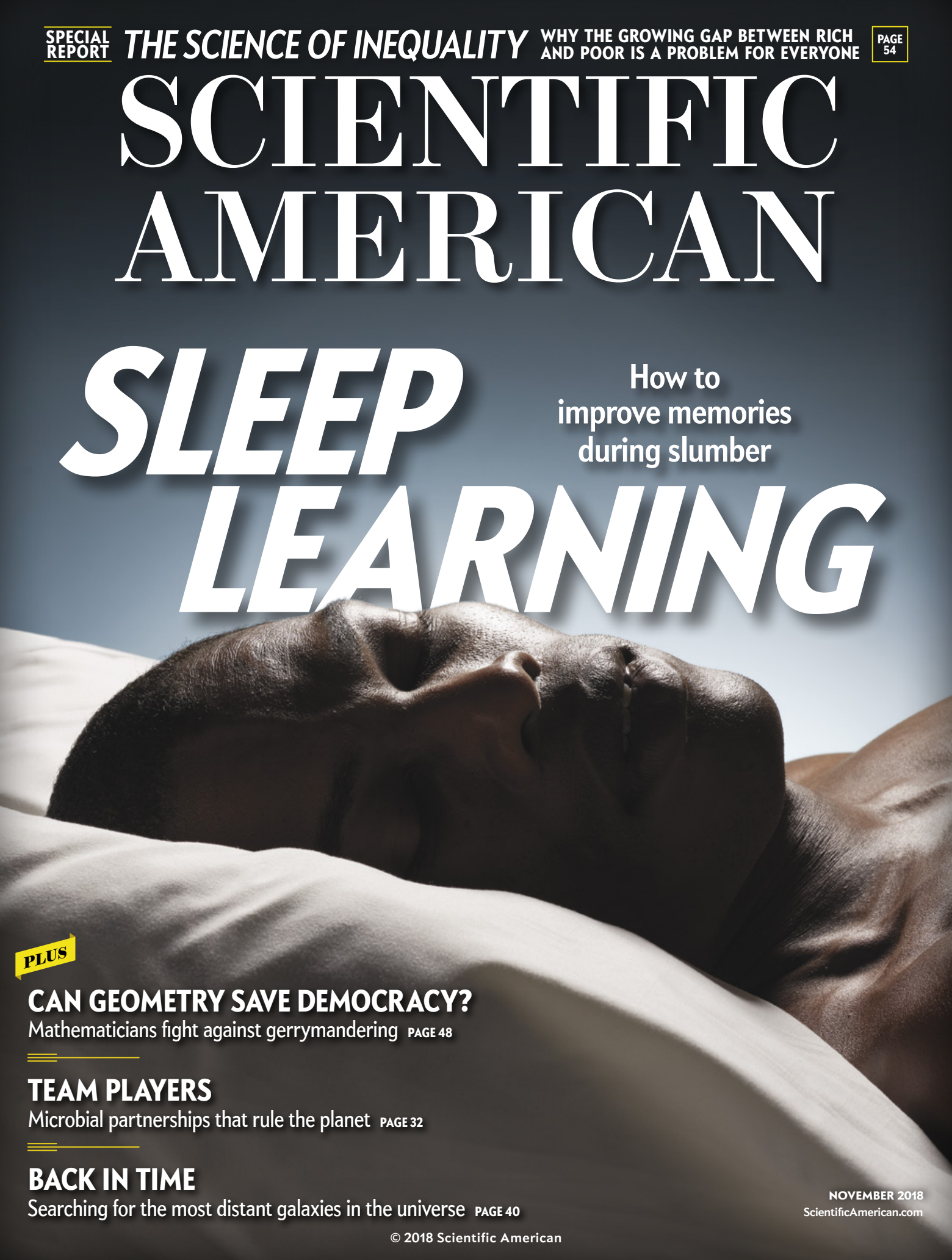
SPECIAL REPORT **THE SCIENCE OF INEQUALITY** WHY THE GROWING GAP BETWEEN RICH AND POOR IS A PROBLEM FOR EVERYONE PAGE 54

SCIENTIFIC AMERICAN

SLEEP LEARNING

How to improve memories during slumber



PLUS

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Mathematicians fight against gerrymandering PAGE 48

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Microbial partnerships that rule the planet PAGE 32

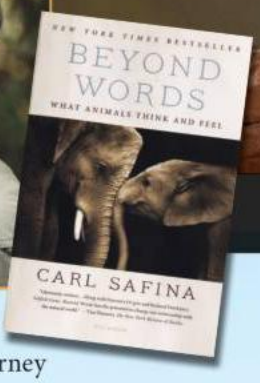
BACK IN TIME
Searching for the most distant galaxies in the universe PAGE 40

NOVEMBER 2018
ScientificAmerican.com

Lions, Tigers and Tradewinds

A PRIVATE JET EXPEDITION

HOSTED BY *Carl Safina*



Conservationist and writer Carl Safina will host this journey throughout, offering insights on wild lands and wildlife, and humans' relationship to the living world. Author of seven books, including *Beyond Words: What Animals Think and Feel*, Dr. Safina's work has been awarded the MacArthur, Pew, and Guggenheim Fellowships, among others.

"Join me and Bushtracks Expeditions' president David Tett as we take a great-cat-sized bite out of a great swath of two continents. And, we will also experience parts of the Middle East and the Indian Ocean. Our itinerary promises lands and luxuries, coasts and comforts, lions and tigers and maybe even bears. This is an itinerary for the curious, for the seeker, for those willing to get the greatest view of all—a view at ourselves not in the mirror but from the outside, looking in. There will be an enormity of concepts to explore, and things to see and enjoy. I hope to see you at boarding!"

Carl Safina

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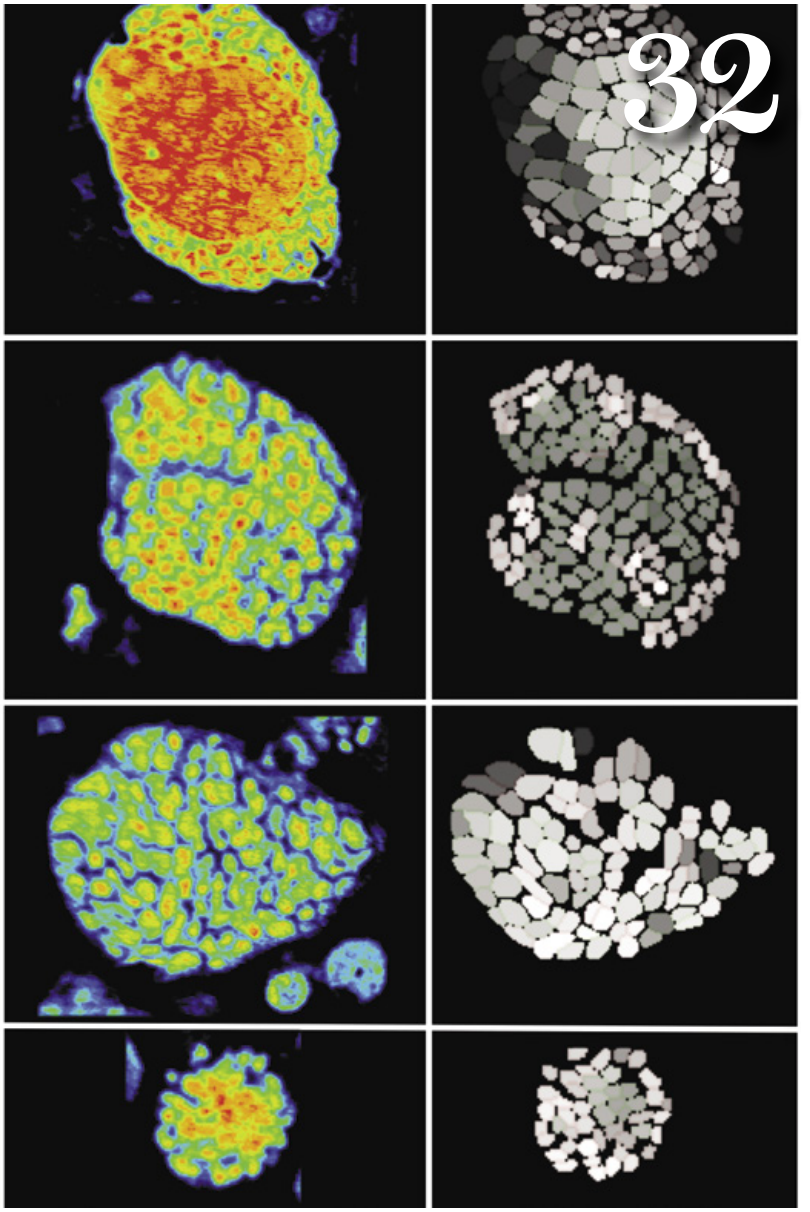

ON THE COVER
Learning while asleep turns up as a trope in novels and in popular culture. Now one form of sleep learning is getting a serious hearing in reputable neuroscience labs. The sleeping brain spontaneously reactivates existing memories. Researchers want to understand how these periods of off-line recall serve as de facto study sessions that help us remember what we learned during the day.
Photograph by Hannah Whitaker.

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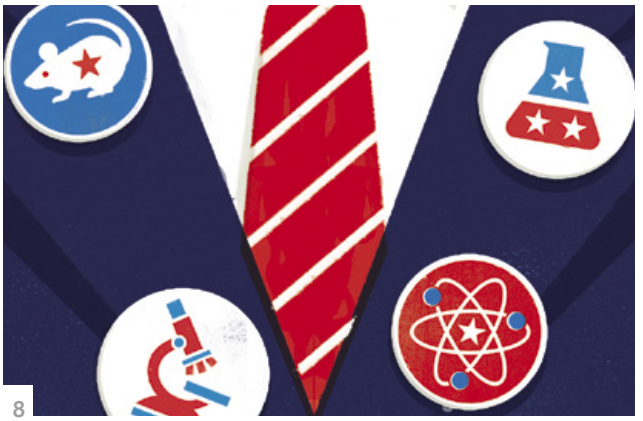

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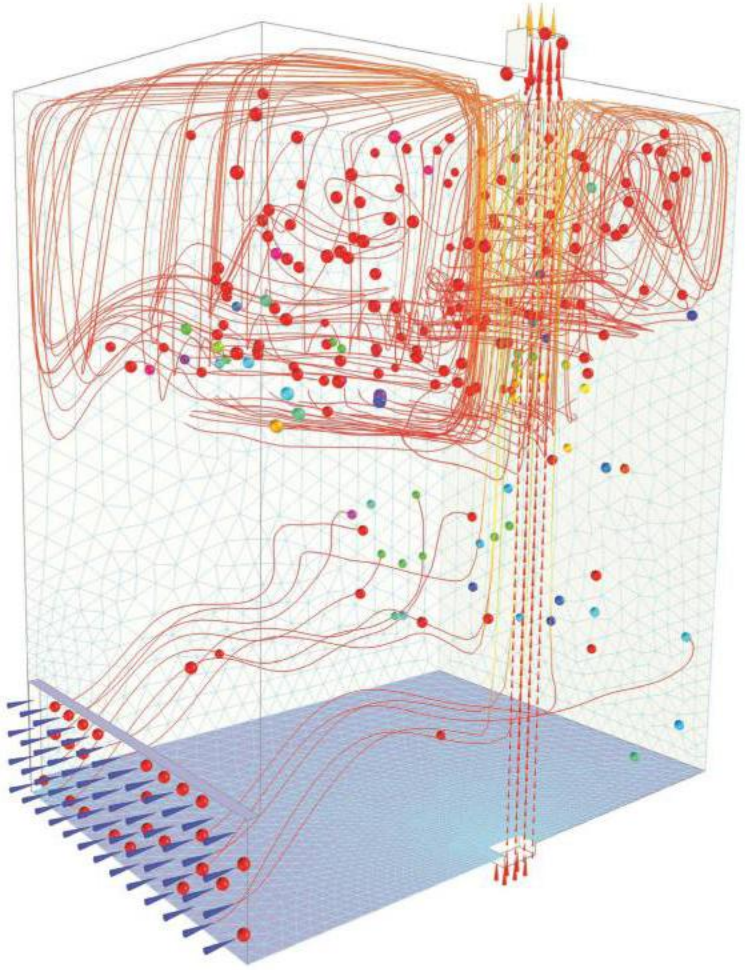
Prevent epidemic outbreaks with mathematical modeling and simulation.



Visualization of the motion of bacteria particles in a room with a displacement ventilation system.

Using math to analyze the spread of epidemic diseases is not a new concept. One of the first compartmental models of mathematical epidemiology dates back to 1760 and was presented by Daniel Bernoulli for studying the mortality rate of smallpox. Today, medical researchers and public health officials continue to use mathematical modeling and simulation to prevent and control epidemic outbreaks in the modern world.

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

When Will We Learn?

In our cover story, "Sleep Learning Gets Real," by Ken. A. Paller and Delphine Oudiette, we focus on a topic that has long held healthy measures of both fascination and speculation for many of us: maximizing the one third of our lifetime spent in slumber. Evoking the cultural allure of the prospect, the article opens with a reference to Aldous Huxley's 1932 classic, *Brave New World,* where students are, in effect, programmed overnight by their totalitarian authorities.

