingly constituted of matter, whereas in the big bang, matter and antimatter must have been created in equal proportion. Nor can it tell us anything about the nature of dark matter, the extra mass in the universe that we cannot see but that we

The Standard Model

The known particles and forces in the universe make up the Standard Model of particle physics. It includes six kinds of quarks and six types of leptons, as well as five bosons, which transfer the forces of nature. But physicists believe there are more particles out there than those in the Standard Model, and they aim to find them through projects such as the Large Hadron Collider beauty experiment.



know must be there to drive the observed motion of the stars and galaxies. Indeed, the Standard Model does not include gravity, the dominant force on large scales, and all attempts to include it so far have failed.

And even in the world of the known subatomic particles, many puzzles remain. The Higgs boson happens to have a mass not much larger than the *W* and *Z* bosons, whereas the Standard Model suggests it should be about 10,000 trillion times heavier. There is no reason that we can discern for the three-generation arrangement of the matter particles. The generations appear to be copies of one another, except for the fact that there is a striking hierarchy of mass, from the up and down quarks, which "weigh" very little, to the top quark, which is almost as heavy as a gold nucleus. On these and many other questions, the model is silent. Hence, despite its long track record of success, the Standard Model must still be only an approximation, the visible facade of a higher theory that we hope will yield solutions to these puzzles. Our goal at LHCb, along with ATLAS, CMS and many other experiments around the world, is to discover elements of that higher theory in the form of particles that exist in nature but have not yet revealed themselves to us.

THE BEAUTY EXPERIMENT

THE LARGE HADRON COLLIDER, home to LHCb, is a 27-kilometer-long, ring-shaped accelerator in which two beams of high-energy protons circulate in opposite directions at close to the speed of light. Inside LHCb these beams collide up to 40 million times per second. The dense points of energy that are formed when the protons smash together and annihilate one another can condense into particles that are very different than the protons that collided—for example, particles containing beauty quarks. Even if they are very short-lived, these new particles spring into existence and then decay into products that LHCb can detect.

The LHCb experimental site sits approximately four kilometers from the main CERN lab, nestled against the perimeter fence of the Geneva Airport. The surface buildings are functional in design and mostly inherited from a previous experiment. A large, circular window, a sole concession to aesthetics, allows passengers looking out from planes on the nearby runway to easily spot the main hall. Inside one of these buildings, in a well-appointed control room, physicists sit day and night monitoring the status of the experiment, which is situated in a cavern 100 meters below.

Although modest in size compared with its bigger siblings around the LHC ring, the LHCb detector is still an imposing and impressive sight spanning around 20 meters in length and 10 meters in height. Its elongated design gives LHCb a very different appearance to the cylindrical geometries of ATLAS and CMS and allows it to record the signals of particles produced close to one wall of the cavern. This stretched geometry helps in the study of beauty hadrons, which are particles containing beauty quarks. Because of their relatively modest mass (around 5 GeV, or giga electron volts, which is only a little heavier than a helium nucleus), when beauty hadrons form at the LHC there is always plenty of surplus energy left over. This extra energy tends to throw the newly created beauty quarks forward from the collision point into the detector. Despite its unusual layout, LHCb has many of the same components as other experiments. These include a large magnet, tracking stations to reconstruct the trajectories of particles produced in the collisions and calorimeters to measure the particles' energies.

But several attributes are unique to LHCb and are designed specifically for beauty physics. For instance, a silicon-strip detector placed just eight millimeters from the LHC particle beams can reconstruct the position of a particle decay with great precision—a useful tool because beauty hadrons typically fly forward just a centimeter or so before decaying into a collection of lighter particles. LHCb also has a system of so-called RICH (*r*ing-*i*maging *Ch*erenkov) counters, which can determine the identities of the beauty hadron decay products based on the patterns of light many of them emit.

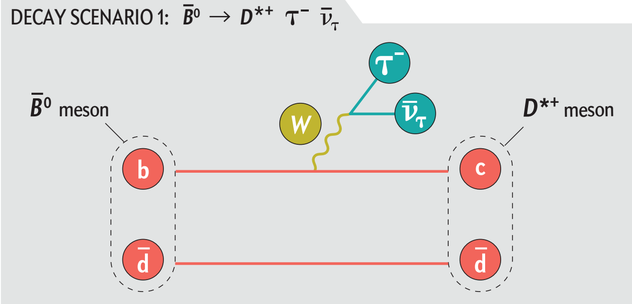
THE SEARCH FOR NEW PHYSICS

DURING THE LHC'S FIRST RUN, from 2010 to 2012, the accelerator produced almost a trillion beauty hadrons inside our experiment. These particles can decay in a huge number of ways, some of which are more interesting than others. We are looking for decays that may serve as signposts to "new physics"—behavior that the Standard Model cannot explain.

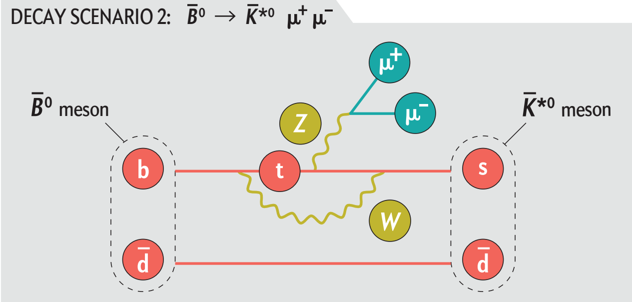
Theoretical physicists have many hypotheses for what this theory could be, but most ideas involve new particles that are somewhat heavier than those we know of. This heaviness is one excellent reason the LHC is so well equipped to seek new physics: the high energy of its collisions means that it can produce and detect rather massive particles, up to a few thousand GeV in equivalent mass (by way of comparison, the Higgs boson weighs around 125 GeV and the humble proton 0.9 GeV). The ATLAS and CMS experiments have been designed to search directly for such massive particles through the distinctive signatures their decays would create. Yet there is another, more cunning way to look for new physics. We can detect the presence of new particles through their "virtual" effects on the decay of Standard Model particles.

To understand the idea of virtual particles, we must turn to Feynman diagrams [*see boxes below*]. The renowned 20th-century American theoretician Richard Feynman invented these diagrams as a way to visualize and calculate the decays and interactions of subatomic particles. Here we will examine the Feynman diagrams of two possible decay paths of beauty hadrons (particles that unfortunately tend to be called by rather ungainly conglomerations of Greek letters and symbols).

DECAY SCENARIO 1: $\bar{B}^0 \rightarrow D^{*+}\ \tau^-\ \bar{\nu}_\tau$



DECAY SCENARIO 2: $\bar{B}^0 \rightarrow \bar{K}^{*0}\ \mu^+\ \mu^-$



In both examples, we start with a so-called $\bar{B}^0$ (pronounced "b zero bar") meson, a hadron composed of a beauty quark and an anti-down quark (antimatter particles are denoted with the suffix "bar"). In the diagrams, time runs from left to right. In the first case, we can see that our starting meson decays into a D^{*+} meson (made of a charm and an anti-down quark), a negatively charged tau lepton (τ^-) and an anti-tau neutrino ($\bar{\upsilon}_\tau$); hence, the process is designated $\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\upsilon}_\tau$. The other decay, $\bar{B}^0 \rightarrow \bar{K}^{*0}\mu^+\mu^-$, produces a $\bar{K}^{*0}$ meson (built of a strange quark and an anti-down quark), a muon and an anti-muon. The law of conservation of energy, as well as the equivalence of mass and energy as described in Albert Einstein's famous equation $E = mc^2$, requires that these final particles have a total mass that is less than that of the initial beauty meson. The difference in mass turns into the kinetic energy of the decay products.

Let us focus on what is happening at the heart of the diagrams, where the decay occurs. In the first case, we see a W boson, one of the particles that carries the weak force, appearing at the point where the beauty quark transforms into a charm quark. This W boson then decays into a tau and anti-tau neutrino. What is striking is that the W is around 16 times more massive than the initial $\bar{B}^0$ meson. Why does its appearance in the decay process not violate the rule of energy conservation? According to the mysterious accounting of quantum mechanics, such violation is actually allowed as long as it happens over a sufficiently short timescale! In this case, we say that the W boson is *virtual*. Now turning to the $\bar{B}^0 \rightarrow \bar{K}^{*0}\mu^+\mu^-$ decay, we see that the decay process is more complicated, involving a loop structure and three internal points of decay. But here, in addition to a W, several other virtual particles also participate: a virtual top quark (t) and a virtual Z boson, both much more massive than the initial meson. Virtual particles may sound fanciful, but the rules of quantum mechanics allow us to draw such diagrams, and these diagrams have proved correct time and time again at predicting the probability that these decays will occur. Indeed, it was by such methods that physicists first predicted the existence of the charm quark and the top quark and made the first estimates of their mass.

The diagrams we have discussed represent only two possibilities for how those particular decays can proceed. We can imagine others, some with particles we have never seen tracing the path between the internal decay points or even finding different ways to link the initial and final state particles. And what is amazing is that all these possibilities matter. The rules of quantum mechanics tell us that what happens in nature is driven by the net contribution of *all* the valid diagrams we can draw, although the simplest and most obvious have the greatest weight. Hence, all these possible decay paths should play a role, and we must account for them in the calculations we make predicting the rate of the decay, the trajectories of the products and other particulars. In other words, even when a particle decays in a normal process involving only conventional members of the Standard Model, it feels the effects of every possible particle out there. Therefore, if a measurement of a decay disagrees with our calculations based only on the Standard Model ingredients, we know that something else must be at work.

This fact is the guiding principle behind LHCb's strategy of indirect searches for new particles and new physics. Because these new particles would be virtual participants in every decay that we measure, the mass of the particles we can detect is not limited by the energy capacity of our accelerator. In principle, if we studied the right decay processes with enough precision, we could observe the effects of particles even heavier than those that can be created and detected within ATLAS and CMS.

CRACKS IN THE STANDARD MODEL

MY COLLEAGUES at LHCb and I have already seen hints that all might not be well with the Standard Model description of beauty hadron decays. The clues come from a variety of measurements, but they all share some common signatures. It is important to emphasize that with more data and a better understanding of the theory, we might find that the Standard Model *does* in fact agree with our findings. Even if this turns out to be the case, though, these early hints illustrate how cracks in the Standard Model edifice may develop and widen.

Exhibit A concerns the $\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\upsilon}_\tau$ decay that we discussed earlier and the possible violation of a rule called lepton universality. In the Standard Model, the *W* boson has the same probability of decaying into a tau lepton and its antineutrino as it has of decaying into the members of the muon and electron families (after we account for the different masses of the tau, muon and electron). In other words, the rules of *W* decay should be universal for all leptons. But at LHCb, after we counted the decays in each category, subtracted any processes that might fake the signals of these decays and corrected for the fact that not all decays are observed, we found that beauty hadrons appear to be decaying into taus rather more often than the Standard Model says they should.

Our results are not yet conclusive; the discrepancy we found has a strength of "two sigma," where "sigma" denotes uncertainty. Because of statistical fluctuations, one-sigma effects are not infrequent in experimental science, and physicists really only sit up and take notice when three-sigma deviations occur. Five sigma is the commonly adopted benchmark for announcing the discovery of a new particle or declaring that a prediction is wrong. Hence our two-sigma effect is not so remarkable—unless you consider what physicists are finding at other experiments.