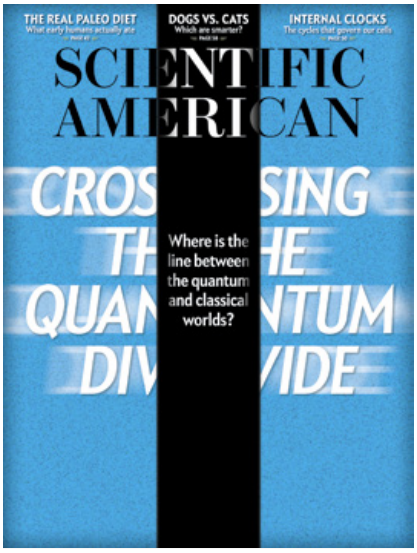
The nonfiction truth is, as usual, both less extreme and, in a number of ways, more illuminating in what it reveals about the brain. As you'll learn when you turn to page 26, we won't be imprinting brand-new ideas into anybody's snoozing brain anytime in the near future. Through controlling the process of memory reactivation, however, researchers are investigating how we can improve learning during our nightly periods of downtime. The work could someday help us promote problem-solving while asleep, stop nightmares or perhaps guide the outcome of our dreams.

Dystopian fiction such as *Brave New World* has a useful role in conjuring possible futures that could arise from today's science and technology trends. But learning while sleeping was only one such idea explored by Huxley. Another was the conception of a society where privileges followed a ranking system based on genes. When I first read the work, in high school, I was struck by the distance between the top and bottom tiers.

But that was fantasy. In the real world, the divide between the wealthy at the top and the poor at the bottom is even worse. The gaps are already severe and growing—with impacts that affect almost every aspect of human well-being, from our personal health to that of the biosphere. In this issue's special report on "The Science of Inequality," led by senior editor Madhusree Mukerjee, we take a deep dive into the challenges—and some ways to alleviate them; it starts on page 54.

For instance, economist Joseph E. Stiglitz looks at why inequality is higher in the U.S. than in almost all other advanced countries ("A Rigged Economy"). Neuroscientist Robert M. Sapolsky looks at the effects of inequality on physical and mental health ("The Health-Wealth Gap"). The most vulnerable members of society are often hurt, rather than helped, by digital systems, explains political scientist Virginia Eubanks ("Automating Bias"). Rounding out the section, economist James K. Boyce describes how inequality damages the environment and some of the ways communities are combating such harm ("The Environmental Cost of Inequality"). Considering the importance of the challenges facing us now and in the future if we don't tackle them, we might ask: When will we learn? Let's hope it's soon. SA

Illustration by Nick Higgins



July 2018

DENYING ADVANTAGE

Douglas T. Kenrick, Adam B. Cohen, Steven L. Neuberg and Robert B. Cialdini explore "The Science of Antiscience Thinking," which includes both the denial of evolution and of climate change.

There are two issues to the challenge of coping with antiscience thinking that they do not deal with. One is that evolution did not prioritize our mental capabilities for abstract careful analysis. Food and self-protection were far more important—and still are. The other is that there are well-organized and frequently well-funded antiscience oppositions that do not have inhibitions against oversimplifying information.

MORT SILVERBERG *via e-mail*

RENEWABLE ENERGY

In "Building a Weather-Smart Grid," Peter Fairley describes the challenges to addressing how weather affects energy production from renewable sources, particularly wind and solar.

I wonder if the models developed to consider weather could also include data on birds and bats. Just like dams are managed for salmon, wind turbines need to be managed to reduce bird and bat kill.

Whereas wind turbine placement and blade design are effective at reducing the number of animals killed, stopping blade rotation at certain times of day—when birds or bats move through the area or during migrations—is also beneficial. The loss of generation at these times could be made part of the models and improve the overall stability of the grid.

MATHIEU FEDERSPIEL *via e-mail*

"There are well-organized antiscience oppositions that do not have inhibitions against oversimplifying information."

MORT SILVERBERG *VIA E-MAIL*

Fairley's article prompts me to suggest that an alternative way to profit from surplus renewable energy may be to use it to produce hydrogen by electrolysis of acidified water. That hydrogen could then be stored and could generate electricity when there is a shortfall of renewable energy.

Another use for excess renewable energy could be to power carbon dioxide–capture plants. Furthermore, captured carbon could be combined with hydrogen to create fuel.

JOHN WATSON *Darlington, England*

QUANTUM COLLAPSE

In "Crossing the Quantum Divide," Tim Folger reports on experiments aiming to probe the boundaries of the microscopic world of quantum mechanics and the macroscopic realm of classical physics.

I am sure the quantum world is indeed weird, as Folger asserts, but the things he explains are not particularly so: If you roll a die under a cloth, it is in a superposition of six states. Lift the cloth, and you see a six. The superposition has collapsed. How is that weird?

Perhaps it would be weirder if the die were to control something physical in the real world? Not really. Take smoke dispersing from a chimney. The positions of the smoke particles can be described by a Gaussian, or normal, probability function. If one particle was radioactive, we could measure where it was with a detector, and its probability function would collapse. In what way is the quantum world weirder than this?

JOHN HOBSON *Devizes, England*

It seems to me that, in focusing solely on their measurements, scientists have developed a view that it is the measurements themselves that are responsible for the so-called collapse of the wave function of a particle into a particular quantum state.

It can't be assumed that this defining interaction is specific to us. It is possible that we may measure a particle to be in one state, based on interactions with our equipment, while that particle continues, unobserved, to act on all the other possibilities it represents.

Think of the story of a group of blind men all touching a different part of an elephant, all of them coming up with different answers as to what it is that they are touching. Our measurements do not show the whole picture. They show only the part of that picture that we have the capacity to measure.

D. AIDAN TUTTLE *New Canaan, Conn.*

FOLGER REPLIES: Hobson shows just how difficult it is to grasp the full strangeness of quantum mechanics. What is it about "lifting the cloth" that causes the six possible configurations of the die to "collapse" into one value? No one knows. Physicists have proposed different mechanisms, which I wrote about in my article, but there is no physical explanation for why we perceive one value of a quantum die rather than another—or all of them simultaneously!

As for the smoke coming out of a chimney: According to classical physics, we could, in principle, predict the shape and direction of the smoke plume if we could track each individual particle in it. But that's not the case with quantum mechanics. Unlike the smoke particles, which are described by classical physics, quantum particles have no fixed position, momentum or any other property until the time of measurement. What makes the quantum world so mysterious is not our ignorance of the details of a physical system, it's that those details don't exist without a measurement.

Tuttle describes a phenomenon that physicists call decoherence, in which

GENE THERAPY POISED FOR IMPACT ON CHILDHOOD DISEASES

A conversation with **KEVIN FLANIGAN**, MD, director, Center for Gene Therapy, Nationwide Children's Hospital

Nationwide Children's Hospital, in Columbus, OH, cares for children from around the world. Its research institute is among the top 10 free-standing children's hospitals in terms of National Institutes of Health funding. Its Center for Gene Therapy develops treatments for a variety of childhood disorders, particularly neuromuscular and neurodegenerative diseases, and collaborates with pharmaceutical companies to move potential therapies into clinical trials.

What is the state of the art of gene therapy today?
After more than 20 years of research into gene transfer, it is finally reaching the clinic in a meaningful way. Part of this is based on the increasingly successful development of the viral vector systems we now use, adeno-associated viruses (AAVs), which have become the workhorses for gene therapy. After many years of preclinical research with AAV vectors, gene therapies for many single-gene disorders are now in clinical trials. Some have already shown extraordinary promise for changing the disease course for devastating childhood illnesses.

What success have you had in developing therapies?
The most striking published result so far has been in gene transfer of the SMN1 gene into patients with spinal muscular atrophy type 1, where the first human trial showed a dramatic improvement in outcomes. This devastating disorder affects the motor neurons, and typically causes death or the need for mechanical ventilation by the age of two years. Using a vector developed by Brian Kaspar in his lab at Nationwide Children's, Jerry Mendell's team treated 15 patients with systemic delivery of an AAV9 vector carrying the SMN gene. They showed it was safe, but more strikingly, all of the patients were alive or without mechanical ventilation at age 20 months, as compared to only the 8% expected based upon natural history studies. This is really quite a dramatic change in the clinical course, and has the potential to change treatment of the disease around the world.

What other diseases are you tackling?
We have trials under way for Duchenne muscular dystrophy, which affects about 1 in 5200 boys. These trials include gene transfer of micro-dystrophin, miniaturized to fit into an AAV capsid, as well as a surrogate gene (GALGT2) that can in some ways substitute for the missing protein. We have trials under way or planned for some forms of limb-girdle muscular dystrophy and Charcot-Marie-Tooth disease, and ongoing preclinical projects addressing facioscapulohumeral muscular dystrophy, myotonic dystrophy type 1, and a variety of other neuromuscular disorders. In addition, we have trials under way for other diseases that primarily affect the central nervous system, such as Sanfilippo syndrome (or mucopolysaccharidosis type 3) and Batten disease.

Why do you emphasize childhood neuromuscular diseases?
Most importantly, many childhood neuromuscular diseases are absolutely devastating disorders for which no other therapy is available. I have studied these diseases for 25 years, and my colleague Jerry Mendell has worked on them for more than 50 years, so we know this patient population well. We have viruses that are taken up by skeletal muscle quite well, and we can biopsy muscle to directly evaluate how our viral payloads are expressed, which is very helpful. We also have an excellent clinical research team that continues to develop and validate appropriate functional outcomes in these diseases, which is necessary for good clinical trials.

Could you move into treating other diseases?
The lessons learned from preclinical and clinical studies with vectors for neuromuscular diseases are applicable to many other diseases. We don't expect these approaches will work only for neuromuscular diseases, but that's where our areas of interest have historically been, and these studies have allowed us to demonstrate proof of concept in human safety and efficacy. As I mentioned earlier, we have programs directed toward the central nervous system as well. We've gained a lot of experience in navigating the regulatory process. We have an in-house regulatory group, and it's one of the reasons that we've submitted more than 15 active gene therapy Investigational New Drug applications. We will have multiple new INDs coming out within the next year.

How does gene therapy fit with pediatric medicine?
Many pediatric disorders are devastating or lethal, which makes the argument for starting with these most severe diseases. One advantage in pediatric medicine is that one of the great challenges of gene therapy is manufacturing sufficient quantities of any viral vector. Since many of these therapies dose by weight, using a given number of virus particles per kilogram, we can test them more readily in pediatric diseases, and can design trials that involve more patients.

Are you optimistic that gene therapy will reach the clinic?
I am very optimistic. One sign that it's moving toward practice is the number of biopharmaceutical companies that are now developing gene therapies. Some of these are companies that we have partnered with, but regardless of whether we consider products licensed from Nationwide Children's or elsewhere, the enthusiastic and growing engagement of biopharma partners signals great confidence in the field.

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- The Institute for Genomic Medicine at Nationwide Children's is one of few programs in pediatric genomic medicine, focusing on the root causes of many childhood diseases.
- Nationwide Children's Center for Gene Therapy has a robust pipeline of more than 20 genetic targets to treat various disorders.
- AveXis, a clinical stage company founded on Nationwide Children's gene therapy programs, was recently sold to Novartis.
- The Nationwide Children's cGMP facility focuses on first-in-human clinical trials, with lab spaces reserved for viral vector manufacturing and cell-based therapies.
- Four additional startups are based on Nationwide Children's gene therapies and genome analysis capabilities:

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complex, entangled interactions among quantum systems give rise to the world we perceive. But not all physicists believe that decoherence solves the measurement problem. What is it that causes us to see one part of the quantum elephant and not another? It seems we still need to invoke some kind of collapse to explain why we see the elephant's trunk rather than its tail.

DRUG ADDICTION

In "Safe Injection Facilities Save Lives" [Science Agenda], the editors argue for the use of places in which addicts can consume illegal drugs under medical supervision as a way to fight the opioid crisis. The essay rings true to me. I am a Canadian, and we continue to go through the same issues of resistance to such sites, which are very much a public health measure rather than a way to encourage user activity.

The reasons for promoting safe sites are many: people who use drugs will keep doing so regardless, and is it not better to do so in a warm, dry setting rather than behind some dumpster? Additionally, clean, sterile injection equipment means there is much less chance of contracting an infectious disease. Medical costs for prevention are also much less than for treatment.

J. M. Stone *via e-mail*

MANAGING PAIN

In "Why We Won't Miss Opioids" [The Science of Health, June 2018], Claudia Wallis reports on research finding that opioids are not more effective at combating chronic pain than nonopioid drugs are.

As a practicing dentist, I can say that Wallis is spot on about the numbers and amounts of opioids prescribed in dentistry in particular. Even if it's impossible to totally ditch opioids, especially if you're doing surgery involving bone cutting, nonsteroidal anti-inflammatory drugs (NSAIDs) are an excellent substitute. And there is a significant difference in pain control between 400 milligrams of ibuprofen and 600 to 800 mg. Ask me how I know: back surgery!