Researchers have also looked for violations of lepton universality at BaBar and Belle, two beauty physics experiments in California and Japan, respectively, that collected data in the first decade of the millennium. The results from these experiments consistently favor taus in the same decays we measured as well as similar processes. Furthermore, at LHCb we made a new measurement of lepton universality in these decays earlier this year using a different technique, and once again we found that taus come in slightly above expectations. Altogether this ensemble of measurements gives a result that is separated by four sigma from conventional predictions. This is one of the most striking discrepancies in all of particle physics and constitutes a real problem for the Standard Model.

What could be going on? Theorists have some ideas. A new type of charged Higgs particle, for example, could be involved. Higgs bosons do not respect lepton universality, and they decay preferentially into particles of higher mass, hence favoring the production of tau particles. Yet the exact size and pattern of the discrepancies we see do not fit neatly into the simplest theories that predict such additional Higgs species. Another, even more exotic explanation would be a leptoquark, a hypothetical particle that can allow quarks and leptons to interact. Finally, of course, the results we are seeing could be an experimental effect caused by a misunderstood signal masquerading as the decays we are looking for. To sort through these possibilities, we need new, more precise measurements. We expect several in the coming years, from LHCb as well as from a new-generation Belle II experiment that will soon begin operation.

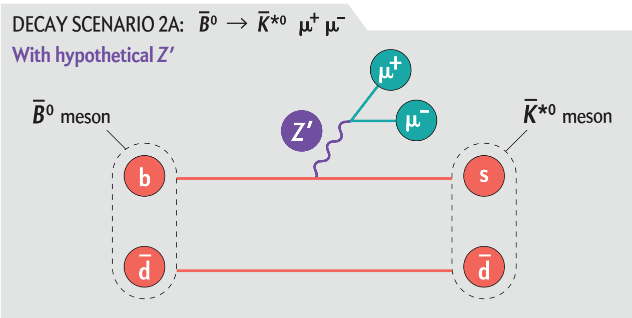
Our next example showing hints of new physics comes from the decay $\bar{B}^0 \rightarrow \bar{K}^{*0}\mu^+\mu^-$, which we discussed earlier. Decay processes of this kind are an excellent place to search for signs of new physics for two reasons. First, the "loopy" structure at the heart of the Feynman diagram immediately tells us that elaborate gymnastics are necessary for the decay to occur in the Standard Model; however, new physics particles might have an easier time bringing the process about, and hence their presence may be more evident. Second, this decay has many properties that we can measure: we can note the rate at which the process occurs, as well as the angles and energies of the decay products and other types of information. We can then build these properties into various "observables"—quantities that we can compare directly with Standard Model predictions (but that, unfortunately, do not always equate to properties that are easy to picture).

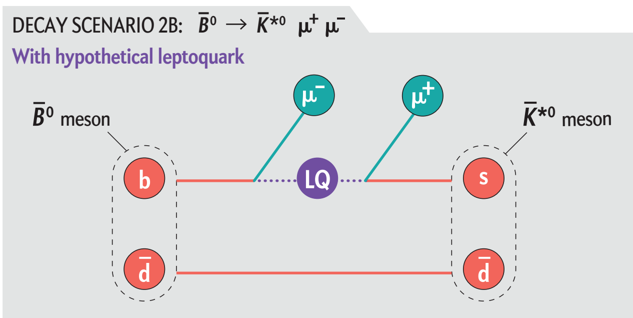
In many ways, $\bar{B}^0 \rightarrow \bar{K}^{*0}\mu^+\mu^-$ is the poster child of beauty physics, with its virtues evident by the huge body of theory papers that were written about it well before the LHC even turned on. The only thing that this decay lacks is a decent nomenclature, as the names used to label the different observables are rather underwhelming, such as "P_5'" (pronounced "p5 prime"), which is nonetheless the hero of our story.

We made a first analysis of P_5' with some of the early LHCb data, measuring this observable for different categories of the decay characterized by the directions and energies of the pair of muons produced in the end. For certain configurations we found a significant discrepancy between predictions and our observations. Based on these first results, the physics community eagerly awaited the updated analysis we unveiled a couple of years later using the complete run-one data set. Would the discrepancy persist, or would it prove to be a statistical fluke? It remained. The size of the effect is now around 3.5 sigma, which is not large enough to justify ordering champagne but certainly sufficient to be taken seriously. And we find further encouragement from the fact that measurements of other observables in similar decay processes also exhibit intriguing discrepancies. Altogether the total disagreement with the Standard Model rises to as much as 4.5 sigma—a problem for the theory that we cannot ignore.

Theorists have come up with a whole swathe of potential new physics explanations for this effect. The leptoquark, already invoked in the $\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\upsilon}_\tau$ decay, is a possibility. Another is a Z' ("z prime") particle, which would be an exotic, heavier cousin of the well-known *Z* boson but one that decays into quarks and leptons in its own distinctive manner. Such speculation, however, must always respect the constraints that already exist from other measurements. For example, the mass and behavior of these hypothetical new particles must be such that it makes sense that they have not yet shown up in direct searches at ATLAS and CMS.

Theorists are nothing if not ingenious, and there are plenty of plausible scenarios that satisfy these criteria. But we must be cautious. Some physicists worry that the Standard Model predictions for these observables are not fully under control, meaning that the real discrepancy between measurement and theory may be much smaller than imagined. In particular, the repercussions of difficult-to-calculate but mundane effects associated with the strong force may be larger than first thought. The good news is that there are ways to test these ideas through additional measurements. These tests require detailed analysis and more data, but these data are arriving all the time.





The final puzzle LHCb has turned up involves a twin set of measurements that has something in common with both our previous examples but that may turn out to be the most interesting of the three. Here we investigated a ratio, dubbed R_{K^*} ("r k star"), that compares the rate of the process that we studied for $P_5{}'$, where beauty hadrons decay into a $\bar{K}^{*0}$ meson and a muon-antimuon pair, to the rate of a similar decay that produces an electron and antielectron in place of the muon pair. We also examined a second ratio, R_K, comparing decays where the $\bar{K}^{*0}$ meson has been replaced with another kind of strange hadron called simply a K meson. Again, we are trying to test lepton universality, but in this case, between the first two generations of leptons—the electrons and muons.

Within the Standard Model the prediction is trivial—the two decays in each ratio should occur at the same rate, giving the two ratios R_K and R_{K^*} expected values of very nearly one. Again we expected that lepton universality would hold. And the measurements, though far from straightforward, have fewer experimental challenges than in the previously discussed lepton universality analyses and therefore constitute an extremely clean and crisp test of the Standard Model.

We performed the R_K analysis first and found that it came in low, with a value of 0.75, with a precision that put it 2.6 sigma away from predictions. This deviation was sufficiently intriguing that we were all very eager to know the value for R_{K^*}, which we finally published earlier this year. The wait was well worthwhile because, for the same conditions where we examined R_K, R_{K^*} showed remarkably similar behavior. We measured a ratio of 0.69, lying 2.5 sigma below the Standard Model prediction. Although it is quite possible that these undershoots are statistical fluctuations, the fact that we found them in two different measurements, as well as the pristine nature of the tests, means that this anomaly is getting a great deal of attention.

If the R_K and R_{K^*} measurements are a true representation of reality, they indicate that something in nature favors decays that produce electrons over those that create muons, with leptoquarks or a Z' boson again being likely culprits. It seems as if muons, in fact, are being underproduced, whereas electrons are sticking more closely to the Standard Model script. If so, whatever mechanism is responsible would not only explain the R_K and R_{K^*} oddities but would also neatly account for the muon-based $P_5{}'$ measurement. For good measure, some more ambitious theorists have even proposed solutions that would also make sense of the $\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\upsilon}_\tau$ puzzle, but conceiving of a particle with the necessary characteristics to explain all three measurements looks to be a tall order.

What is clear is that we will know more very soon. We are analyzing new data from the LHC's second run now, and our knowledge of the values of R_K and R_{K^*} will rapidly improve. Either the significance of the discrepancies will grow, and then these anomalies will become the biggest story in physics, or they will diminish, and the caravan will move on.

GALILEO'S MOTTO

THE RESULTS WE HAVE discussed are only the most prominent examples of a host of interesting measurements that have recently emerged in beauty physics. They rightly excite many in the particle physics community, but the older and wiser scientists among us have seen such effects come and go in previous experiments, so we are content to wait and see.

What would it mean if one or more of these anomalies move from the category of "intriguing hint" to "clear contradiction of the Standard Model"? For sure, it would be the most important development in particle physics for many decades, giving us a window onto the landscape that lies beyond our current understanding of the laws that govern the universe. At that point we would need to discover exactly what is responsible for this breakdown in the Standard Model. Depending on the nature of the new physics particle—whether it be an exotic Higgs, a leptoquark, a Z' or something else entirely—its effects should appear in other beauty hadron decays, giving us more clues. Moreover, unless it is very heavy, this new particle could also appear directly in collisions at the LHC's ATLAS or CMS or at some future accelerator of even higher energy.

Regardless of how the future unfolds, LHCb's exquisite sensitivity and the excellent prospects for significant improvement in the coming years are undeniable. We do not know if the road to new physics through indirect searches will be short or long, but most of us feel sure that we are heading in the right direction. After all, it was Galileo who is said to have instructed us to "measure what is measurable, and make measurable what is not so." We could have no finer motto for LHCb. SA

MORE TO EXPLORE

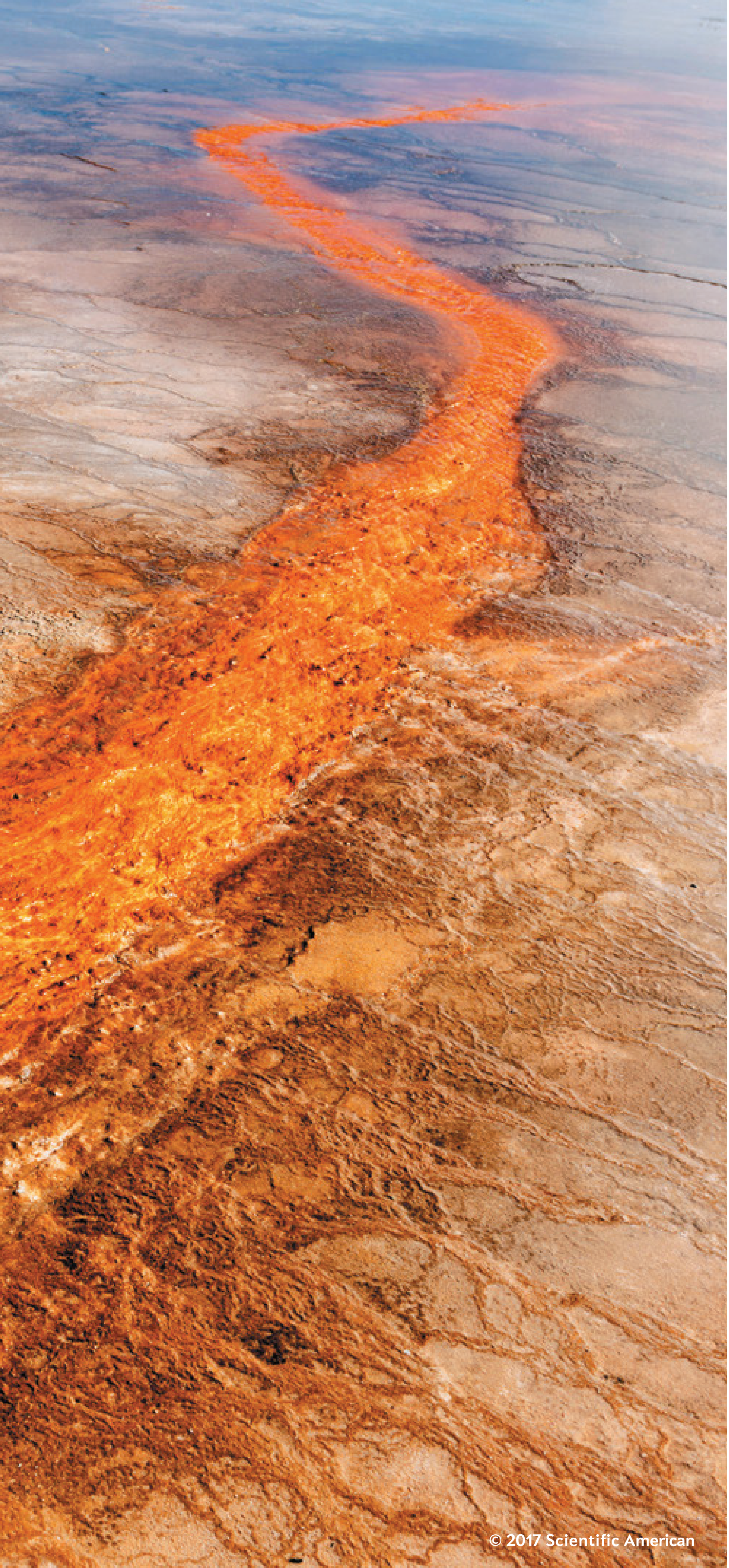
A Challenge to Lepton Universality in *B*-meson Decays. Gregory Ciezarek et al. in *Nature*, Vol. 546, pages 227–233; June 8, 2017.
Flavour-Changing Neutral Currents Making and Breaking the Standard Model. F. Archilli et al. in *Nature*, Vol. 546, pages 221–226; June 8, 2017.
Large Hadron Collider beauty experiment (LHCb): **http://lhcb-public.web.cern.ch/lhcb-public**