Wes Blakeslee *Wall Township, N.J.*

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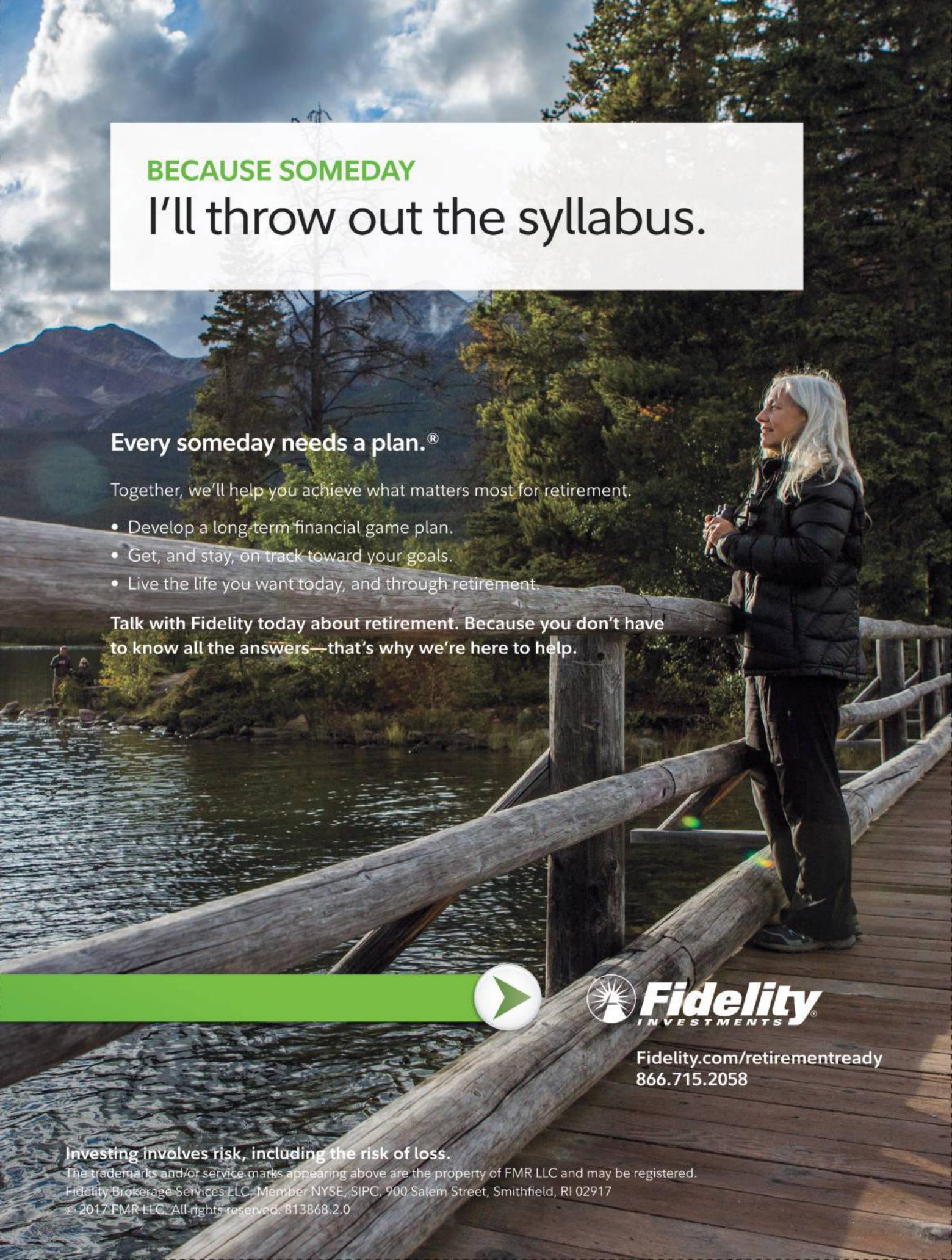
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Dereliction of Duty

The U.S. Congress has not protected health or the environment. Time to make it step up

By the Editors

There are several hundred people in Washington, D.C., paid with taxpayer dollars, who are not doing their jobs. This November we have the chance to do something about that because these people are members of the U.S. Congress, and in upcoming elections, they can be replaced with representatives who will live up to their responsibilities.

Those responsibilities, set out by the Constitution, include oversight of the executive branch, in this case the Trump administration. That administration's agencies are supposed to craft policies based, in part, on good evidence and good science. For the past 21 months, many of them have not. Yet Congress has refused to hold them accountable.

Exhibit A is the Environmental Protection Agency. Its mission, the agency says, is "to protect human health and the environment … based on the best available scientific information." Instead the EPA has ignored scientific evidence to justify lowering power plant emissions and greenhouse gas targets; made it more difficult for people to learn about potentially dangerous chemicals in their communities; replaced independent scientists on advisory boards with people connected to businesses the agency is supposed to regulate; and tried to make it harder to use science as a basis for regulations to protect human health.

During all of this, Congress has done next to nothing.

Consider what happened this past spring , when EPA director Scott Pruitt, who has since resigned amid a dozen ethics investigations, proposed that no research could be used to form environmental policy unless all data connected to it were publicly available. He said this proposed rule would ensure transparency. It was really a transparent effort to ignore science.

Specifically, it would ignore research that links industrial pollution to human health. These studies include confidential patient data, such as names, addresses, birthdays and health problems—data that were only provided by patients under a guarantee of privacy. The Six Cities study, begun in the 1970s, was the first research to show that particulate matter in the air hurts and kills people. It has been replicated several times. But because its publications do not include all private patient data, the study would be ignored by the EPA when it considers permissible pollution levels. The World Health Organization estimates that this kind of pollution, largely from minute particulates, kills three million people worldwide every year. For these reasons, the rule has been condemned by every major health and science group.

There were two congressional hearings involving the EPA after this rule was proposed. The House Committee on Energy and Commerce's environmental subcommittee interviewed Pruitt, starting off with the chair, Republican Representative John Shimkus of Illinois, stating he was "generally pleased" with what the agency was doing. The senior minority member, Democratic Representative Paul Tonko of New York, did voice concerns about science, but the focus of the hearing remained elsewhere. In the Senate, an appropriations subcommittee gave Pruitt a much tougher time on his personal ethics but also spent almost no effort on science.

Pruitt has departed, but there is no reason to think that his antiscience approach has gone with him. The health studies rule is still under active consideration. Further, the EPA announced looser power plant standards this August despite admitting, in its own document, that the extra pollution would lead to 1,400 additional deaths in the U.S. each year.

Similar evidence-free approaches have taken hold at the Department of the Interior, which is scuttling a wildfire-fighting science program whose discoveries help firefighters save lives by forecasting the direction of infernos. The Department of Energy has stopped a set of new efficiency standards for gas furnaces and other appliances. Congress has been quiet.

Congressional committees work by majority rule, so if the Republicans in the current majority do not want to hold hearings or use their control over agency budgets to compel changes, there are none. But the American people can make a change. The entire House of Representatives and one third of the Senate are up for reelection right now (except for those who are retiring). We can, with our votes, make them do their jobs. SA

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Illustration by Chris Gash

Maia Szalavitz is a journalist and author. Her latest book is *Unbroken Brain: A Revolutionary New Way of Understanding Addiction* (St. Martin's Press, 2016).

Income Inequality and Homicide

Where financial disparities are greatest, the murder rate tends to be high

By Maia Szalavitz

Income inequality can cause all kinds of problems across the economic spectrum—but perhaps the most frightening is homicide. Inequality—the gap between a society's richest and poorest—predicts murder rates better than any other variable, according to Martin Daly, a professor emeritus of psychology at McMaster University in Ontario, who has studied this connection for decades. It is more tightly tied to murder than straightforward poverty, for example, or drug abuse. And research conducted for the World Bank finds that both between and within countries, about half the variance in murder rates can be accounted for by looking at the most common measure of inequality, which is known as the Gini coefficient.

The murders most associated with inequality, it seems, are driven by a perceived lack of respect. Like most killings, these are mostly perpetrated by males—and in societies with low inequality, there tend to be very few murders. To an outsider, these deaths, which make up more than a third of the homicides with known motives reported to the FBI, seem senseless: a guy looks at someone else the wrong way, makes a disrespectful remark, or is believed to have winked at another man's wife or girlfriend. These incidents seem too trivial to be matters of life and death. "A prosperous guy like me, if someone [insults me] in a bar, I can roll my eyes and leave," Daly says. "But if it's your local bar, you are unemployed or underemployed, and your only source of status and self-respect is your standing in the neighborhood, turning the other cheek looks weak, and everyone soon knows you are an easy mark."

Some argue that in these cases, the real issue is poverty, not inequality. For example, William Pridemore, dean of criminology at the University at Albany, S.U.N.Y., says that the inequity correlation is a methodological artifact. He gives a theoretical example of a country in which everyone is meaningfully employed, can afford vacations and other small luxuries, and lives in a safe neighborhood with free health care—but some of them are billionaires. He asks whether this sort of place would have the same level of violence as places where those at the bottom are in abject poverty instead. Whereas the size of gaps between rungs on the financial ladder may be identical in both cases, the level of relative deprivation experienced by people at the bottom rung may not be—inequality is not just about having less when others have more; it is about how low status is perceived.

That, Daly argues, is what can make status differences deadly. The living standards of poor people in developed countries today would be beyond the dreams of kings in the past because of technology—but we do not rate our social status by comparing ourselves with medieval lords; we do so by looking at those around us.

That specific and mostly local level of comparison may, in turn, explain one of the biggest mysteries in homicide and inequality research. Why, as inequality has skyrocketed in the U.S. in recent years, has the murder rate continued to fall? One explanation is a time lag: it takes a while for people to recognize their loss of status as the middle class erodes and they either plummet downward or join the tiny minority at the top. Indeed, murder rates have lately stopped falling and may even be ticking upward. And we have seen rises in what have been labeled "deaths of despair," such as suicide and opioid overdoses, which research also links with inequality.

Another possible explanation is that as richer people retreat into ever more exclusive communities, their virtual disappearance masks rises in local inequality that are felt by former neighbors. A society in which millions struggle to pay their student loans and make a decent living while watching U.S. secretary of education Betsy DeVos—a woman of enormous wealth—cut the education budget and protect predatory for-profit schools is unlikely to be a safe and stable one. When men have little hope of a better future for either themselves or their kids, fights over what little status they have left take on outsize power. To break the cycle, everyone must recognize that it is in no one's interest to escalate such pain.

For more on "The Science of Inequality," see our special report, starting on page 54.

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Illustration by Benjamin Currie

ADVANCES

Researchers altered dogs' genes to treat Duchenne muscular dystrophy. It could one day lead to a treatment for humans.

INSIDE

MAGONE Getty Images

GENETICS

Fixing Wasting Muscles

Scientists edited dogs' genes to correct a common form of muscle dystrophy

Duchenne muscular dystrophy is a life-threatening muscle-wasting illness. Occurring mostly in males, it is the most common type of muscular dystrophy, striking about one in 3,500 boys and causing their muscles to start breaking down in early childhood. It often confines patients to wheelchairs by the time they are teenagers and usually leads to an early death from heart or respiratory failure. There is no cure—but a genetic fix tested in dogs may offer new hope.

The disease is caused by gene mutations that make patients' muscle cells unable to produce enough dystrophin, a protein that helps muscles absorb shocks and protects them against degradation over time. In a recent study, scientists used a gene-editing technique called CRISPR/Cas9 to pump up muscle protein levels in four dogs suffering from Duchenne. The advance may hasten clinical trials for similar treatments in humans.

The research team, led by the University of Texas Southwestern Medical Center, worked with young beagles bred to have Duchenne. The scientists edited the dogs' muscle cells to remove a key barrier to higher protein production—a short, problematic segment of protein-coding DNA that occurs in both canines and humans with the illness. Within about two months the dogs were

producing greater amounts of dystrophin; levels in skeletal muscle ranged up to 90 percent of normal, depending on the muscle type and dosage used. (Some dogs produced significantly less.) In cardiac muscle, a crucial target for treatment, levels climbed to as high as 92 percent of normal. The U.T. Southwestern researchers, who published their findings in August in *Science,* report that they did not detect any unintended changes to other regions of the genome—a common concern with gene-editing technology—and there was no evidence the technique made the dogs ill.

To deliver this technology to the dogs' muscles, senior author Eric Olson, a molecular biologist at U.T. Southwestern, and his colleagues engineered viruses to act as delivery trucks, stripping out some of the viruses' own DNA to make room for gene-editing machinery. A number of the viruses were then loaded up with the Cas9 enzyme, which acts like molecular "scissors"; this was used to cut out the DNA sequence that hinders dystrophin production in muscle cells. Other viruses carried a guide molecule to help the Cas9 identify where it should make the needed cuts.

Olson's team had previously demonstrated that CRISPR could be used to treat Duchenne in rodents and in human cells in the laboratory. The new work marks the first success in a large mammal. For this study, the team focused only on measuring protein-level restoration. It has not explored how the intervention might have changed the dogs' behavior or day-to-day lives.

Exactly how long one injection with CRISPR gene-editing machinery might last in human Duchenne patients remains unknown. Olson and his colleagues hope the intervention might be durable enough with a single dose, but they need further results to get a clearer idea. If patients require more treatments over time, they might not be able to use the same viral vehicle, says Elizabeth McNally, a geneticist and cardiologist who directs the Center for Genetic Medicine at Northwestern University. "The body may develop neutralizing antibodies, so there are a lot of questions about the viral delivery piece of that," says McNally, who is also on the scientific advisory board of Olson's spin-off company trying to commercialize this Duchenne technology but was not involved with this study.

The sole Duchenne treatment currently approved for the U.S. market—an injectable drug made by Sarepta Therapeutics that requires continuous delivery—increases dystrophin levels by less than 1 percent. This approach, which has yet to show a clinical benefit, differs from Olson's in that it works on RNA (the molecule into which DNA is eventually transcribed) but leaves the abnormal DNA sequence unchanged.

Duchenne researcher Amy Wagers, a professor of stem cell biology and regenerative medicine at Harvard University, who is not involved with developing either therapy, says these two approaches could potentially be used in tandem to help boost dystrophin. "I think it's really exciting to see this new work in mice now translated to a large animal model," she says, adding that "the authors very appropriately note that this is a preliminary study with a small number of animals and a short follow-up time."

Both Sarepta's approved technology and Olson's experimental one target a subset of the Duchenne population: patients with a particular dystrophin gene mutation that affects about 13 percent of those with the disease. There are at least 1,000 such cases in the U.S. "We need to do long-term safety and efficacy studies in dogs," Olson says. "It will be a few years before we're ready to test this in humans if it continues to hold up."

—Dina Fine Maron

MATERIALS SCIENCE

Artificial Wood

The synthetic material is both robust and versatile

A new lightweight substance is as strong as wood yet lacks its standard vulnerabilities to fire and water.

To create the synthetic wood, scientists took a solution of polymer resin and added a pinch of chitosan, a sugar polymer derived from the shells of shrimp and crabs. They freeze-dried the solution, yielding a structure filled with tiny pores and channels supported by the chitosan. Then they heated the resin to temperatures as high as 200 degrees Celsius to cure it, forging strong chemical bonds.

The resulting material, described in August in *Science Advances,* is as crush-resistant as wood, says author Shu-Hong Yu, a materials chemist at the University of Science and Technology of China in Hefei. Faster freeze-drying creates even smaller channels and pores, which further strengthens the material, Yu says. And higher curing temperatures increase bonding within the resin and increase the material's strength, the team found. Adding human-made or natural fibers to the mix could also help.

Unlike natural wood, the new material does not require years to grow. Moreover, it readily repels water—samples soaked in water and in a strong acid bath for 30 days scarcely weakened, whereas samples of balsa wood tested under similar conditions lost two thirds of their strength and 40 percent of their crush resistance. The new material was also difficult to ignite and stopped burning when it was removed from the flame.

The mock wood could be used to make dding-resistant packaging, says Lennart Bergström, a materials scientist at Stockholm University in Sweden, who was not involved in the work. Its porosity lends an air-trapping capacity that could make it suitable as an insulation for buildings, he adds. Eco-friendly alternatives to the polymer resins also could boost interest in the material.

—Sid Perkins

FROM "BIOINSPIRED POLYMERIC WOODS," BY ZHI-LONG YU ET AL., IN *SCIENCE ADVANCES*, VOL. 4, NO. 8; AUGUST 10, 2018

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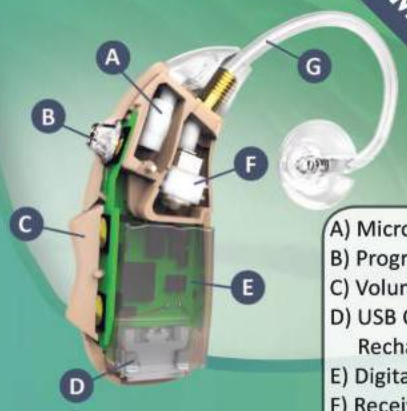

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Flooding in the state of Kerala in India in August 2018. Climate change is making extreme weather events more likely.

GETTY IMAGES

PSYCHOLOGY

Flooding the Senses

Visualizing climate catastrophes may spur people to act

Many people view climate change as a distant, abstract threat. But having them imagine the tangible consequences of resulting droughts or floods may help shift this perception and encourage proenvironmental behavior, a new study suggests.

Researchers asked 93 college students in Taiwan to read a report on temperature anomalies, floods and other climate change-related events that have affected the island. The scientists then asked 62 of the participants to write down three ways in which such phenomena might impact their future lives. Half the people in that group were instructed to imagine such scenarios in detail, including specific individuals and settings. The remaining 31 students did not complete either the writing or imagining steps, acting as a control group.

All the participants then rated their perceptions of climate change risks by responding to prompts such as "How likely do you think it is that climate change is having serious impacts on the world?" They used a scale from 1 ("very unlikely") to 7 ("very likely"). The average score was higher among subjects who had been asked to envision detailed scenarios than among those who had not. The results were later confirmed in a second experiment involving 102 participants.

Individuals in the first experiment who had visualized the effects of climate change were subsequently more likely to say they would use air conditioning in an energy-saving manner. In the second

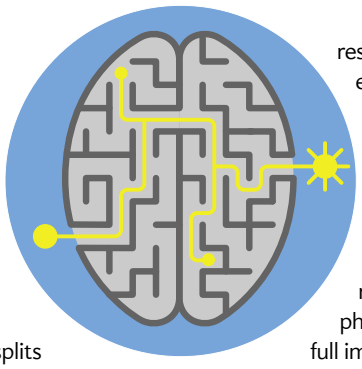
TECH

Lifelong Learning

Creating artificial intelligence that continues to adapt

What if you stopped learning after graduation? It sounds stultifying, but that is how most machine-learning systems are trained. They master a task once and then are deployed. But some computer scientists are now developing artificial intelligence that learns and adapts continuously, much like the human brain.

Machine-learning algorithms often take the form of a neural network, a large set of simple computing elements, or neurons, that communicate via connections between them that vary in strength, or "weight." Consider an algorithm designed to recognize images. If it mislabels a picture during training, the weights are adjusted. When mistakes are reduced below a certain threshold, the weights are frozen at set values.



The new technique splits each weight into two values that combine to influence how much one neuron can activate another. The first value is trained and frozen as in traditional systems. But the second value continually adjusts in response to surrounding activity in the network. Critically, the algorithm also learns how adjustable to make these weights. So the neural network learns patterns of behavior, as well as how much to modify each part of that behavior in response to new circumstances. The researchers presented their technique in July at a conference in Stockholm, Sweden.

Applying the technique, the team created a network that learned to reconstruct half-erased photographs after seeing the full images only a few times. In contrast, a traditional neural network would need to see many more images before it could reconstruct the original. The researchers also created a network that learned to identify handwritten alphabet letters—which are nonuniform, unlike typed ones—after seeing one example.

In another task, neural networks controlled a character moving in a simple maze to find rewards. After one million trials, a network with the new semiadjustable

Illustrations by Thomas Fuchs

experiment, nearly two thirds of people in the visualizing group signed up to help clean a beach, compared with 43 percent in the nonvisualizing one. And when offered a choice of a vegetarian or nonvegetarian lunch box, nearly half the visualizers selected the environmentally friendlier meatless option—compared with about 28 percent of the nonvisualizers, the researchers reported online in July in *Environment and Behavior.*

The investigators did not track people to see if they behaved differently in their day-to-day lives—something further studies should examine, says study co-author Wen-Bin Chiou, a professor of psychology at Taiwan's National Sun Yat-sen University. Moreover, the research "should be replicated in other places with other populations," says Robert Gifford, a professor of psychology at the University of Victoria in British Columbia, who was not involved in the work.

The findings could nonetheless be applied to raise public concern about climate change, Chiou says. For example, he suggests that news reports about the phenomenon could include vivid descriptions of its effects on people's lives and ask readers to imagine experiencing such impacts. Having virtual-reality demonstrations in local science museums of the consequences of climate change would be another way of putting the research into practice, Chiou adds. *—Agata Blaszczak-Boxe*

weights could find each reward three times as often per trial as could a network with only fixed weights. The static parts of the semiadjustable weights apparently learned the structure of the maze, whereas the dynamic parts learned how to adapt to new reward locations. "This is really powerful," says Nikhil Mishra, a computer scientist at the University of California, Berkeley, who was not involved in the research, "because the algorithms can adapt more quickly to new tasks and new situations, just like humans would."

Thomas Miconi, a computer scientist at the ride-sharing company Uber and the paper's lead author, says his team now plans to tackle more complicated tasks, such as robotic control and speech recognition. In related work, Miconi wants to simulate "neuromodulation," an instant networkwide adjustment of adaptability that allows humans to sop up information when something novel or important happens.

—Matthew Hutson

Amy Adams and an alien character in the film *Arrival*.

ASTROBIOLOGY

Decoding Alien Senses

A linguist explains how limited our thinking about extraterrestrials can be

In the 2016 blockbuster film *Arrival,* aliens with inscrutable motives descend on Earth—and it is up to a scientist played by Amy Adams to help communicate with them. Were this to occur in real life, it might be Sheri Wells-Jensen who gets the call. A linguist at Bowling Green State University, Wells-Jensen has thought a lot about just how different alien minds might be.

Many researchers have automatically presumed extraterrestrials would possess senses like the ones most of us use every day. But Wells-Jensen's sensory experience of the world—as a blind person—has given her a rare perspective when it comes to imagining the alternatives and what they might mean for humans' ability to understand aliens.

Scientific American spoke with Wells-Jensen about language, crab-shaped aliens and multidimensional ways to view the world. An edited excerpt follows. —*Adam Mann*

Can linguists inform the search for extraterrestrial intelligence?

If we are expecting to come across an alien language, we have to start thinking about what language is, how we recognize it and how it could be different from what we know. We need to create a bunch of crazy hypotheses, and we need to start thinking outside our box.

How are you trying to think outside the box with your research?

Back in 2014, I got a call to talk to the SETI [Search for Extraterrestrial Intelligence] Institute and was trying to get up to speed on the literature. And one of the presumptions I kept coming across is that any extraterrestrial civilization would have to be sighted. I'm trying to break that box down. The dangerous thing about presuppositions is that you don't know you are making them.

For me, this ties back into lots of other anthropological questions about how we treat one another. If we as a species cannot even deal with minor differences such as race and gender, why do we think we are going to get along with crab-shaped aliens, for example? Can we be kind and empathetic to one another, which is a small task compared to saying, "Yeah, let's welcome the crab-shaped aliens with their intestines on the outside of their bodies who chew with their mouths open"?

Do our bodies influence our cognition?

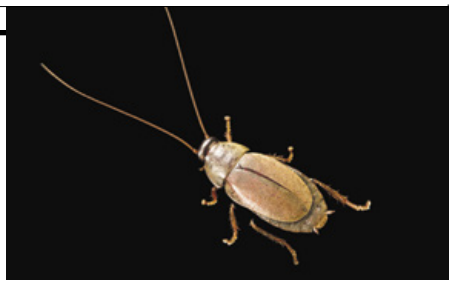
I can give you a bunch of minor examples—the word for "see" also means "understand" in some languages. Or we have words for "left" and "right," "straight ahead" and "back"—kind of in four directions, which is correlated with human body symmetry. But if we had three hands, would we have "left," "right" and, uh, "the other hand"?

This is a question that fascinates me. The structure of ASL (American Sign Language) conforms largely to the same rules as spoken language, except you can do more things simultaneously. But it is not alien. It is recognizably a human language, and we can all learn it. And blind people can learn the languages of the sighted people around them. One of the questions I have is, How dissimilar does your body shape have to be to really test this hypothesis?

Alien bodies could be very different from ours. They could use sonar and live in water, for instance—and have that third hand.

Exactly. For example, I can imagine right, left and some other direction called "squirk." It would take a while to learn it fluently, but I feel like I could learn it. But how far do you have to go before it slips over into incomprehensibility? It could be that alien languages just get harder and harder to understand as the forms of the body diverge. Or is there this barrier? For instance, "No, my brain can't do that"? Would the two languages forever be incompatible? We have to practice thinking about these examples—even the ones we don't like.

PHOTOFEST. *ARRIVAL* © 2016 PARAMOUNT PICTURES (*movie still*); COURTESY OF SHERI WELLS-JENSEN (*Wells-Jensen*)



JOEL SARTORE *Getty Images*

ANIMAL BEHAVIOR

Unwanted Advances

Female cockroaches gather in groups to avoid male attention

Humans are not the only species that deals with harassment. According to new research, female cockroaches may cluster together to keep male suitors at bay.

Christina Stanley, an animal behavior lecturer at the University of Chester in England, and her colleagues put Pacific beetle cockroaches in special containers to observe their social behavior. The roaches would gather in primarily female groups and jostle out the males. "Female [roaches] created this better social environment by excluding the males," says Stanley, who led the study published online in July in *Ethology.* Because the females are much larger than the males, they "are more dominant, so they are more able to push the males out of the way," she adds.

The researchers also ran an experiment with a higher ratio of male to female roaches. Under this condition, the females received more approaches and antenna investigations from males intent on mating. Thus, the females might flock as a strategy to deflect males' advances, Stanley says.

Coby Schal, an entomology professor at North Carolina State University, who was not involved in the research, is unconvinced that the females were all trying to avoid male attention; he says the size difference between the sexes alone could account for the males getting kicked out.