FROM OUR ARCHIVES

The Dawn of Physics beyond the Standard Model. Gordon Kane; June 2003.

scientificamerican.com/magazine/sa

BACTERIAL RIVER: At Grand Prismatic Spring in Yellowstone National Park, bacteria and algae band together to form a giant, orange biofilm.

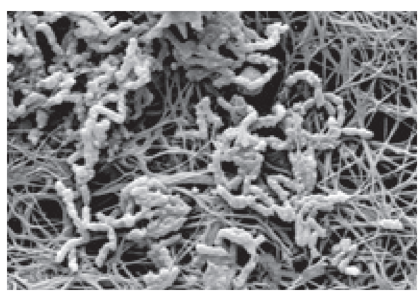


BIOCHEMISTRY

Biofilms—3-D mats of bacteria—kill as many people as cancer does and fight off antibiotics. Now scientists are turning biofilms' own weapons against them

By Karin Sauer

THE WAR ON SLIME



MICRO MENACE: The insides of a medical catheter are covered with a bacterial biofilm (*micrograph*) that can cause blood infections.

Karin Sauer is a biology professor at Binghamton University, State University of New York, and associate director of the Binghamton Biofilm Research Center, where she researches the mechanisms underlying biofilm development, dispersion and antimicrobial resistance.

I love Yellowstone National Park.

I have visited countries as far east as Japan, followed the footsteps of Romans, looked up at the Leaning Tower of Pisa, experienced volcanoes from afar and close up, and touched glaciers. Yet I return to Yellowstone again and again, gazing at waterfalls and lakes but especially at the vivid rainbow colors of many of the park's hot springs, geysers, mud pots and fumaroles.

These colors draw me in. They are produced by millions and millions of tightly packed bacterial cells enmeshed in a slimy matrix. Although individual bacteria are not visible to the naked eye, in this slime they form easily seen communities referred to as microbial mats, or "biofilms." Through a microscope these films show remarkable three-dimensional structure, with microbes glued onto one another to form many levels of filaments, winding pathways and features resembling tiny towers. To me, they look like cities of slime, a pulsing metropolis with blocks and skyscrapers and streets that are busier than major avenues in Tokyo or New York. And you've seen biofilms, too: they form the thick and slimy buildup in your drains and the stubborn rings around your bathtub.

In medicine, biofilms are not a nuisance or pretty, however. They are a dire threat to our health. When bacteria succeed in forming a biofilm within people, they resist antibiotics and can be the culprits in chronic infections of surgical sites, lungs and urinary tracts. Biofilms can colonize medical devices and implants such as catheters, prosthetic joints and heart valves. Overall, 65 percent of hospital-acquired infections are caused by bacteria growing as biofilms. There are 1.7 million of these infections annually in U.S. hospitals alone, and 99,000 associated deaths, so that is a tremendous amount of harm. Biofilms are thought to claim as many lives as cancer every year—a grim statistic indeed.

The problem is that our strategies to combat bacterial infections are geared toward individual bacteria, not biofilms. Biofilms not only have an extreme capacity for evading our host defenses and immune responses and thus fail to respond to vaccines, but often they turn out to be untreatable with antibiotics. This extraordinary resilience is not linked to bacteria having acquired drug resistance or becoming the "superbugs" that we hear so much about these days. The 3-D matrix is what makes biofilms so hardy. Within it, bacteria communicate and exchange information that lets them organize their architectural features and support and protect one another by manufacturing proteins and other substances needed for survival.

My colleagues and I can now break into the matrix and listen to the information signals that bacteria pass back and forth. Sometimes we can even take the signals over and use them against the microbes. Our attempts are much like hacking the system of a city. We want to put in a red light where there was not one before or redirect traffic. In our case, we are beginning to be able to tell biofilms to leave their protective matrix, rendering them vulnerable to drugs. We are building on early clues that bacteria within biofilms become fundamentally different from single cells. In 1998 researchers George A. O'Toole and Roberto Kolter demonstrated that biofilm formation by the soil bacterium

IN BRIEF

Biofilms form when groups of bacteria encase themselves in a slime matrix that blocks antibiotics and toxins.

Biologists have figured out some chemical cues microbes use to signal one another to disperse from films.

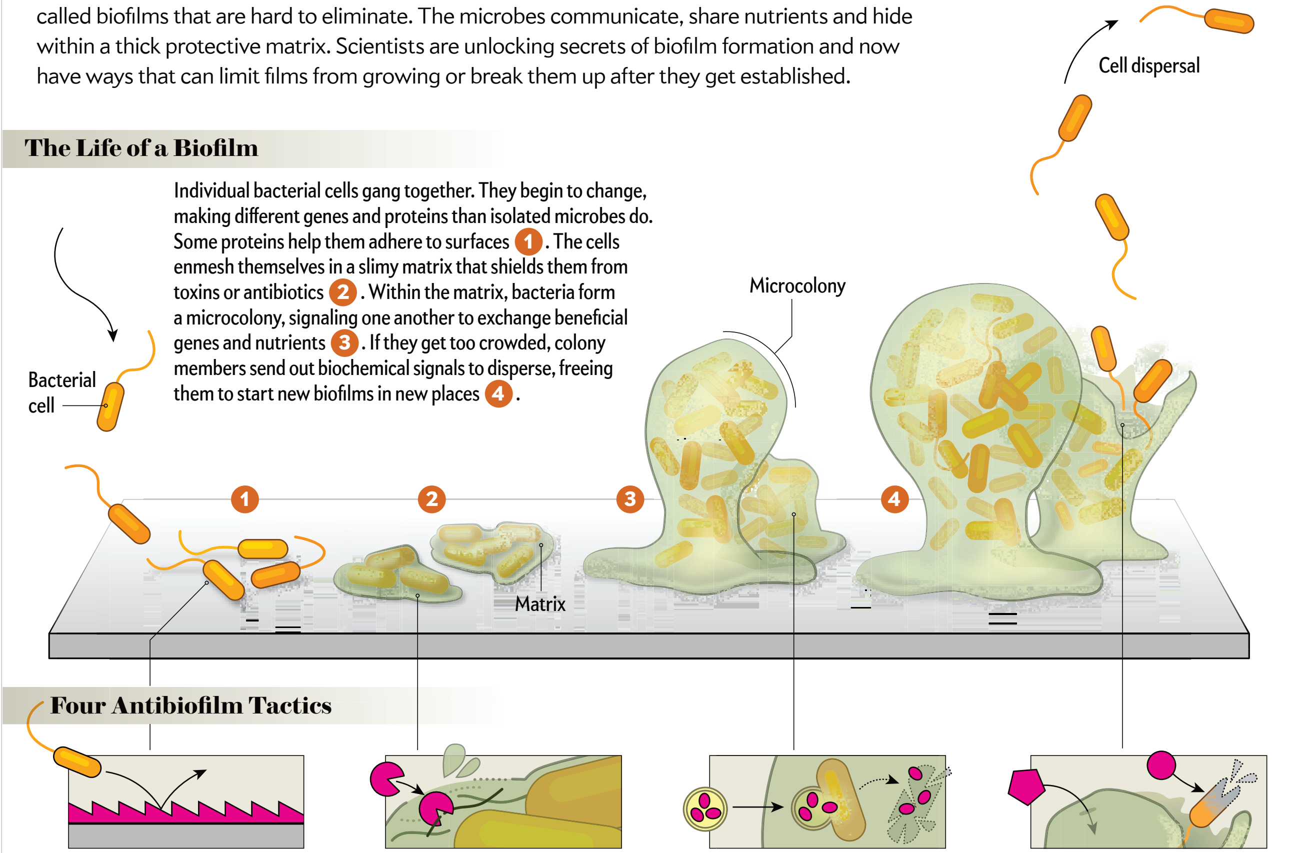
Dispersion leaves bacteria vulnerable to antimicrobial treatments and can be combined with other tactics.

New nanomaterials can now be engineered to retard biofilm attachment in the first place.

PRECEDING PAGES: GETTY IMAGES

Making—and Destroying—Biofilms

Bacteria are not loners. Most thrive in large groups: complex, mutually supportive communities called biofilms that are hard to eliminate. The microbes communicate, share nutrients and hide within a thick protective matrix. Scientists are unlocking secrets of biofilm formation and now have ways that can limit films from growing or break them up after they get established.



The Life of a Biofilm

Individual bacterial cells gang together. They begin to change, making different genes and proteins than isolated microbes do. Some proteins help them adhere to surfaces (1). The cells enmesh themselves in a slimy matrix that shields them from toxins or antibiotics (2). Within the matrix, bacteria form a microcolony, signaling one another to exchange beneficial genes and nutrients (3). If they get too crowded, colony members send out biochemical signals to disperse, freeing them to start new biofilms in new places (4).

Four Antibiofilm Tactics

A New materials make it harder for biofilms to grab onto surfaces. These materials are made deliberately rough at the nanometer scale, with structures that interfere with proteins that bacteria use for attachment.

B Weakening the matrix can cause structural collapse of the biofilm. The slime contains DNA molecules, which can be broken apart by an enzyme called DNAse I. It is being tested on biofilms that cause ear infections.

C Hollow spheres called liposomes, ferrying antimicrobial compounds, can sink into the matrix. They meld with bacteria, releasing their toxic cargo. Bacteria-infecting viruses can also be inserted into the matrix.

D Biofilm bacteria use a specific fatty acid to signal one another that it is time to leave. In the open, microbes are vulnerable, so scientists are using the acid to trick bacteria into departing. The gas nitric oxide can be used as a similar signal.

Pseudomonas fluorescens required the synthesis of new proteins as well as the presence of 24 genes. Most of the genes were of unknown function, although some encoded proteins used for surface attachment, such as adhesins. The mystery genes suggested that becoming an attached cell meant taking on a novel bacterial physiology. Then, in 2002, my colleagues and I demonstrated that bacteria not only change on surface contact but keep transforming and adapting as the biofilm develops from just a few attached cells into a community, producing different sets of proteins at each stage. Further work showed that the proteins enable the transition from one biofilm stage to the next in a set sequence.

These findings suggested that biofilms, like cities, are built from the ground up, with the construction following a master plan, one building phase and one city block at a time. In the laboratory, by adding chemicals that inhibit or enhance some of these proteins, we can stop biofilms at a particular developmental stage or even remodel them, making them revert to earlier stages. This approach can be added to other tactics against the films, such as adding nanostructured coating to surfaces that prevent bacteria from holding on.

AN UNHEALTHY ATTACHMENT

PREVENTING BACTERIAL ATTACHMENT in the first place is a good place to start. Much of this research has focused on the development of surface materials or coatings capable of killing bacteria on contact. That can be accomplished using surface coatings or impregnated surfaces that enable local delivery of antibacterial agents at high concentrations. Several such surfaces are already commonplace in hospitals and include antibiotic-impregnated sutures and bone cement containing antibiotic-impregnated beads, as well as catheters, wound dressings, and endotracheal tubes coated with colloidal silver or silver nanoparticles. The silver

Illustration by Jen Christiansen

ions kill bacteria on contact. The killing mechanism is not fully understood, but we do know that silver ions cause oxidative damage (where oxygen atoms pull electrons away from a microorganism's essential biomolecules), leading to bacterial cell death. In addition to silver, metal oxide and metal salts—iron, mercury, tellurium, zinc, titanium—are being tested for clinical purposes.

Surface coatings and impregnated surfaces, however, have an Achilles' heel because the antimicrobial substance in the coatings eventually run out. Combined with the concerns of overuse of drugs and compounds that are aimed at killing bacteria (including silver) and the consequent emergence of bacterial resistance, this has spawned the development of new surface materials that control attachment in more mechanical ways. The surfaces are inspired by nature, emulating the texture of shark skin, or self-cleaning textures found in lotus leaves, or the chemical functions used by mussels to repel bacteria. Bioinspired surfaces do not necessarily prevent bacteria from attaching but instead interfere with the proteins they use as attachment platforms. This process works by changing, at a microscopic level, surface roughness. That can be done by adding nanostructures such as brushes, crystals and tubules made of polymers that are attracted to water molecules, such as polyethylene glycol (PEG, inspired by mussels), and compounds known as zwitterionic polymers that were inspired by the antibiofouling properties of blood cells.

TOGETHERNESS: *Bacillus* bacteria (*oblong shapes in micrograph*) cover themselves in a protective matrix.

DENNIS KUNKEL *Science Source*

The nanostructures can be arranged at varying distances to reduce bacterial attachment to different degrees. Some of these bioinspired surfaces have now been widely used in clinics. Others are still at the proof-of-concept stage, with hurdles such as manufacturing limitation and toxicity issues to be overcome. Eventually randomized clinical trials will determine which of these new surfaces will make it to the clinical setting.

ATTACK THE MATRIX

DESPITE THE PROMISE of antibiofilm surfaces, very different strategies are needed to treat films that overcome such attachment barriers or that form on medical implants, making them both dangerous and hard to treat. In such cases, the slimy matrix surrounding biofilms becomes the target. This matrix, composed of long strands of sugar molecules called polysaccharides, proteins and DNA, helps the sheets of microbes in several ways. For one, the matrix functions as a protective layer. It blocks or restricts some antibiotics or immune system markers known as antibodies from reaching bacteria within the film. In addition, the matrix serves as a structural framework that glues the community together and to the surface. Thus, removal of this framework can result in loss of structural integrity and subsequent collapse, as the large bacterial gang breaks up into smaller cell clusters or individual cells. When that happens, the liberated bacterial cells become vulnerable once again to drugs and the immune system.

Matrix degradation has been accomplished by enzymes, proteins that accelerate chemical reactions. Unfortunately, the composition of the matrix, more specifically the type of proteins and polysaccharides present in the matrix, varies greatly among bacteria, with each type requiring a specific degradative enzyme. Therefore, treatments aimed at the degradation of proteins and polysaccharides need to be tailored to the type of bacterium that forms the film.

In contrast, the DNA present in the matrix may be a more straightforward target. It appears to be universal and susceptible to degradation by one enzyme alone: DNAse I. Several clinical trials are focusing on the use of this substance; it is being evaluated for the treatment of chronic middle ear (otitis media) and other biofilm infections in combination with antibiotics. DNAse I is already used in the treatment of cystic fibrosis patients with early lung disease, with treatment coinciding with significantly improved lung function. (In this case, however, the enzyme seems to be reducing the stickiness of the sputum, thus enhancing lung clearance and antibiotic efficacy rather than inducing a collapse of the biofilms.)

SOUND THE RETREAT

A STRATEGY OF A DIFFERENT nature has been gleaned from watching the way in which biofilms develop. After bacteria form these films, they can disassemble them via a process called dispersion. Dispersion occurs when resources within the biofilm, such as nutrients, become exhausted, or when biofilms become too overcrowded, or when the outside environment becomes unstable. Breaking up can help biofilm members survive and spawn new communities at other locations.

Single cells leaving the biofilm are, however, exactly the kinds of unprotected bacteria we are good at treating with medicine. So how can we redirect film-forming bacteria to switch their lifestyle and escape from the biofilm? Researchers have identified several triggers capable of inducing the switch. For one, bacteria seem to have their own way of telling members in the biofilm community to disperse. Research on *Pseudomonas aeruginosa,* a model bacterium for biofilm formation and the cause of a large number of hospital-acquired and chronic infections, has shown that this bacterium produces a small molecule, a fatty acid named *cis*-2-decenoic acid (*cis*-DA), that enables this bacterium to signal to its community members that it is time to leave. Other experiments have shown that *cis*-DA can signal biofilms formed by other bacteria—not *P. aeruginosa*—to break up. Overall, *cis*-DA has been shown to induce biofilm dispersion by at least five other bacterial species and yeast. There is also evidence that other bacteria produce different versions of this fatty acid, which means that biofilm bacteria may use particular "dialects" to tell members to disperse. Though still at the lab stage of testing, using such communication molecules in combination with antibiotics may very likely represent a future treatment strategy.

Breakup triggers based on changing environmental conditions are also being discovered. These triggers—more heavy metals, less oxygen and others—are quite diverse. But they all induce dispersion by lowering the level of a universal intracellular signaling molecule named cyclic di-GMP. Levels of cyclic di-GMP determine the stickiness of bacteria to surfaces, with high levels being linked to surface-associated biofilm growth and matrix production and low levels being linked to bacteria growing as single cells. Although changes to cyclic di-GMP levels in response to these triggers have been linked with 80 percent or more of the biofilm biomass being removed, not all triggers are suitable for use in medical settings.

One viable candidate to emerge is the colorless gas nitric oxide. Our own immune system makes use of nitric oxide to fend off bacterial invaders, and it is used medically to improve oxygenation in patients who have various forms of pulmonary hypertension (for example, chronic obstructive pulmonary disease). Lab studies have shown that nitric oxide mediates biofilm dispersal across a broad range of bacteria. Nitric oxide alone reduces biofilms on average by 63 percent. When combined with antimicrobial compounds such as colistin, the oxide was able to almost completely remove biofilms in test-tube experiments.

Still, despite the promising results, nitric oxide poses some clinical challenges. It can be toxic if it spreads to different areas of the body, so delivery and restriction to a specific site of infection are important—and hard to do with a gas. To better address some of the concerns, several formulations and devices have been developed. One example is cephalosporin-3′-diazeniumdiolates. This combination drug is composed of an antibiotic (cephalosporin) and a nitric oxide–producing substance that activates only on contact with bacterial cells that harbor an enzyme called β-lactamase. Bacteria resistant to antibiotics such as penicillin and ampicillin typically have this enzyme.

DETECT AND INFECT

ANOTHER STRATEGY to combat biofilms is to cause a lethal infection of their bacterial constituents. Like people, bacteria are susceptible to viruses, which in the case of these microbes are referred to as phages. Yet while people are not affected by phages, bacteria will be either permanently infected or killed. Since early studies in 1996 examining the interaction of phages with biofilms, research has aimed at identifying phages capable of killing bacteria within a biofilm. Moreover, phages that enter but do not kill bacterial cells can still be used as cargo trucks to deliver an antibiotic or a matrix-degrading agent (such as DNAse I) to each and every bacterium within the biofilm. Phage therapy is currently being used outside the U.S. in the treatment of biofilm-derived lung infections by cystic fibrosis patients.

But the therapy, like other tactics, comes with its own set of problems. Because phages infect and kill bacteria with high specificity, a particular phage infects only a specific type of bacterium, meaning they cannot be used as broad-spectrum killers. And bacteria can become resistant to phage attack, just like they develop resistance to antibiotics.

To overcome potential resistance, researchers have developed liposomes, or lipid-enclosed vesicles, as alternative cargo carriers. Referred to as nanoparticles because of their small size, the idea behind these mini transporters is to deliver compounds that kill biofilm cells or destabilize biofilms such as antibiotics, antibacterial compounds or matrix-degrading enzymes directly to where they are needed, into the biofilm or to the bacteria themselves. The targeting mechanism is based on lipids in the liposomes that mimic the lipids on bacterial cell membranes. The similarity allows them to diffuse into the matrix. Here lies the beauty of the system. The matching lipids enable liposomes to fuse with a bacterium and, consequently, enable the transport system to directly spill its cargo into the microbe in a manner similar to an injection. An advantage of this strategy is the targeted approach because antibacterial and antibiofilm compounds are delivered only to the biofilm and nowhere else. Liposomes are already a very widely used antimicrobial drug-delivery system.