But the changed behavior in the experiment with the excess males shows that more is at play, Stanley says. Also, female Pacific beetle roaches can store sperm from a single mating. Therefore, any further copulation would waste energy and could result in injury (not uncommon among roaches). Beyond brief time windows for initial encounters, the otherwise social females appear to have little use for males. —*Joshua Rapp Learn*

GENDER EQUALITY

Time for Women Leaders

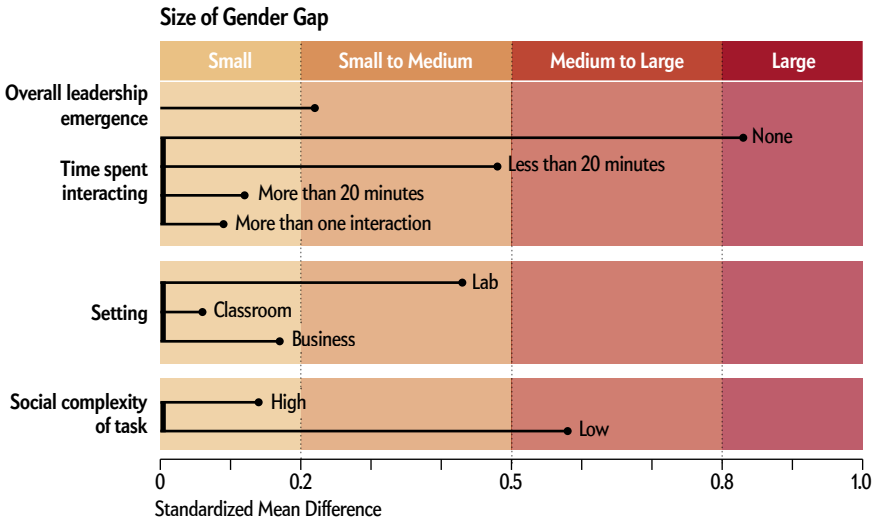
The gender gap in leadership narrows when groups spend more time together

Only 28 percent of American CEOs are women. To find out why such a gap exists, a study published this fall in *Personnel Psychology* analyzed more than 100 papers on leadership emergence published between 1957 and 2017. In the papers, samples of students or co-workers were asked to select group leaders or to rate one another on the extent to which they led a group. Some of the papers also measured group participation and personality traits such as assertiveness. As predicted, men emerged as leaders more often than women. But that gap varied depending on the length of interaction and other factors (*graphic*).

The data suggest that men were more likely overall to be chosen or rated as leaders, in part because they had more assertive personalities and thus spoke up more. Men and women were equally likely to emerge as leaders, however, when groups interacted for more than 20 minutes—possibly, the researchers write, because members relied less on gender stereotypes as they became better acquainted.

Other research shows that male and female leaders perform equally well. Considering the gender gap at the top of organizational charts, "that's a ton of human capital that organizations are ignoring," says Katie Badura, a management researcher at the University at Buffalo, S.U.N.Y., and the lead author of the new study. She says women should not be asked to change their behavior as a way of addressing this situation; rather organizations should train employees to change their perspectives.

Alice Eagly, a psychologist now at Northwestern University, who conducted a similar analysis 27 years ago, praised the project's large scale. Eagly advocates for women's empowerment, but she also has advice for men: "Be less dominant. Let other people have some time to talk." —*Matthew Hutson*



People are generally less likely to recognize leadership qualities in women than in men. But this gender gap shrinks when a group interacts for longer periods of time, a study shows. Researchers also looked at other variables, including the setting and social complexity of tasks being studied. Laboratory settings had a larger gender gap than business ones, but once the length of time employees interact with one another was considered, the gap became wider in business settings. This indicates that whereas length of interaction time is important, business environments may have additional factors that perpetuate the gender gap. Groups engaged in socially complex activities—such as innovative problem-solving—exhibit a relatively small gender gap, but this disappeared after accounting for other factors.

SOURCE: "GENDER AND LEADERSHIP EMERGENCE: A META-ANALYSIS AND EXPLANATORY MODEL," BY KATIE L. BADURA ET AL., IN *PERSONNEL PSYCHOLOGY*, VOL. 71, NO. 3; AUTUMN 2018

Graphic by Amanda Montañez

SCIENTIFIC STANDARDS

Measure for Measure

Officials will vote to overhaul the standard system of scientific measurements

Kilogram No. 20, in the U.S., is one of several "working standards."

SCIENCE SOURCE

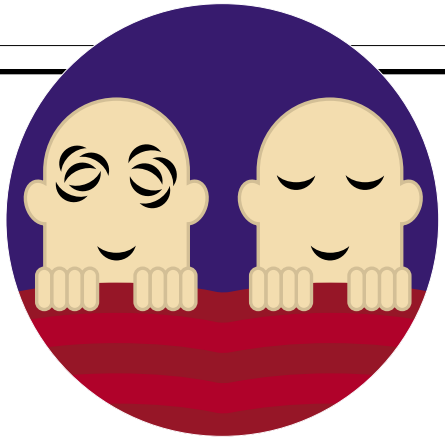
The kilogram is shrinking.

The official object that defines the mass of a kilogram is a tiny, 139-year-old cylinder of platinum and iridium that resides in a triple-locked vault near Paris. Because it is so important, scientists almost never take it out; instead they use copies called working standards. But the last time they did inspect the real kilogram, they found it is roughly five parts in 100 million heavier than all the working standards, which have been leaving behind a few atoms of metal every time they are put on scales. This is one of the reasons the kilogram may soon be redefined not by a physical object but through calculations based on fundamental constants.

"This [shrinking] is the kind of thing that happens when you have an object that needs to be conserved in order to have a standard," says Peter Mohr, a physicist at the National Institute of Standards and Technology (NIST), who serves on the committee that oversees the International System of Units (SI). "Fundamental constants, on the other hand, are not going to change over time."

The redefinition of the kilogram will be part of a planned larger overhaul to make SI units fully dependent on constants of nature. Representatives from 57 countries will vote on the proposed change this month at a conference in Versailles, France, and the new rules are expected to pass. Along with the kilogram, the ampere (the unit of electric current), kelvin (temperature) and mole (amount of a substance) will get new definitions. The four will be based on Planck's constant, the elementary charge, the Boltzmann constant and the Avogadro constant, respectively. All these constants are determined by laboratory measurements, which have some inherent uncertainty. But if the vote is successful, countries using SI will agree on a fixed value for each constant based on the best data available and use them to derive the units.

What will happen to the old kilogram artifacts after the redefinition? Rather than packing them off to museums, scientists plan to keep studying how they fare over time. "There is so much measurement history on these," says physicist Stephan Schlamminger of NIST. "It would be irresponsible to not continue to measure them." —*Clara Moskowitz*



SLEEP SCIENCE

To Sleep, Perchance to Gene

Researchers identify genes linked to rapid eye movement sleep

Scientists have known about the stage of sleep called rapid eye movement, or REM—which is associated with dreaming as well as improved learning and memory—since the 1950s. Many of its mechanisms remain mysterious, however. Now a study has identified two genes that play a key role in REM.

Mice that lack the genes *Chrm1* and *Chrm3* sleep fewer hours than typical mice and have almost undetectable REM levels, the researchers find. This is the first time scientists have homed in on genes essential for REM sleep, says Hiroki Ueda of Japan's RIKEN Center for Biosystems Dynamics Research, who conducted the study published in August in *Cell Reports.*

Ueda and his colleagues focused on the neural signaling chemical acetylcholine and its receptors in brain cells. Previous research had linked acetylcholine to REM sleep regulation, but Ueda's team wanted to find out which specific genes and receptors were involved. Using a variation of the gene-editing method CRISPR/Cas9, they produced seven mice lacking genes that encode different acetylcholine receptors. They measured REM and non-REM sleep in the genetically altered mice and in eight control mice, using electroencephalogram and electromyogram recordings.

Mice without both the *Chrm1* and *Chrm3* genes slept less than the normal mice and got almost no REM sleep, the researchers found. Mice lacking only *Chrm1* had shorter and more fragmented REM sleep; those without only *Chrm3* had shorter non-REM sleep.

Yu Hayashi of the International Institute for Integrative Sleep Medicine at the University of Tsukuba, who was not involved in the study, says the results could mean that REM sleep is not necessary for survival; that the mutant mice somehow circumvent the need for it; or that the mice were engaging in REM sleep in deeper brain layers that the experiment did not detect. More research is needed to tease apart these possibilities.

Ueda says the findings could help illuminate sleep and mood disorders in people because REM sleep and its associated intense dreams are thought to affect depression and other illnesses. —*Tim Hornyak*

IN THE NEWS

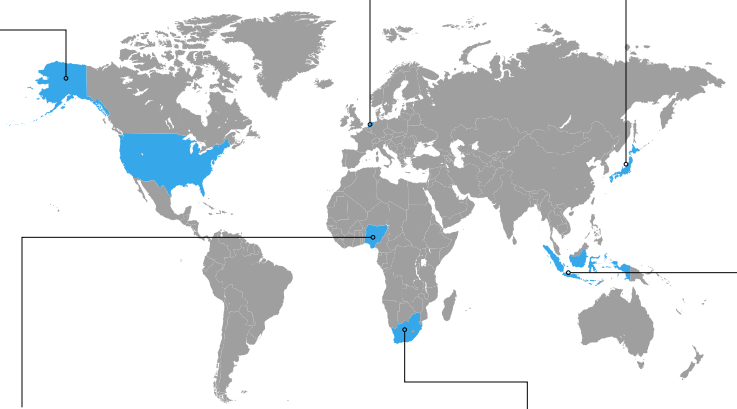
Quick Hits

By Ankur Paliwal

THE NETHERLANDS
The world's first offshore dairy farm is expected to open near the port of Rotterdam by the end of the year. The idea is to produce food closer to urban areas, where two thirds of people will live by 2050, and to reduce pollution caused by transporting food over long distances.

JAPAN
The Japanese government has lifted its ban on juvenile use of the flu drug Tamiflu. The ban was imposed following reports of patients jumping off houses after taking the drug, but scientists have found no direct link between Tamiflu use and this behavior.

U.S.
Scientists mapped one of the world's fastest-moving underwater faults in Alaska, which has a slip rate of five centimeters a year. These data could help coastal communities in Alaska and Canada prepare for earthquakes and tsunamis.



INDONESIA
Jakarta is sinking fast. Indonesia's capital is built on ground that is subsiding as a result of flooding and sea-level rise, and about 95 percent of North Jakarta could be underwater by 2050. The government is now building a 32-kilometer seawall to protect the city.

NIGERIA
Nigeria has launched its first renewable energy association, with the goal of generating about 40 percent of the country's total energy from green sources by 2030. More than 50 percent of the population currently lacks access to any energy sources.

SOUTH AFRICA
South Africa has completed MeerKAT, the largest and most powerful radio telescope in the Southern Hemisphere. The telescope—part of the multicontinent Square Kilometer Array—will study how hydrogen gas moves into galaxies to fuel star formation.

For more details, visit www.ScientificAmerican.com/nov2018/advances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Why Oral Cancer Threatens Men

Researchers wrestle with the rising rates of virus-related tumors

By Claudia Wallis

Back in 2006, when the vaccine for human papillomavirus (HPV) was introduced, I rushed to get my teenage daughters immunized. Here, amazingly, was a vaccine that could actually prevent cancer. By blocking HPV infection, it protects girls from the leading cause of cervical malignancies. I didn't give much thought to my son, and neither did the medical establishment. It wasn't until 2011 that health authorities recommended the vaccine for boys.

In hindsight, that delay was a mistake, though perfectly understandable: the vaccine was developed with cervical cancer in mind and initially tested only in girls. Today, however, we see a rising tide of cancers in the back of the throat caused by HPV, especially in men, who are three to five times more vulnerable than women. This surge of oropharyngeal cancers, occurring in many developed nations, took doctors by surprise. Oral cancers were expected to decline as a result of the drop in smoking that began in the 1960s.

Smoking-related oropharyngeal cancers are, in fact, down. But making up the difference, particularly in men, are those related to HPV, which have more than doubled over the past two decades. With cervical cancer waning (thanks to screening and prevention), this oral disease is now the leading HPV-related cancer in the U.S.

Claudia Wallis is an award-winning science journalist whose work has appeared in the *New York Times, Time, Fortune* and the *New Republic.* She was science editor at *Time* and managing editor of *Scientific American Mind.*

Nearly 19,000 cases were reported in 2015, according to a recent report by the Centers for Disease Control and Prevention. Roughly nine out of 10 involve a nasty strain called HPV-16.

Researchers link the rise of these cancers to changing sexual practices, perhaps dating back to the 1970s. "People have more partners than they had in the past, and they initiate oral sex at an earlier age than previous generations did," says Gypsyamber D'Souza, associate professor of epidemiology at the Johns Hopkins Bloomberg School of Public Health. Greater exposure to oral sex means that the nearly ubiquitous virus gets transferred from the genitals to the mouth.

Studies suggest that most women develop protective antibodies to HPV after having a few sexual partners, but for men, it may take more than 10 partners. A likely reason for the difference, says oncologist Maura Gillison of the University of Texas MD Anderson Cancer Center, is that "in women, the infection is vaginal-mucosal; in men, it's entirely on the skin," where it is much less likely to trigger an antibody response. Males can get an active infection again and again, and it lingers longer than in women, making them the "Typhoid Marys of HPV," as Gillison puts it. The path from infection to cancer may take decades and is not well understood.

Fortunately, the HPV vaccine should prevent these oral cancers, just as it protects against cervical cancer (as well as virus-related cancers of the vulva, labia, penis and anus). After lagging for years, U.S. rates of vaccination of boys are catching up with that of girls. New CDC data show that in 2017, 68.6 percent of girls and 62.6 percent of boys, ages 13 to 17, had received at least one dose of the vaccine—up from 65.1 and 56 percent, respectively, in 2016. If the trend continues, HPV-related cancers will ultimately become a scourge of the past in the U.S.

The tough question is what to do in the meantime for the large number of people, especially at-risk men, who have never been immunized. The CDC recommends the vaccine for children as young as nine and up to age 21 for boys and 26 for girls. Merck, which makes the only HPV vaccine now used in the U.S., is seeking approval to make it available up to age 45, but the $130-a-dose vaccine is less cost-effective in older populations. "It's best given before people are sexually active," explains Lauri Markowitz, team lead and associate director of science for HPV at the CDC. "The vaccine is not therapeutic; it's prophylactic." A vaccine advisory committee meeting this fall will weigh whether to revise current recommendations. One possibility, she says, is raising the upper age for boys to 26, matching that for girls.

D'Souza, Gillison and others are investigating ways to identify and screen people who may be at an especially high risk for oral HPV cancers—a significant challenge. There is no Pap-smear equivalent for this devastating disease, no reliable way to spot precancerous or early-stage lesions. And research by and her colleague Carole Fakhry shows that even if you focus on a high-risk group such as men in their 50s—8 percent of whom are infected with one of the noxious HPV strains—only 0.7 percent will go on to develop the cancer. There's little point in terrifying people about the small odds of a bad cancer, D'Souza says, so "we're working on understanding which tests would be useful." SA

Illustration by Celia Krampien

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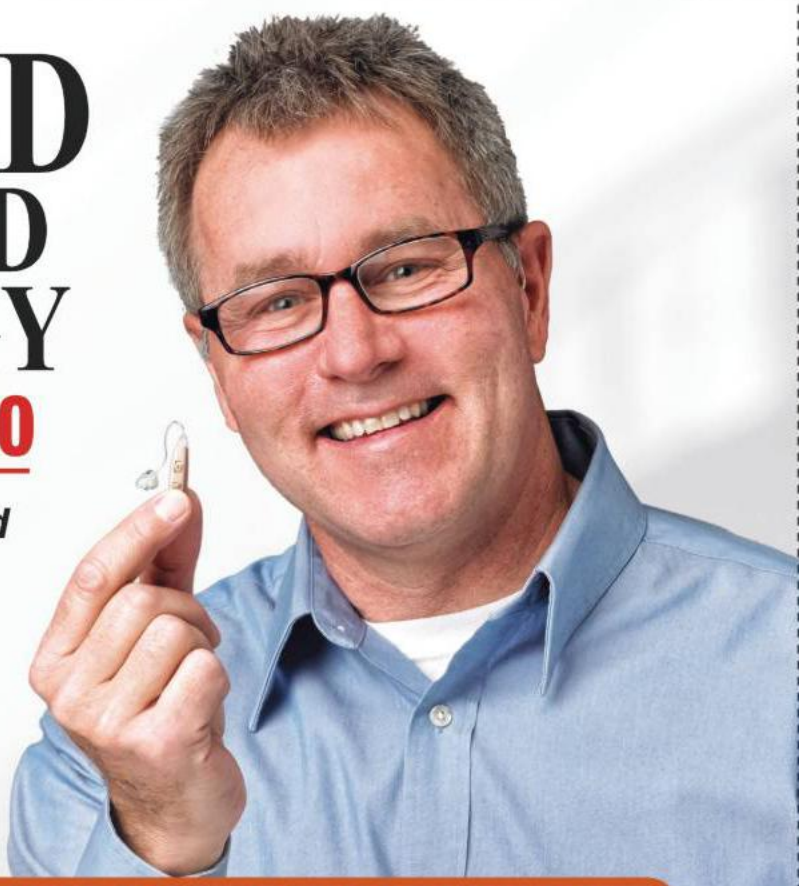

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Driving Mr. Pogue

Take a ride with Tesla's Enhanced Autopilot feature

By David Pogue

Car companies predict that self-driving cars will save millions of lives. They talk about a future without personal auto ownership, drivers' licenses, car insurance or the search for parking. When you need a ride, simply use an app to call an autonomous taxi.

But not everyone is sold on the dream. In fact, 73 percent of respondents told the American Automobile Association in a recent survey that they wouldn't want to ride in a self-driving car. They don't want to give up control to a machine. They don't trust it, don't think it's safe.

After two years of waiting, I'm finally the proud owner of a Model 3, the latest and least expensive Tesla—and among the most autonomous cars on the road. I've used its Enhanced Autopilot a lot. It's had some near misses and required some adjustments, but I can now say whether it's really safer than my own driving.

To be clear, no car is fully autonomous yet, meaning that you can't just enter a destination and then go to sleep. That's considered level 5 autonomy, the high end of the scale determined by the Society of Automotive Engineers.

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

Today's smartest cars are mostly level 2, meaning that they can drive themselves on the highway. They stay in their lane automatically and adjust their speed to traffic as necessary (you specify a maximum speed and a minimum distance between you and the car ahead of you). But they can't turn onto new roads, read stop signs or traffic lights, or make lane decisions.

With its eight video cameras, 12 ultrasonic sensors and a front radar, the Tesla Model 3 goes a bit further—I'd call it level 2.3.

For example, if you put on your turn signal, the Tesla watches for an opportunity, accelerates if necessary and then smoothly changes lanes, all by itself. If you're exiting, it eases onto the ramp and slows down. (Ingeniously, it knows how *much* to slow down based on the behavior of Tesla owners who have taken that ramp before you.) Enhanced Autopilot also knows to slow down on a curve, can recognize pedestrians and bicycles, and can slam on the brakes to avoid a collision.

The manual teems with warnings, especially this one: you still have to pay attention. In my Tesla, if it notices your hands have been off the wheel for too long (three minutes in most situations), the screen shows increasingly frantic warnings. If you ignore them, Autopilot shuts off for the rest of your trip, punishing you for your carelessness. If there's *still* no response from you, Autopilot activates the hazard blinkers and slowly stops. If you've fallen asleep or taken ill, that's a much better outcome than crashing.

Autopilot has saved me from some near misses. Once it noticed before I did that highway traffic had suddenly slowed, and it braked automatically. It's also given me a couple of scares: it didn't see a parked utility truck jutting into my lane. Another time it didn't hug a curve when the outside painted line was missing. (The manual does warn about both these situations.) Its self-driving maneuvers are generally graceful, but I've experienced a few bafflingly jolty ones. On balance, though, I'm convinced that Autopilot makes me safer. It takes care of fussy, mechanical operations, leaving you to focus on larger-level issues, like what's around you or what your next turn should be. By off-loading the second-by-second, fight-or-flight decisions, you're free to destress a little, making driving less fatiguing and more pleasant.

Now, self-driving skeptics note that two people are confirmed to have died in Autopilot crashes. But software updates continuously improve these cars; many of the behaviors described here are new since those tragedies. And Tesla points out that, statistically, Autopilot is already much safer than humans. Tesla crashes average one death per 320 million miles; for U.S. human drivers, it's one every 86 million. If everyone used Autopilot, the company calculates, we'd save 900,000 lives a year worldwide.

Operating a partly automated car really is a different kind of driving. It involves different muscles—mental and physical—and some adaptation. If you resist change, you may not ever want a self-driving car, and that's okay. But if you're willing to try something new, I predict you'll enjoy driving more—and crash less. SA

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Illustration by Jay Bendt


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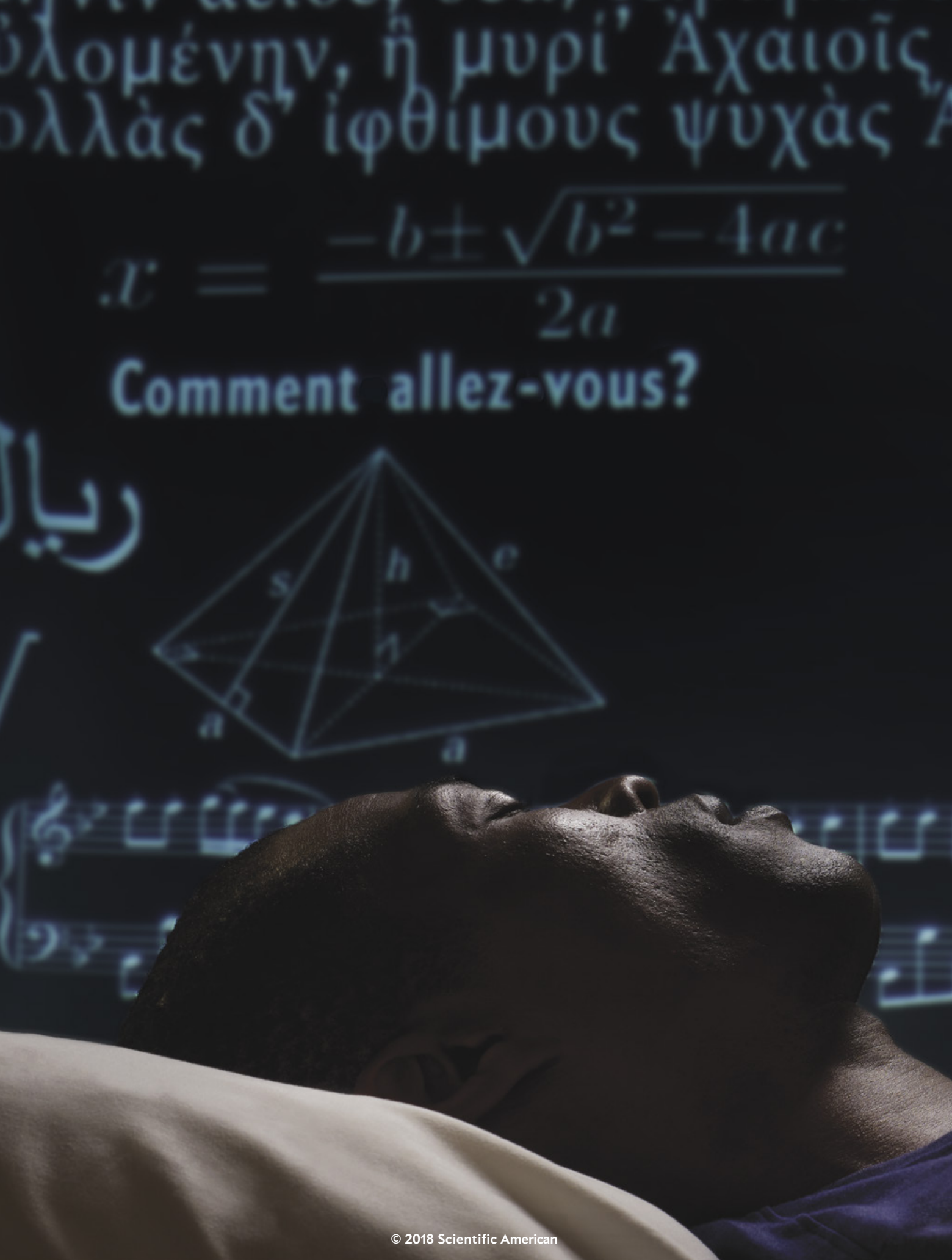


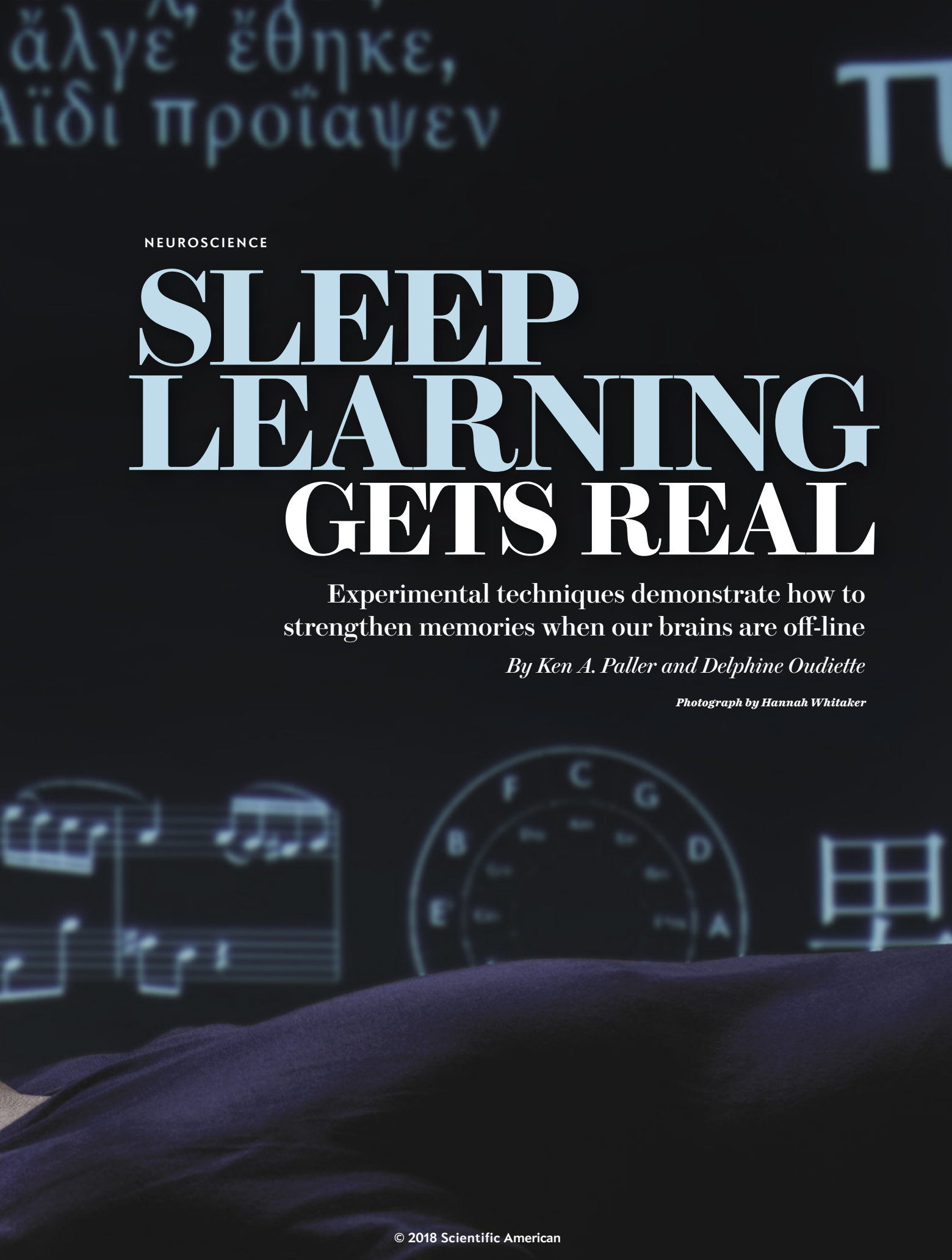
NEUROSCIENCE

SLEEP LEARNING GETS REAL

Experimental techniques demonstrate how to strengthen memories when our brains are off-line