WINNING COMBINATION

IN ADDITION TO THE TACTICS I have described, other research efforts, some at early stages of development, some at the clinical stage, are aimed at preventing and controlling biofilms. The approaches presented here are some of the most promising, but there are many more strategies that are being tested worldwide, which indicates the importance of biofilm control as well as how difficult it is to truly get a handle on slime. One overarching challenge is that all biofilms are not the same. Each bacterial species makes and escapes from biofilms in slightly different ways, using their own matrix variations or communication molecules, producing different proteins and more. But we are cataloguing those differences, and each bit of knowledge brings us closer to a treatment that can help people. In the end, we will probably need many strategies, employed in combination, to take a wrecking ball to the bacterial cities that threaten our lives. SA

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FROM OUR ARCHIVES

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scientificamerican.com/magazine/sa

A new, epic voyage through all known scales of reality charts the outer limits of existence, from the edge of the observable universe to the subatomic realm

By Caleb Scharf

Illustrations by Ron Miller

COSMOLOGY

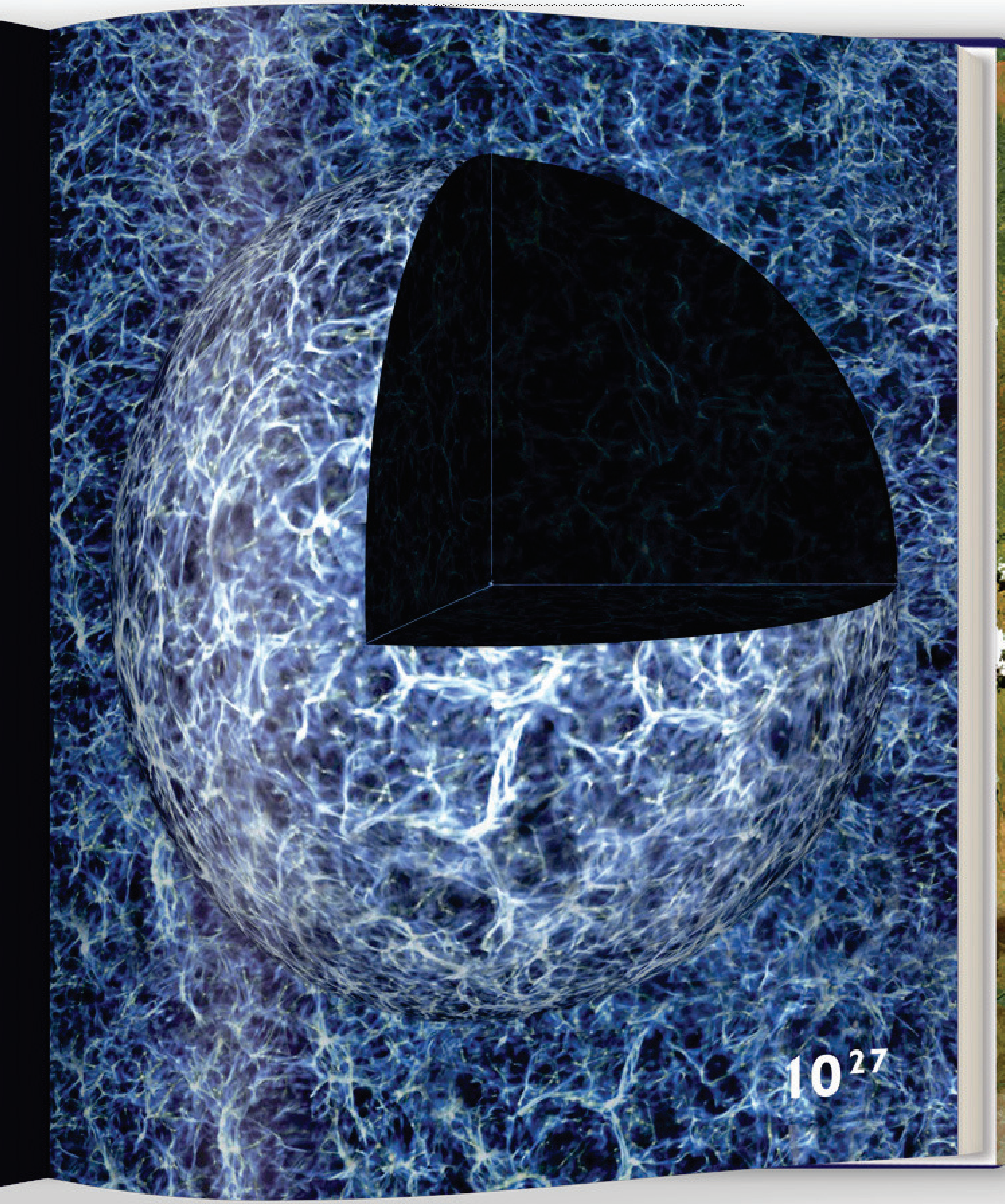
THE ZOOMABLE UNIVERSE

DO YOU WANT TO HEAR THE MOST EPIC STORY EVER?

A long time ago the atoms in your body were spread across trillions of kilometers of otherwise empty space. Billions of years in the past there was no hint that they would eventually come to be configured as your eyes, your skin, your hair, your bones or the 86 billion neurons of your brain. Many of these atoms came from deep inside a star—perhaps several stars, themselves separated by many more trillions of kilometers. As these stars exploded, they hurled parts of themselves outward in a flood of scorching gas that filled a small part of one galaxy out of hundreds of billions of other galaxies, arrayed throughout a gaping span of space and time almost a trillion trillion kilometers across.

Some of these atoms have been in the shell of a trilobite, perhaps thousands of trilobites. Since then, they've been in tentacles, roots, feet, wings, blood, and trillions, quadrillions of bacteria in between. Some have floated in the eyes of creatures that once looked out across the landscapes of 100 million years ago. Yet others have nestled in the yolks of dinosaur eggs or hung in the exhaled breath of a panting creature in the depths of an ice age. For others, this is their first time settling into a living organism, having drifted through eons in oceans and clouds, part of a trillion raindrops or a billion snowflakes. Now, at this instant, they are all here, making you.

Adapted from The Zoomable Universe: An Epic Tour Through Cosmic Scale, from Almost Everything to Nearly Nothing, *by Caleb Scharf, with illustrations by Ron Miller, by arrangement with Scientific American/Farrar, Straus and Giroux (US), Atlantic Books (UK), Cheers Publishing Company (China).*



OUR OBSERVABLE UNIVERSE is a sphere some 93 billion light-years wide, or close to 10^{27} meters, with Earth at its center.

Each atom is itself a composite that's one tenth of a billionth of a meter across—sitting on the precipitous edge of a universe between our perceived reality and the quantum world. Electrons hazily occupy much of the atom's empty space. Protons and neutrons cluster in a nucleus, 100,000 times smaller than its atom, and are themselves composed of other stupendously small things: quarks and gluons. An electron may have no meaningful property of size but could be thought of as 10 million times smaller than the nucleus.

Add up all the recognizable matter and there may be 10^{80} particles such as protons, neutrons, electrons and other subatomic items in the known universe. That's a very big number, but it's also just peanuts, because there are probably a billion times more photons zinging around the cosmos. Yet this stuff is barely 5 percent of what we think is the total matter and energy content of space. Astronomical evidence suggests that there is a shadow realm of still mysterious subatomic particles and funda-

Caleb Scharf is director of the Columbia Astrobiology Center and author of *Gravity's Engines* (2012) and *The Copernicus Complex* (2014). He writes the Life, Unbounded blog for *Scientific American* and has written for many other publications. He lives in New York City with his wife and two daughters.

Ron Miller is an award-winning illustrator and author whose work has appeared in *Scientific American, National Geographic* and *Smithsonian,* among many other publications, as well as in the definitive editions of Jules Verne's *20,000 Leagues Under the Sea* and *Journey to the Center of the Earth.* He lives in Virginia.

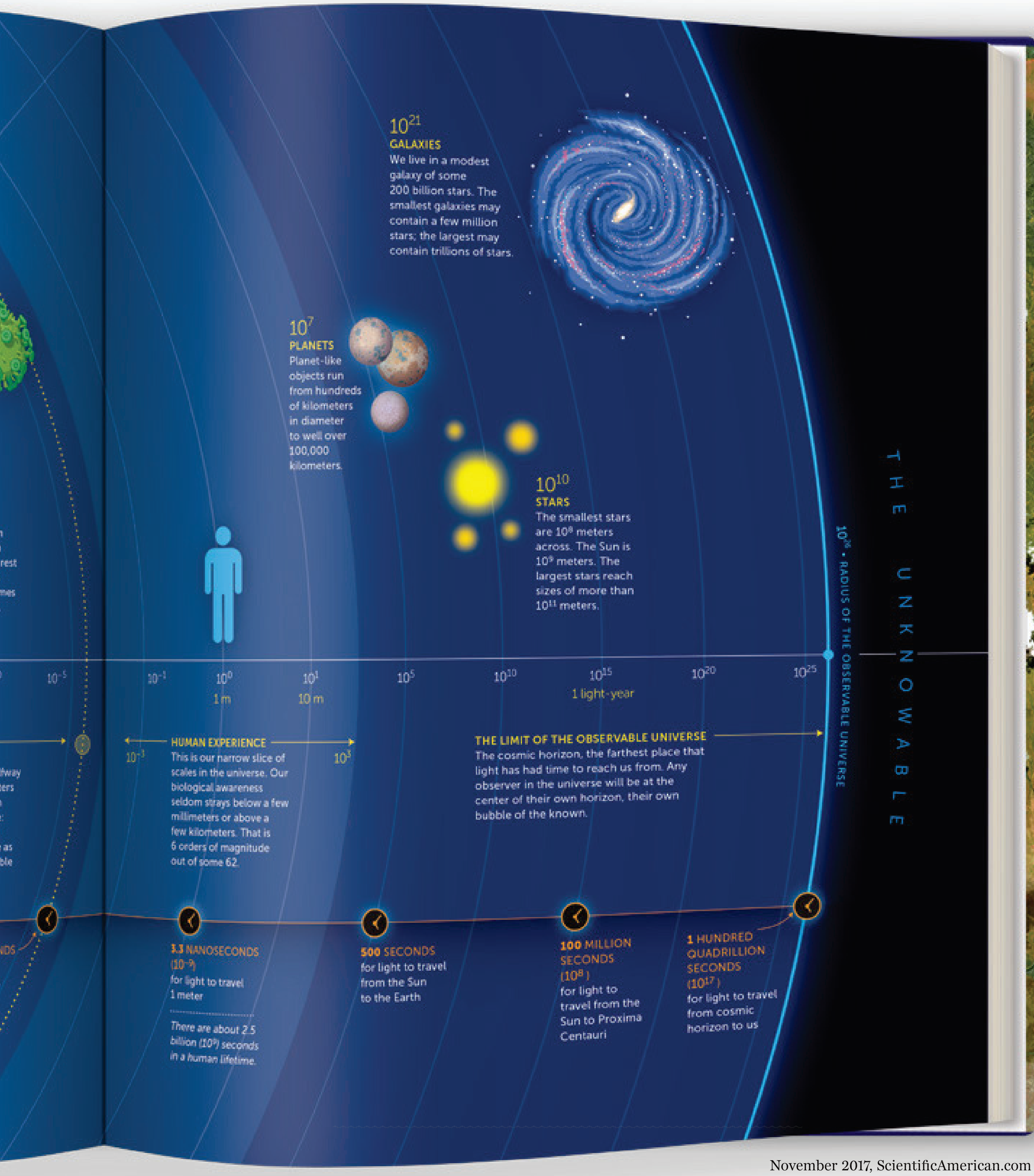
Graphics by 5W Infographics

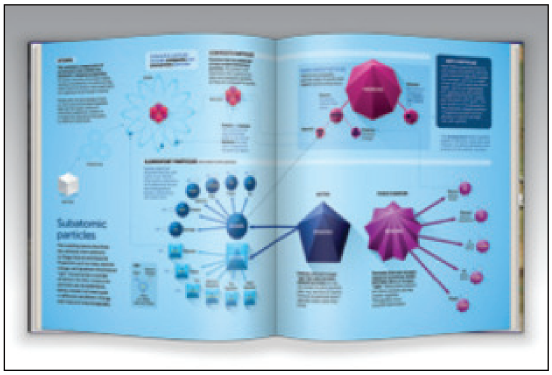
mental forces that constitute most of the cosmos—an underworld of dark matter and dark energy, dominating the entire universe but unseen by us.

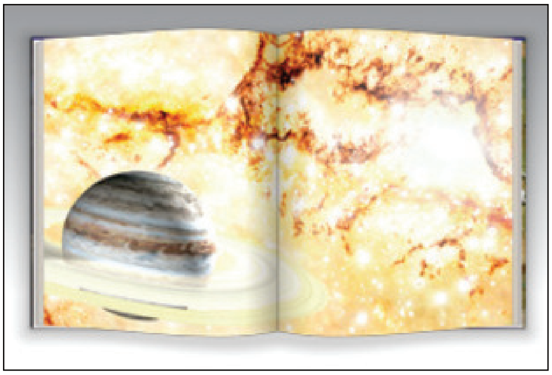
Moreover, at some point 13.8 billion years ago all of this, seen and unseen alike, was squeezed into a far smaller, hugely energetic origin of space and time that we are still inside, along with any being that may exist a billion light-years from here. We're not truly disconnected, even now.