By Ken A. Paller and Delphine Oudiette

Photograph by Hannah Whitaker



Ken A. Paller is a professor of psychology and director of the cognitive neuroscience program at Northwestern University. His recent research on targeted memory reactivation was funded by the U.S. National Science Foundation.

Delphine Oudiette is a research associate for the French National Institute for Health and Medical Research (INSERM) at the Brain & Spine Institute and at the sleep disorder unit located at Pitié-Salpêtrière Hospital, both in Paris.

IN ALDOUS HUXLEY'S *BRAVE NEW WORLD,* A BOY MEMORIZES EACH WORD OF A LECTURE IN ENGLISH, a language he does not speak. The learning happens as the boy sleeps within earshot of a radio broadcast of the lecture. On awakening, he is able to recite the entire lecture. Based on this discovery, the totalitarian authorities of Huxley's dystopian world adapt the method to shape the unconscious minds of all their citizens.

Sleep learning turns up throughout literature, pop culture and ancient lore. Take Dexter, the lead character in the animated television series *Dexter's Laboratory*. In one episode, Dexter squanders his time for homework, so instead he invents a contraption for learning to speak French overnight. He wakes up the next day unable to speak anything but French. The idea of sleep learning isn't just a modern invention. It also appears within a centuries-old mind-training practice of Tibetan Buddhists; a message whispered during sleep was intended to help a monk recognize the events in his dreams as illusory.

Everyone knows we learn better when we are well rested. Most people, however, dismiss the notion of sleep learning out of hand. Yet a set of new neuroscientific findings complicates this picture by showing that a critical part of learning occurs during sleep: recently formed memories resurface during the night, and this playback can help reinforce them, allowing at least a few to be remembered for a lifetime.

Some studies have even explored whether sleep might be manipulated to enhance learning. They reveal that sleep's program for making daytime memories stronger can be boosted using sounds and odors. Results in rodents have even demonstrated a primitive form of memory implantation: using electrical stimulation while animals slept, researchers taught them where they should go in their enclosures on awakening. Huxley's imagined version of sleep education, in which entire texts are absorbed verbatim during the night, is still relegated to the pages of his 1932 classic. But experiments now indicate that it is possible to tinker with memories while a person is immersed in the depths of slumber, creating the basis for a new science of sleep learning.

THE PSYCHOPHONE

FOR THESE TECHNIQUES to work, scientists have to explore how information can be absorbed when consciousness is seemingly on a well-deserved break. Around the time that Huxley was writing *Brave New World,* serious explorations into the possibility of meddling with sleep had begun. In 1927 New Yorker Alois B. Saliger invented an "Automatic Time-Controlled Suggestion

IN BRIEF

Sleep has long remained a mystery, and the possibility of using it to learn has long been disparaged. If the sleeping brain is turned off, the reasoning goes, it cannot learn.

To the contrary, our brains remain highly active during sleep in ways that assist in storing memories. Recent findings, in fact, demonstrate that specific memories are reactivated.

Experimentally controlling the process of memory reactivation makes it possible to study how learning can improve because of nightly periods of downtime.

Future studies that extend this work may examine ways to promote sleep-based problem-solving, eliminate nightmares or perhaps one day gain control over our dreams.

Machine," which he marketed as the "PsychoPhone," to allow a recorded message to be replayed during the night. The setup seemed to evoke Huxley's imagined technology except that the user, rather than the state, could select the message to be played.

Saliger's invention was followed, in the 1930s and 1940s, by studies documenting ostensible examples of sleep learning. A 1942 paper by Lawrence LeShan, then at the College of William & Mary, detailed an experiment in which the researcher visited a summer camp where many of the boys had the habit of biting their fingernails. In a room where 20 such boys slept, LeShan used a portable phonograph to play a voice repeating the sentence "My fingernails taste terribly bitter." The string of words recurred 300 times each night, beginning 150 minutes after the onset of sleep. The experiment continued for 54 consecutive nights. During the last two weeks of camp, the phonograph broke, so the intrepid LeShan delivered the sentence himself. Eight of the 20 boys stopped biting their nails, whereas none of 20 others who slept without exposure to the recording did so. These early efforts did not use physiological monitoring to verify that the boys were really asleep, though, so the results remain suspect.

The whole field took a severe hit in 1956, when two scientists at RAND Corporation used electroencephalography (EEG) to record brain activity while 96 questions and answers were read to sleeping study participants. (One example: "In what kind of store did Ulysses S. Grant work before the war?" Answer: "A hardware store.") The next day correct answers were recalled only for information presented when sleepers showed signs of awakening. These results led to a shift in the field that persisted for 50 years, as researchers began to lose faith in sleep learning as a viable phenomenon: participants in these experiments appeared to learn only if they were not really sleeping when information was presented to them.

Most scientists during this time tended to avoid the topic of sleep learning, although a few researchers did plug away at asking whether sleep assists in remembering new information. One typical study protocol probed whether overnight sleep deprivation affected recall the day after learning something new. Another asked whether remembering was better after a nap than after an equal period of time spent awake.

Various confounding factors can interfere with such studies. For example, the stress of sleep deprivation can harm cognitive functions that then decrease memory recall. Eventually cognitive neuroscientists began to tackle these challenges by bringing together evidence from multiple research methods. A substantive foundation of evidence gradually accrued to confirm that sleep is a means of reviving memories acquired during the day, reopening the relation between sleep and memory as a legitimate area of scientific study.

Many researchers who took up the challenge focused on rapid eye movement (REM) sleep, the period when dreams are the most frequent and vivid. The guiding assumption held that the brain's nighttime processing of memories would be tied to dreaming, but clear-cut data did not materialize. In 1983 two noted scientists—Graeme Mitchison and Francis Crick, neither psychologists—went so far as to speculate that REM sleep was for forgetting. In a similar vein, Giulio Tononi and Chiara Cirelli, both at the University of Wisconsin–Madison, proposed that sleep could be the time for weakening connections among brain cells, making it easier for new information to be acquired the following day.

Instead of REM, some investigators focused their attention on slow-wave sleep (SWS), a period of deep slumber without rapid eye movements. In 2007 Björn Rasch, then at the University of Lübeck in Germany, and his colleagues prepared people for a sleep experiment by requiring them to learn the locations of a set of objects while simultaneously smelling the odor of a rose. Later, in their beds in the laboratory, sleeping study participants again encountered the same odor as electrical recordings confirmed one sleep stage or another. The odor activated the hippocampus, a brain area critical for learning to navigate one's surroundings and for storing the new knowledge gained. On awakening, participants recalled locations more accurately—but only following cueing from odors that emanated during the course of slow-wave (not REM) sleep.

TARGETED MEMORY REACTIVATION

IN 2009 OUR LAB EXTENDED this methodology by using sounds instead of odors. We found that sounds played during SWS could improve recall for individual objects of our choosing (instead of the recall of an entire collection of objects, as was the case in the odor study). In our procedure—termed targeted memory reactivation, or TMR—we first taught people the locations of 50 objects. They might learn to place a cat at one designated spot on a computer screen and a teakettle at another. At the same time, they would hear a corresponding sound (a meow for the cat, a whistle for the kettle, and so on).

After this learning phase, participants took a nap in a comfortable place in our lab. We monitored EEG recordings from electrodes placed on the head to verify that each individual was soundly asleep. These recordings provided intriguing data on the synchronized activity of networks of neurons in the brain's outer layer, the cerebral cortex, that are relevant for memory reactivation [*see box on next page*]. When we detected slow-wave sleep, we played the meow, whistle and other sounds associated with a subset of the objects from the learning phase. Sounds were presented softly, not much louder than background noise, so the sleeper did not awaken.

On awakening, people remembered locations cued during sleep better than places that had not been flagged during the experiment. Whether sounds or odors served as cues in these experiments, they apparently triggered the reactivation of spatial memories and so reduced forgetting.

At first, the auditory procedures we used were highly controversial. The received wisdom among sleep researchers held that sensory circuits in the cortex are largely switched off during sleep, except for the sense of smell. We were not swayed by this orthodox view. Instead we followed our hunch that the repeated playing of soft sounds might influence the sleeping brain and produce changes in recently stored memories.

Indeed, the same memory benefits were also found in many subsequent studies. A technique called functional magnetic resonance imaging highlighted which brain areas take part in TMR, and EEG results brought out the importance of specific brain oscillations. Two papers published this year—one by Scott Cairney of the University of York in England and his colleagues; the other by James Antony of Princeton University and his colleagues—linked an oscillation, the sleep spindle, with the memory benefits of TMR.

Besides boosting spatial memory, these procedures have also helped improve recall in other settings. TMR can assist in mas-

The Maestros of Slumber

A complex symphony of neural activity governs the connection between sleep and memory

Brain rhythms provide clues to how sleep helps to store memories for later retrieval. One type of neural signal, called a slow wave, cycling from 0.5 to four times a second, orchestrates the activity of neurons in the cerebral cortex. Each slow oscillation consists of a "down" phase, when neurons are silent, and an "up" phase, when they resume activity. This timing pattern helps to reinforce recently formed memories by ensuring that multiple cortical regions remain in an up state at the same time.

The up phase can coincide with sleep spindles, brief increases of a rhythm of 12 to 15 cycles per second. Spindles originate in the thalamus, which serves as a crossroads for information that is transmitted to virtually all parts of the cerebral cortex. Spindles have a rhythm of their own, recurring at approximately five-second intervals. They coordinate the activity of sharp-wave ripples in the hippocampus. Ripples, for their part, are concurrent with the replay of memories. Slow waves, all the while, assume the role of orchestra conductor: their measured oscillations in the cortex coordinate the pacing for sleep spindles and sharp-wave ripples.

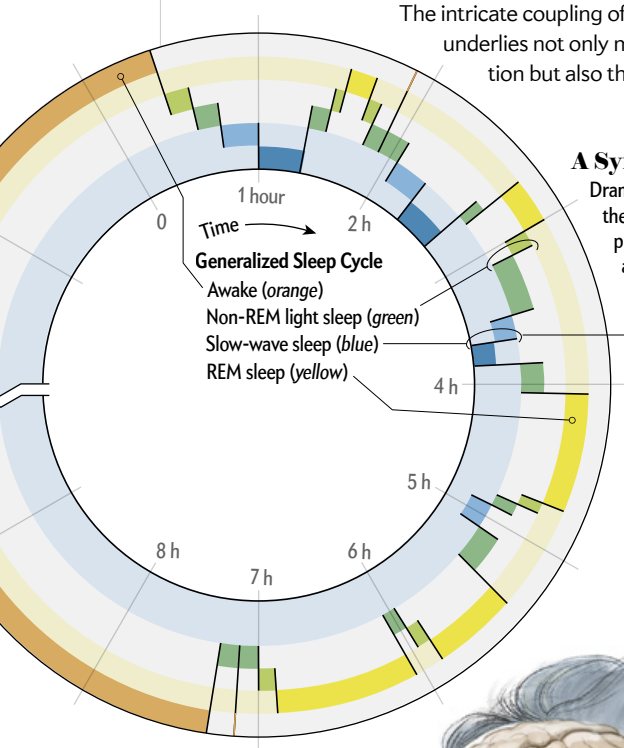
The intricate coupling of these oscillations underlies not only memory reactivation but also the altering of connections among neurons to strengthen memory storage. A dialogue between the hippocampus and the cortex involving all these brain rhythms triggers a set of complex network interactions. Through this process, known as consolidation, new information can become integrated with existing memories. The intertwining of memories, moreover, enables the gist of recent experiences to be extracted to make sense of a complex world.