Quite a tall tale. Except this is not fiction, it is our current understanding of the universe and its history [*see illustration below*].

To examine and display what we truly know (and what we don't) about the entirety of nature, we turn to a tried-and-true approach—the simple premise of a 10-fold zooming view to tour the universe, from the edge of the observable cosmos to the innermost knots of reality. From fingers and toes to modern mathematics and measurements, we can all grasp the notion of powers of 10—sizes that shift by 10 times or by a tenth. Chain







these sliding scales together across the three dimensions of space and that tricky thing we call time, and we have a language for expressing the continuities and relations of nature that extends far outside our common experience. The powers of 10 let us zoom from almost everything to nearly nothing.

Of course, a zoomable overview cannot recount every exact detail of the contents and history of the universe. Instead it takes us to specific waypoints throughout the physical scales of the cosmos across 62 orders of magnitude, from the quantum building blocks of the subatomic world to realms in which entire planets are mere droplets of frozen minerals and onward into the greatest expanse yet discovered, in which entire galaxies swarm like glinting motes of dust against the cosmic horizon.

This journey through all known scales of reality is, in essence, what "everything" really is. You might be tempted to ask what comes next. What is beyond the phenomenon we call the universe, beyond the everything? What might be "outside" the sunlit, mote-filled room of our observable reality? These are great questions, and in a very real sense anything "outside" our universe must be for now simply "not universe." The threshold bridging these domains is a place hovering at our cosmic horizon, its scale set by the distance light travels during the age of the universe. Within the boundary is the observable universe. Just outside is a still-mysterious labyrinth.

We live our lives in a narrow slice of existence sandwiched between these extremes of the very small and the very large, looking, listening, smelling and feeling from inside the membranes of our mostly water multicellular bodies. Somehow, we construct meaning out of those senses, experience that slippery property known as consciousness and perhaps even possess that elusive quality we call intelligence. It may be that other complex life across the cosmos is built the same way, to act and feel and think just as we do. Or perhaps our biology is not the only way to construct living things; perhaps the notion that consciousness and intelligence arise from the electrochemical gunk of our brain does not apply to minds elsewhere in the universe.

Confronting these mysteries of self, and the many scales of the cosmos, all we can really do is cross our fingers and hope that our singular experience will not mislead us as we disentangle the big questions of existence.

Altogether our situation is a bit farcical. We're in a horrendously unsuitable place for gaining objective truths about the nature of reality. Adrift on one small rocky planet that orbits one ordinary star out of a trillion trillion stars in the observable universe, each one of us is locked inside a singular, self-aware speck of flesh, embedded in a web of biological evolution that sprawls across the eons. Even our bodies are not wholly our own, because they also serve as Darwinian battlefields for trillions of bacteria and viruses. And all of it, all of life as we know it, seems to emerge solely from interactions among mind-numbingly large numbers of duplicated molecular structures—the exquisite architectural interplay of DNA and RNA, which itself arises from the physics of protons, neutrons, electrons and electromagnetic forces. Such tiny components simply follow the fundamental "rules" of the universe that were frozen into place some 13.8 billion years ago. Yet, in concert, they build galaxies, planets, humans, birds and who knows what else across the cosmos [*see illustrations above*].

How does all this happen? How did this epic story really begin, and how—if ever—will it finally end? Such questions sit at the heart of our efforts to construct a rational picture of nature from our inconvenient vantage point. Any answer is a work in progress but must already exist in hazy outline among all the myriad intersections of the universe's dizzying scales. We invite you to explore them and delight in their beauty. After all, this is your universe as much as anyone else's. SA

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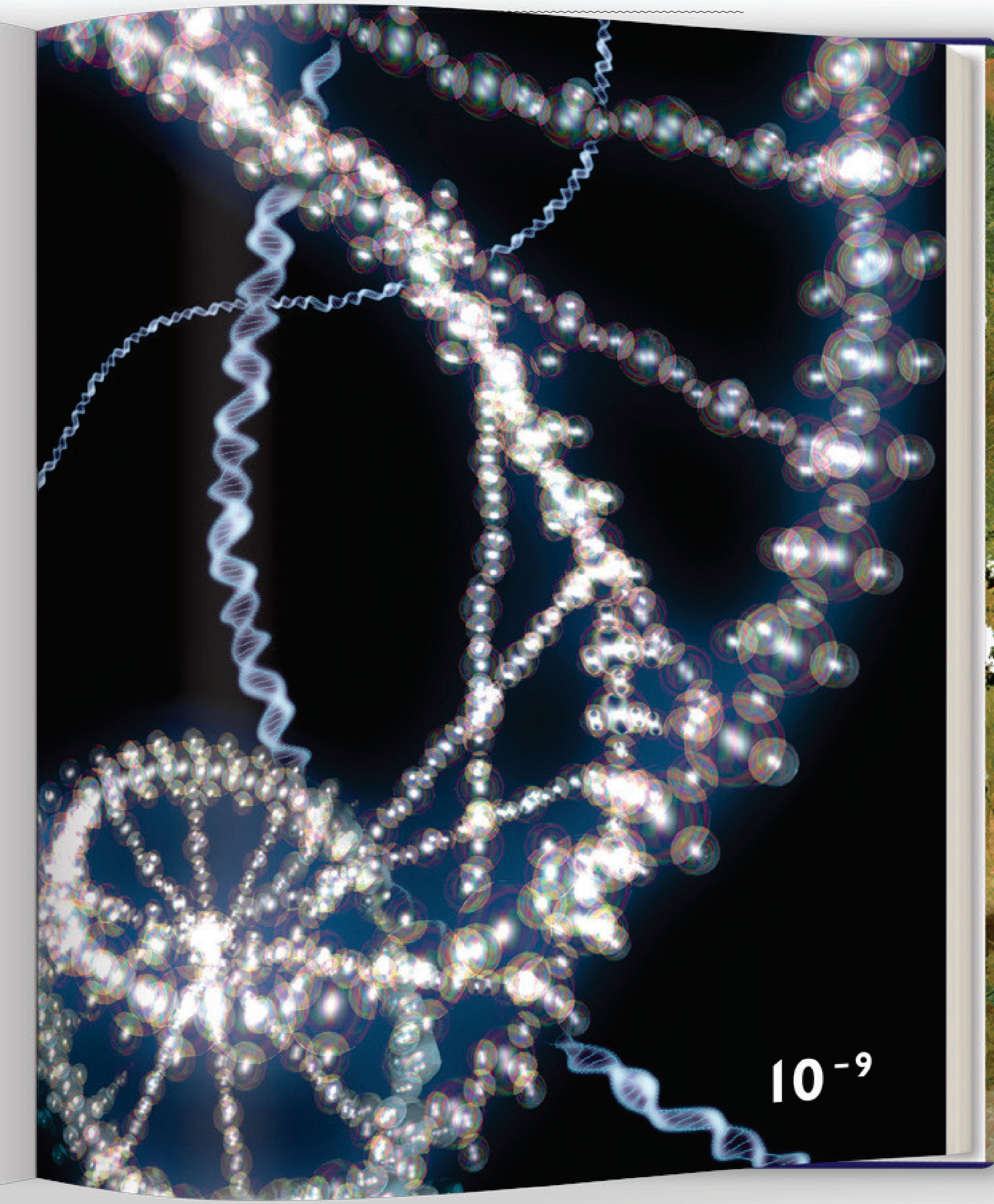
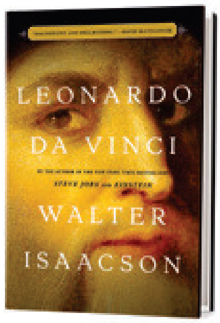


STUFF OF LIFE: At nanometer scales (10^{-9} meter), a molecule of DNA coils within the nucleus of a cell.

Leonardo da Vinci

by Walter Isaacson. Simon & Schuster, 2017 ($35)

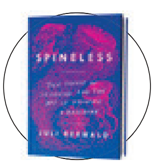


WAR MACHINE drawing by Leonardo da Vinci (1452–1519).

He created the *Mona Lisa* and *The Last Supper* and sketched the legendary *Vitruvian Man.* Yet his tremendous paintings are only part of the story. As historian and writer Isaacson painstakingly chronicles, Leonardo da Vinci was an obsessive learner and thinker who conducted extensive research on human anatomy, the mechanics of flight, optics and mirrors, to name a few. Unlike other Renaissance men of his time, he insisted on discovering things for himself rather than relying on the past work of others. In this way, he set the stage for the scientific method, demanding of himself meticulous observation, experimental procedure and reproducibility of results. Above all, this biography shows that his curiosity drove him in all things—to understand the nuances of the world, from the workings of the smallest feathered creature to the way light enters the human eye.

Spineless: The Science of Jellyfish and the Art of Growing a Backbone

by Juli Berwald. Riverhead Books, 2017 ($27)



After ocean biologist Berwald completed her Ph.D., she landed a job that left her unsatisfied—writing school textbooks on physics, far from the salty waters she loved. Working later as a journalist, she happened on a set of jellyfish photographs and was struck by these unique and mysterious animals. They captivated Berwald, so she decided to use her journalistic skills to dig deeper into their biology. In this memoir/science-reporting mash-up, she profiles one of the ocean's most intriguing creatures—the unique contractions it uses to propel through water, its acidifying habitat and its booming populations. Most of all, Berwald gets back to the ocean science she loves. *—Leslie Nemo*

The River of Consciousness

by Oliver Sacks. Knopf, 2017 ($27)

This bricolage of posthumously published essays by polymath physician and author Sacks forms a brilliant whole, showcasing his lifelong fascinations with evolution, perception, memory, creativity and time. In one exemplary sequence, an essay about Darwinian botany and the locomotion of plants segues seamlessly into another exploring the neurological limits to the speed of thought, which leads into a third speculating about the mental lives of worms, insects and jellyfish—and beyond. By the end, the interconnected ideas and insights flow together like braided streams from Sacks's deep pools of knowledge, forming a final retrospective of one of our age's greatest scientific storytellers. *—Lee Billings*

Whitewash: The Story of a Weed Killer, Cancer, and the Corruption of Science

by Carey Gillam. Island Press, 2017 ($30)

In the 1970s droves of farmers around the world bought the expensive weed killer Roundup. They laid it on heavy, too, applying 101 million pounds of glyphosate—the active ingredient—to soybeans during a 10-year span in the U.S. alone. Unlike other pest agents such as DDT, this chemical was touted as environmentally sound by its producer, Monsanto. But claims began to surface that glyphosate was a carcinogen that persisted in crops and food products. By digging through court documents, FOIA request findings and laboratory results, science writer Gillam traces the rise of the ubiquitous chemical and the controversy that erupted when farmers, researchers and concerned citizens started questioning what Monsanto was selling. *—L.N.*

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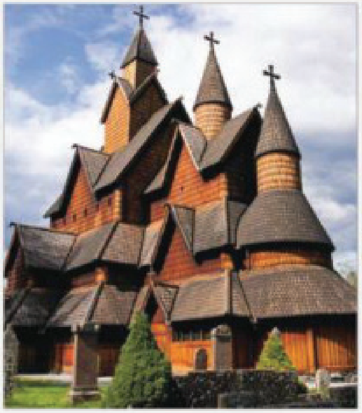

SPEAKERS:

Michael Benton, Ph.D.

Michael Benton is a paleontologist who has made fundamental contributions to understanding the history of life, particularly concerning how biodiversity changes through time. He has led in integrating data from living and fossil organisms to generate phylogenies — solutions to the question of how major groups originated and diversified through time.

This approach has revolutionized our understanding of major questions, including the relative roles of internal and external drivers on the history of life, whether diversity reaches saturation, the significance of mass extinctions, and how major clades radiate. A key theme is the Permo-Triassic mass extinction, the largest mass extinction of all time, which took place over 250 million years ago, where he investigates how life was able to recover from such a devastating event.

Robin Dunbar, Ph.D.

Robin Dunbar is Professor of Evolutionary Psychology at the University of Oxford, and a Fellow of Magdalen College. He has held Research Fellowships and Professorial Chairs in Psychology, Biology and Anthropology at the University of Cambridge, Stockholm University, University College London, and the University of Liverpool. He is an elected Fellow of the British Academy, and was co-Director of the British Academy's Centenary Research Project. His principal research interests focused on the evolution of sociality, with a particular interest in the nature of friendship and the cognitive and behavioural mechanisms that underpin our social relationships. He is best known for the social brain hypothesis, the gossip theory of language evolution and Dunbar's Number (the limit on the number of relationships that we can manage).

Ted Nield, Ph.D.

Ted Nield holds a doctorate in geology and has been writing about science for three decades. He has been published by most U.K. broadsheet newspapers, notably The Guardian, The Independent, New Scientist, Nature, and the New York Academy of Sciences' magazine, The Sciences. For 10 years he was the national spokesman for the U.K. university system, becoming a familiar voice on U.K. radio, before joining the Geological Society of London in 1997, where he edits the monthly magazine Geoscientist.

Dr. Nield is a past chair of the Association of British Science Writers and was a Goodwill Ambassador for the United Nations International Year of Planet Earth in 2008. He is a Fellow of the Geological Society and a member of the Meteoritical Society. He is the author of numerous books, including *Supercontinent: Ten Billion Years in the Life of Our Planet* (2007).

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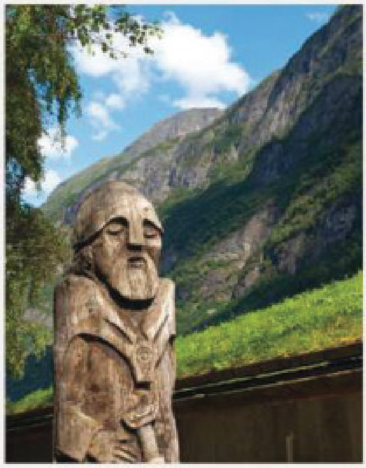

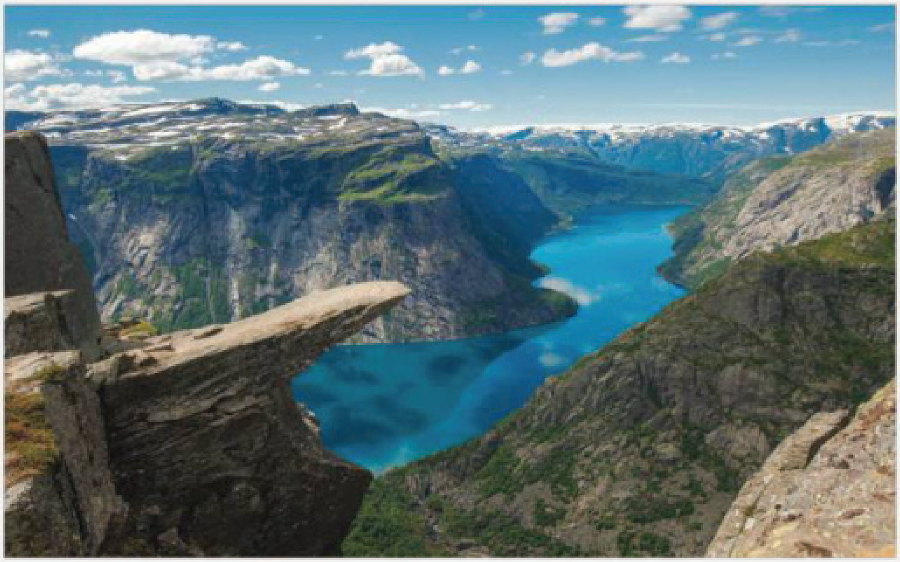

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- The Seven Pillars of Friendship
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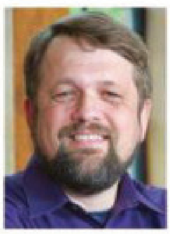
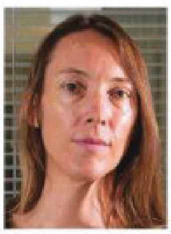
- Particle physics in Space ... and Beyond



Ben Schumacher, Ph.D.

Dr. Benjamin Schumacher is Professor of Physics at Kenyon College, where he has taught for 20 years. He received his Ph.D. in Theoretical Physics from The University of Texas at Austin in 1990. Professor Schumacher is the author of numerous scientific papers and two books, including *Physics in Spacetime: An Introduction to Special Relativity*. As one of the founders of quantum information theory, he introduced the term qubit, invented quantum data compression (also known as Schumacher compression), and established several fundamental results about the information capacity of quantum systems. For his contributions, he won the 2002 Quantum Communication Award, the premier international prize in the field, and was named a Fellow of the American Physical Society. Besides working on quantum information theory, he has done physics research on black holes, thermodynamics, and statistical mechanics.



Tara Shears, Ph.D.

Dr. Tara Shears is an experimental particle physicist and Professor of Physics at the University of Liverpool. She received her Ph.D. in 1995 from the University of Cambridge, and spent the rest of that decade continuing to investigate the behavior of fundamental particles and forces with the OPAL experiment at CERN. Tara was awarded a Royal Society University Research fellowship with the University of Liverpool in 2000 to continue her research at the Collider Detector at Fermilab facility near Chicago. She joined the LHCb experiment at CERN's Large Hadron Collider in 2004, where she initiated a program of electroweak physics. She became an academic in 2007, and the first female professor of physics at Liverpool in 2012. Her current research focus is exploiting LHCb. She has appeared in press, radio, and film and given talks to a wide variety of audiences.

For speakers' complete bios, visit http://InsightCruises.com/events/sa35/#speakers.html

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Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com) and a Presidential Fellow at Chapman University. His next book is *Heavens on Earth*. Follow him on Twitter @michaelshermer

What Is the Secret of Success?

Does it come from talent, hard work—or luck?

By Michael Shermer

At a campaign rally in Roanoke, Va., before the 2012 election, President Barack Obama opined: "If you were successful, somebody along the line gave you some help. There was a great teacher somewhere in your life.... Somebody invested in roads and bridges. If you've got a business—you didn't build that. Somebody else made that happen."

Although Obama was making a larger point about the power of collective action, such as building dams, power grids and the Internet, conservative heads exploded at the final sentiment. "I did build that!" is an understandable rejoinder to which I can relate. I research my books, edit my magazine, teach my courses and write these columns (this one is my 200th in a row for *Scientific American*). If I don't make them happen, nobody else will.

But then I started thinking as a social scientist on the role of circumstance and luck in how lives turn out. It's a sobering experience to realize just how many variables are out of our control:

- The luck of being born in the first place—the ratio of how many people could have been born to those who actually were—is incalculably large, not to mention the luck of being born in a Western country with a stable political system, a sound economy and a solid infrastructure (roads and bridges) rather than, say, in a lower caste in India, or in war-torn Syria, or anarchic Somalia.

- The luck of having loving and nurturing parents who raised you in a safe neighborhood and healthy environment, provided you with a high-quality K–12 education and instilled in you the values of personal responsibility. If they were financially successful, that's an added bonus because a key predictor of someone's earning power is that of their parents.

- The luck of attending a college where you happened on good or inspiring professors or mentors who guided you to your calling, along with a strong peer cohort to challenge and support you, followed by finding a good-paying job or fulfilling career that matches your education, talents and interests.

- The luck of being born at a time in history when your particular aptitudes and passions fit that of the zeitgeist. Would Google's co-founders Larry Page and Sergey Brin be among the richest and most successful people in the world had they been born in 1873 instead of 1973? Both are brilliant and hardworking, so they would probably have been successful in any century—but at the equivalent of nearly $45 billion each? It seems unlikely.

What about intelligence and hard work? Surely they matter as much as luck. Yes, but decades of data from behavior genetics tell us that at least half of intelligence is heritable, as is having a personality high in openness to experience, conscientiousness and the need for achievement—all factors that help to shape success. The nongenetic components of aptitude, scrupulousness and ambition matter, too, of course, but most of those environmental and cultural variables were provided by others or circumstances not of your making. If you wake up in the morning full of vim and vigor, bounding out the door and into the world to take your shot, you didn't choose to be that way. Then there is the problem of übersmart, creative, hardworking people who never prosper, so obviously there are additional factors that determine life outcomes, such as bad luck ... and bad choices.

Volition, too, must be considered in any evaluation of life outcomes, in the sense of knowing your strengths and weaknesses and selecting paths more likely to result in the desired effect. You can become aware of the internal and external influencing variables on your life—and aware of how you respond to them—and then make adjustments accordingly, however restrictive the degrees of freedom may be.

If the cosmic dice rolled in your favor, how should you feel? Modest pride in one's hard work is no vice, but boastful arrogance at one's good fortune is no virtue, so you should cultivate gratitude. What if you've been unlucky in life? There should be consolation in the fact that studies show that what is important in the long run is not success so much as living a meaningful life. And that is the result of having family and friends, setting long-range goals, meeting challenges with courage and conviction, and being true to yourself. SA

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Illustration by Izhar Cohen

Steve Mirsky has been writing the Anti Gravity column since a typical tectonic plate was about 36 inches from its current location. He also hosts the *Scientific American* podcast Science Talk.

Poultry Problems

How chicken farming got juiced

By Steve Mirsky

Summer of '45. The war is winding down. Now the call to arms is about to be replaced by a call to wings. The time has come for the Chicken of Tomorrow contest.

As Maryn McKenna details in her fun, fascinating and sometimes frightening new book *Big Chicken,* the aim of this nationwide breeding challenge was to create, you guessed it, a big chicken. A very big chicken. When the U.S. Department of Agriculture started keeping stats in 1925, the average weight of a chicken at slaughter was 2.5 pounds. The Chicken of Tomorrow winner, one Charles Vantress, bred a chicken that, 86 days after hatching (as per contest rules), weighed a full pound more than that. And a pound of meat multiplied by millions of chickens was worth a lot of bucks.

Nobody bothered to run a follow-up Chicken of the Day After Tomorrow contest. Nevertheless, today's massive, mass-produced U.S. birds can weigh in at *six* pounds—and get there in just 47 days, according to McKenna. This accelerated growth resulted from a combination of continued breeding experiments and widespread use of growth promoters—vitamins and, especially, antibiotics.

Just as the Chicken of Tomorrow contest was wrapping up, Lederle Laboratories biochemist Thomas Jukes discovered that chickens that ate feed spiked with antibiotics really packed on the pounds. Farmers could also pack in the birds cheek by fowl, with decreased concerns about infectious diseases, thanks to this premeditated medication.

The agricultural boom took place despite warnings about the dangers of antibiotic overuse and drug resistance from the discoverer of penicillin himself, Alexander Fleming. But economic euphoria convinced most agricultural businesses to give antibiotic resistance no attention or little. (Chicken. Little. Chicken Little. It's a joke, I say, it's a joke, son.)

The love affair with antibiotics also led to a brief fad in the 1950s captured by the sales pitch "Our Poultry Is Acronized!"—a word created from Greek roots to mean "detached from time" or "timeless." Dead chickens were dipped like little Achilles into a solution of antibiotics. The resulting surface film could make them invulnerable to microbes for up to a month—an infinity in shelf life conferred by the bird bath.

But chicken-dipping workers started getting skin infections. And foodborne illness outbreaks, though not necessarily related to the dipping, prompted fresh research. "Acronizing treatment changed the mix of bacteria on the surface of meat," McKenna writes, "encouraging resistant bacteria to develop and multiply." Eventually a new slogan pitched chickens: "Non-Acronized." *Tempus* sure does *fugit.*

All this tinkering—without genetic modification in the modern GMO sense, by the way—has been part of a chicken explosion. In 1909, McKenna writes, "in the entire United States, 154 million chickens were sold for meat." Today the figure is almost nine billion. That's a lot of chicken salad (especially with the human population increasing only about fourfold). And the vast majority of antibiotics sold in the U.S.—some 80 percent—go to animals. Because most of those drugs are also used to fight human infections, drug-resistant bugs that arise on the farm continue to threaten our own health.

But an almost breathtaking development (not the result of a respiratory infection) is under way. As McKenna notes, in 2014 Perdue Farms chair Jim Perdue (who holds a fisheries doctorate, go figure) announced that his company had stopped using growth-promoting antibiotics in 2007—and was still able to raise profitable poultry. It helped that Perdue's research showed that growth promoters had lost their oomph, but let's not look a gift chicken in the beak. A few months before Perdue went public, Chick-fil-A joined the same sect, declaring that its chicken would be antibiotic-free by 2019. McDonald's, Subway, Costco, Walmart all followed, as did Tyson Foods—America's most prolific chicken king.

As antibiotic-raised chicken flickers across the land, recall the poetic words of Emily Dickinson: "Hope is the thing with feathers." Even if it ends up plucked. SA

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Illustration by Matt Collins

50, 100 & 150 YEARS AGO

INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Daniel C. Schlenoff

NOVEMBER

1967 Moon Texture

“When men first set foot on the moon, what will the ground be like? Will it perhaps be soft and powdery, as some have suggested, or hard and crusty, as has been proposed by others? The most specific evidence has come from Surveyor III, which was equipped with a device that could dig into the surface of the moon and place samples of lunar material in front of a television camera for close examination. The samples tested by Surveyor III showed a surface material that is granular and rather like loose soil. Surveyor III was one of the more recent space vehicles the U.S. has sent to or around the moon in preparation for the Apollo flights that will take men there.”

Education Expectations

“Can a teacher’s expectations of his pupils’ performance affect that performance? Apparently so. When teachers in an elementary school were told that certain children were likely to ‘bloom’ intellectually, those children (whose names had been picked at random) showed greater gains than others during the year. This ‘self-fulfilling prophecy’ was reported at an American Psychological Association meeting in September by Robert Rosenthal of Harvard University and Lenore Jacobson of the South San Francisco Unified School District. Teachers also characterized the ‘bloomers’ as having a better chance of becoming successful and as being significantly more interesting, curious and happy. Rosenthal and Jacobson point out that their findings may bear on current efforts to improve the education of children in city slums.”

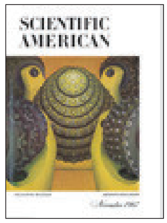
1917 Bolshevik Revolution

SCIENTIFIC AMERICAN, VOL. CXVII, NO. 18; NOVEMBER 3, 1917

“What effect will the Russian Revolution have upon the war is the question which rises instinctively to every lip of whatever nationality. When we attempt to consider the revolution from this point of view, the first thing which we must realize is that we are at once separating ourselves from the revolutionists by a tremendous gap. The Russian as a class regards the war as an incident of the revolution, rather than the other way about; he is interested in making sure that the war shall not interfere with his revolution rather than that his revolution shall not compromise our war. Alike because of this and because of the physical condition of Russia, we must face the bald fact that this nation is out of the war so far as effective participation is concerned.”

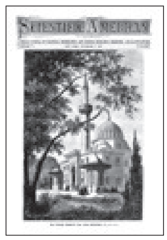
The Value of Skunk

“When Dame Fashion calls for skunk fur this animal has been trapped in all parts of the country and its numbers greatly reduced. Curious results have come from this. The staple food of skunks in summer is insects, and the number of insects a single skunk devours is enormous. The great economic importance of the skunk has been illustrated during the past summer in the plague of yellow jackets. Skunks ordinarily dig up the nests that these sharp-stinging hymenoptera build in the ground and eat the insects and larvae. The increase in yellow jackets is no doubt due to the extensive trapping of skunks. So troublesome are they that fruit growers are considering asking for a law to protect the skunk.”



1967

1917



1867

1917: British troops in Mesopotamia during the First World War patrol the Tigris River in a hydroplane powered by an aircraft engine.

1867 Coal vs. Oil

“The petroleum excitement reached its climax immediately after the trials with the retort apparatus on the U.S.S. *Palos,* in Boston Harbor. The results after these experiments were proclaimed on all sides as eminently successful; ‘the days of coal were numbered,’ so said one of the experts at a Babylonian banquet given in Boston in honor of ‘the great event of the age.’ The Cunard line have not adopted it, neither is it used on railroads, and it would seem that if the petroleum companies themselves have any confidence in the wares they are trying to persuade the public to buy, they would be introduced practically so that there might be a fair comparison with coal.”

Russian Gamble Fails

“The complete success of the Atlantic telegraph cable has been the death blow of the Russian telegraph enterprise, which was started immediately after the loss of the earlier trans-Atlantic cable of 1865. The *San Francisco Bulletin* gives the particulars of the construction party which for two years and four months have been working on the northwestern coast. Their summers were passed in a country in which for weeks it never grew dark, and in which the thermometer in winter in Russian America [Alaska] went to minus 69 F. The work is now abandoned; all the valuable material, stores and constructors having been brought back.”

Safer by Kindergarten

School immunization laws are working

The number of U.S. children fully vaccinated against potentially deadly diseases such as diphtheria and measles had been slipping before 2011. Since then, national declines have slowed or even reversed. Rates for kindergartners are noticeably higher than for children 19 to 35 months old because of state laws requiring them to have the full series of inoculations before they can enter the classroom. The laws vary, "but overall they say, 'We have to protect our children.' It's terrific," says William Schaffner, professor of preventive medicine at Vanderbilt University. Vigilance remains needed, however; levels have eroded slightly for the older group. That may be because laws in some states do not require the entire series of recommended doses or allow parents to easily obtain exemptions. Young parents may seek to opt out because they do not think diseases are serious and may not have learned about them in middle or high school health classes, which tend to focus on subjects such as sexual activity and drug use.

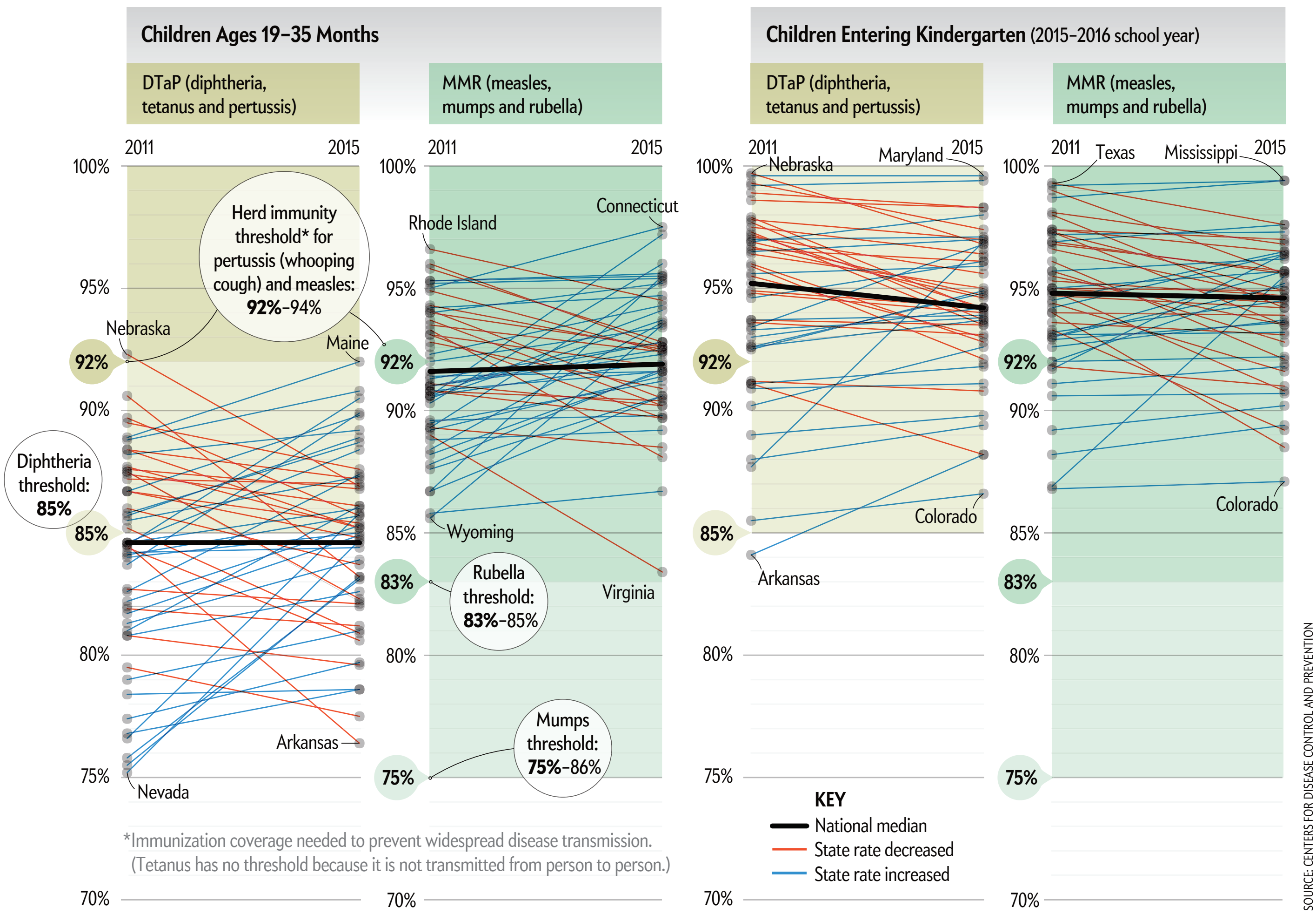
How Many Doses?

The U.S. Centers for Disease Control and Prevention recommends four doses of DTaP vaccine and one dose of MMR vaccine by the time children are 19 to 35 months old. It recommends five doses of DTaP and two of MMR by ages four to six, which is what most states require for school entry. Data below are for these levels.

No More Exemptions

Some parents are determined to skirt kindergarten immunization laws, which can pull down a state's average. In 2016, when California ended exemptions based on a parent's religious or philosophical beliefs, medical exemptions—authorized by doctors or forged in their names—tripled, compared with 2015.

Changes in Vaccination Coverage by State, 2011–2015

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