Memory difficulties can arise when this neural dialogue becomes impaired. Individuals with major damage centered in the hippocampus or parts of the thalamus may develop a profound amnesia. Without the expected interactions with these brain regions during both sleep and waking, the cortex cannot store mental records of facts and events known as declarative memories. In addition, a milder form of memory disorder may result when memory processing during sleep is seriously disrupted.

As our understanding of the physiological orchestration of the sleeping brain continues to expand, new strategies may be used to enhance the brain's natural rhythms with various forms of electrical or sensory stimulation. Humans have always had such inclinations, having taken advantage of a lullaby's rhythm or rocking motions to lull a baby to sleep. *—K.A.P. and D.O.*

A Symphony in Two Movements

Dramatic differences characterize two key sleep phases. The slow waves of deep sleep dominate the early part of the night. During slow-wave sleep, some memories spontaneously reactivate. Interventions that promote this process can ensure that memories are retained. Rapid eye movement (REM) sleep prevails in the latter part of a night's slumber, but how it interacts with memory remains controversial.



Harmonizing Brain Waves

Brain oscillations during sleep appear to play a role in strengthening new memories. A key event is the "up" phase of a slow oscillation that coordinates the activity of other brain rhythms. The ascending part of a slow oscillation in the cortex synchronizes with sleep spindles in the thalamus. The spindles coordinate the activity of sharp-wave ripples in the hippocampus. Ripples tend to coincide with a spindle trough.

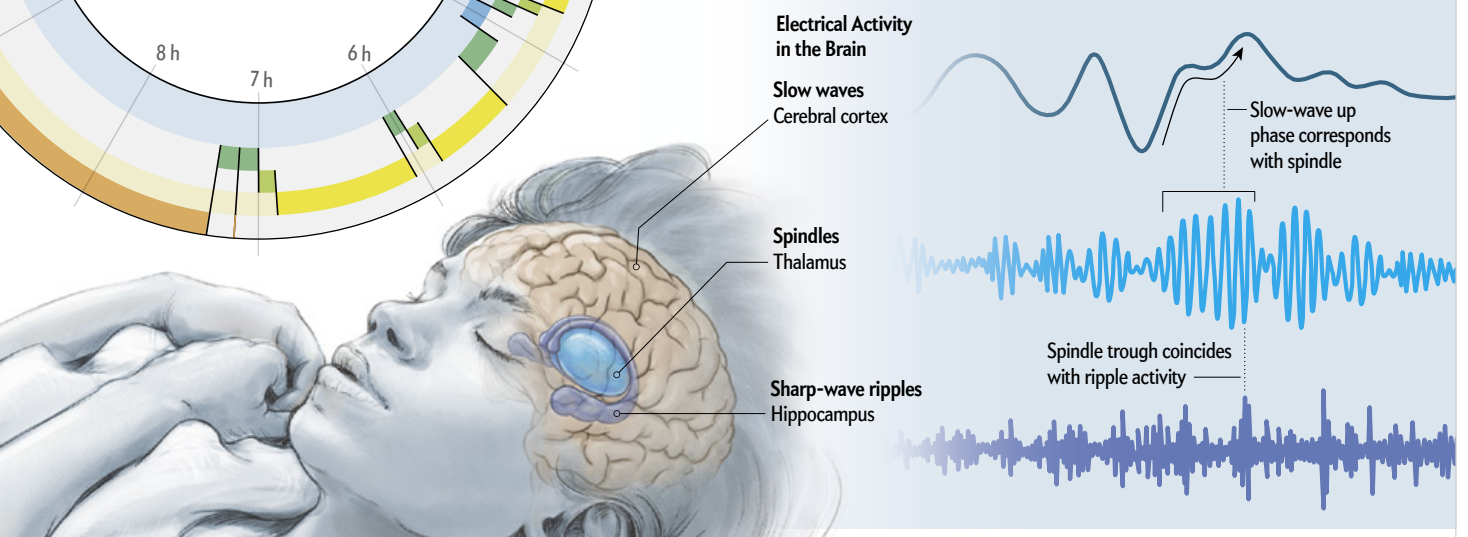


Illustration by Mesa Schumacher

tery of playing a keyboard melody and learning new vocabulary or grammatical rules. The technique can also help with simpler types of learning, such as adjustments in one's body image. In conditioning experiments, TMR alters prior learning of an automatic reaction to a stimulus caused by an earlier pairing of that stimulus with an electric shock. Ongoing studies are examining still other types of recall, such as associating names with faces when first meeting new people.

As the technology evolves, TMR should be tested to see if it could help to treat various disorders, reduce addictions or speed recovery from illness. Our lab, together with Northwestern University neurologist Marc Slutzky, is currently testing a novel rehabilitation procedure for recovering arm-movement abilities after stroke. Cue sounds are incorporated as part of the therapy and are replayed during sleep to try to accelerate relearning of lost movements. The prospects appear promising because TMR can alter similar forms of motor learning in healthy individuals.

Future programs for sleep learning might help in preserving memories, speeding acquisition of new knowledge, or even changing bad habits such as smoking.

WHAT ABOUT LEARNING FRENCH?

THE DEMONSTRATED ABILITY to reinforce memories raises the question of whether new information can be loaded into a person's brain after falling asleep, a technique that calls forth the ethical specter of mind control invoked by *Brave New World*. Is it going too far, though, to imagine that memories can be created surreptitiously?

Although the orthodox response to such conjectures has for many years been an unqualified no, studies by Anat Arzi, now at the University of Cambridge, and her colleagues demonstrated the creation of relatively simple memories using odors. In one experiment, the researchers succeeded in diminishing the desire for tobacco in smokers who were keen to quit. When asleep, study participants were exposed to two odors, cigarette smoke and rotten fish. During the following week, those who had smelled the mix of both odors lit up 30 percent less, having apparently been conditioned to associate smoking with the aversive fish odor.

Acquiring a more complex memory is not as easy, but even that may one day prove possible. Karim Benchenane of the French National Center for Scientific Research (CNRS) and his colleagues have shown how to literally change the mind—of a mouse. When they began their work, Benchenane and his team knew that when a mouse explores a new environment, neurons called place cells fire as the animal traverses specific parts of an enclosure. These same neurons discharge again during sleep as the memory is apparently replayed.

The researchers stimulated the reward system of the mouse brain (the medial forebrain bundle) precisely when place cells became spontaneously active while the animal was asleep. Amazingly, mice subsequently spent more time at the locations that corresponded to the stimulated place cells, heading there directly after they woke up. More experiments still need to disentangle whether fully formed false memories were implanted in the mice during sleep or whether they were automatically guided to those spots by a process of conditioning, without any knowledge about why they were drawn to those locations.

The boundaries of what may be possible remain to be tested, but this research has established that a normal component of learning continues nocturnally off-line. Sleep is needed not just to stay alert and rejuvenated but also to reinforce memories initially acquired while awake. We still need to learn much more about off-line memory processing. Further work must ascertain how sleep helps learning and which brain mechanisms are engaged to preserve the most valuable memories. It is also essential to find out more about the perils of poor or inadequate sleep that might be affected by various forms of life stress, certain diseases or the experience of growing older.

A study led by Carmen Westerberg, then at Northwestern, points in the desired direction. Westerberg tested patients with the memory dysfunction that often precedes Alzheimer's disease—amnestic mild cognitive impairment. The results documented a link between poor sleep and reduced ability to remember information after an intervening overnight delay.

All of this knowledge might help in creating programs of sleep learning to preserve memories, to speed the acquisition of new knowledge, or even to change bad habits such as smoking. Looking still further ahead, scientists might also explore whether we can gain control over our dreams, which could lead to the prospect of nightmare therapies, sleep-based problem-solving and perhaps even recreational dream travel. In a culture that already offers wrist-based sleep trackers and mail-order gene tests, we can begin to contemplate new ways to convert daily downtime into a productive endeavor—for some, a chilling prospect, and for others, another welcome opportunity for hacking the self. SA

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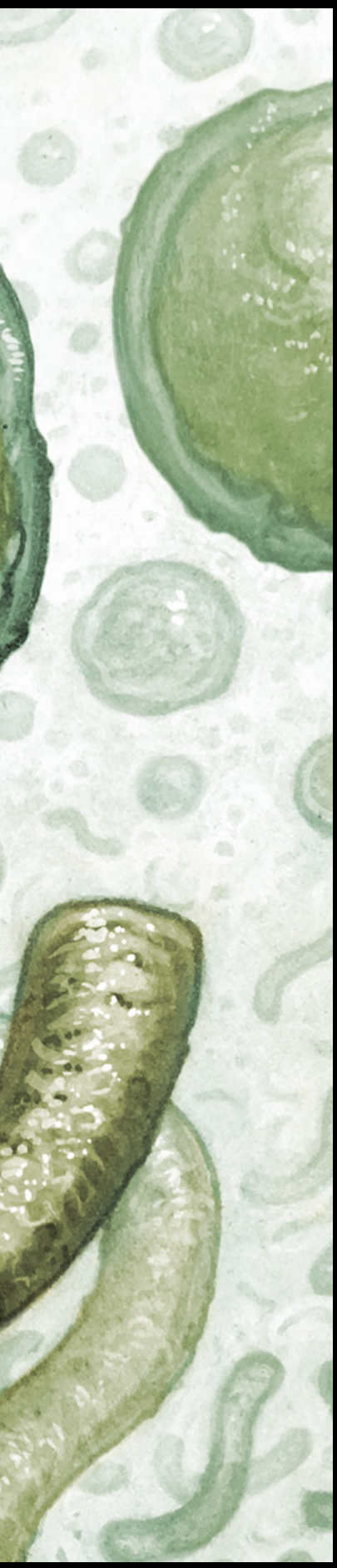


MICROBIOLOGY

MVP PLAYERS

Microbial partnerships turn out to be more common and influential than scientists could have ever imagined

By Jeffrey Marlow and Rogier Braakman

Illustration by William B. Hand

Jeffrey Marlow is a postdoctoral scholar at Harvard University. His research focuses on microbial metabolic activity in complex environmental systems.

Rogier Braakman is a research scientist at the Massachusetts Institute of Technology, where he studies metabolic evolution and the feedbacks between Earth and life.

HALF A MILE BELOW THE SURFACE OF THE OCEAN, OFF THE COAST OF OREGON, THE *ALVIN* submersible's headlights flicker on to reveal a colorful oasis. Plush carpets of white, yellow and orange microbes cover the seafloor, punctuated by fields of clams and mussels. Red rockfish watch the vessel warily with bulbous milky eyes, while bubble plumes belch from mounds of chalky, variegated rock. The halo of illumination draws visitors forward like a lure, exposing this alien terrain bit by unexpected bit while obscuring its true extent.

Hours earlier on this expedition in 2010, one of us (Marlow) had wriggled his way into *Alvin*'s titanium sphere, along with two other explorers. We pressed our faces to the circular windows as we descended through a kaleidoscope of blue. Our destination was Hydrate Ridge, a rocky precinct where vast quantities of methane are being squeezed out of Earth's crust. With the accelerating pace of discovery of such methane seeps, as they are known (450 were found during a single 2016 expedition in the eastern Pacific), scientists are racing to understand their environmental impact. Methane, after all, is a strong greenhouse gas: although it constitutes only 0.00018 percent of the atmosphere, it accounts for 20 percent of the atmosphere's overall warming potential. Estimates suggest that roughly 10 percent of atmospheric methane emerges from seafloor seeps every year. Unchecked, this bubble stream could wreak climate havoc, but something prevents more methane from reaching the atmosphere: the microbes living in the seeps.

These microbes, which dwell underneath the white microbial mats and clam shards, consume methane with remarkable voracity. Individually minuscule but collectively mighty, they work together in ways that help to shape landscapes, sustain ecosystems and impact the planet's climate. Their power lies in their cooperation. Scientists have known about these microorganisms for decades, yet they remain mysterious in many respects. Key among the unknowns is the extent of their influence: Do they reside in only a few regions of the ocean floor, or are they widespread? More broadly, is their propensity for cooperation exceptional among microbes, or is it commonplace? Prevailing views long held that such organisms mostly compete with one another for resources. But maybe teamwork is actually their default mode. We were there—a speck of light suspended in the inky expanse—to figure out just how pervasive this way of life really is.

A MICROBIAL WORLD

IN A SENSE, our journey to collect microscopic organisms from the deep sea was a logical step in the broader scientific quest to understand how our planet works—how elements such as carbon, nitrogen, sulfur and phosphorus move between ecosystems or how greenhouse gases enter the atmosphere. We live, after all, in a microbial world: from rocks deep below the seafloor to desert dust particles high up in the atmosphere, microbes exist almost everywhere we look. And scientists have long recognized that they perform important roles in distributing these elements and compounds in ways that help make Earth the planet it is today, conveniently habitable for animals like us.

But the approach that researchers have typically taken to studying the microbial world has limited their understanding of these globally relevant processes. For decades investigators focused their attention on individual species and their molecular components. From the teeming microbial masses between grains of sand, they isolated single organisms and poked and prodded them to suss out their biochemistry and the functions of their genes. This method has produced reams of information about

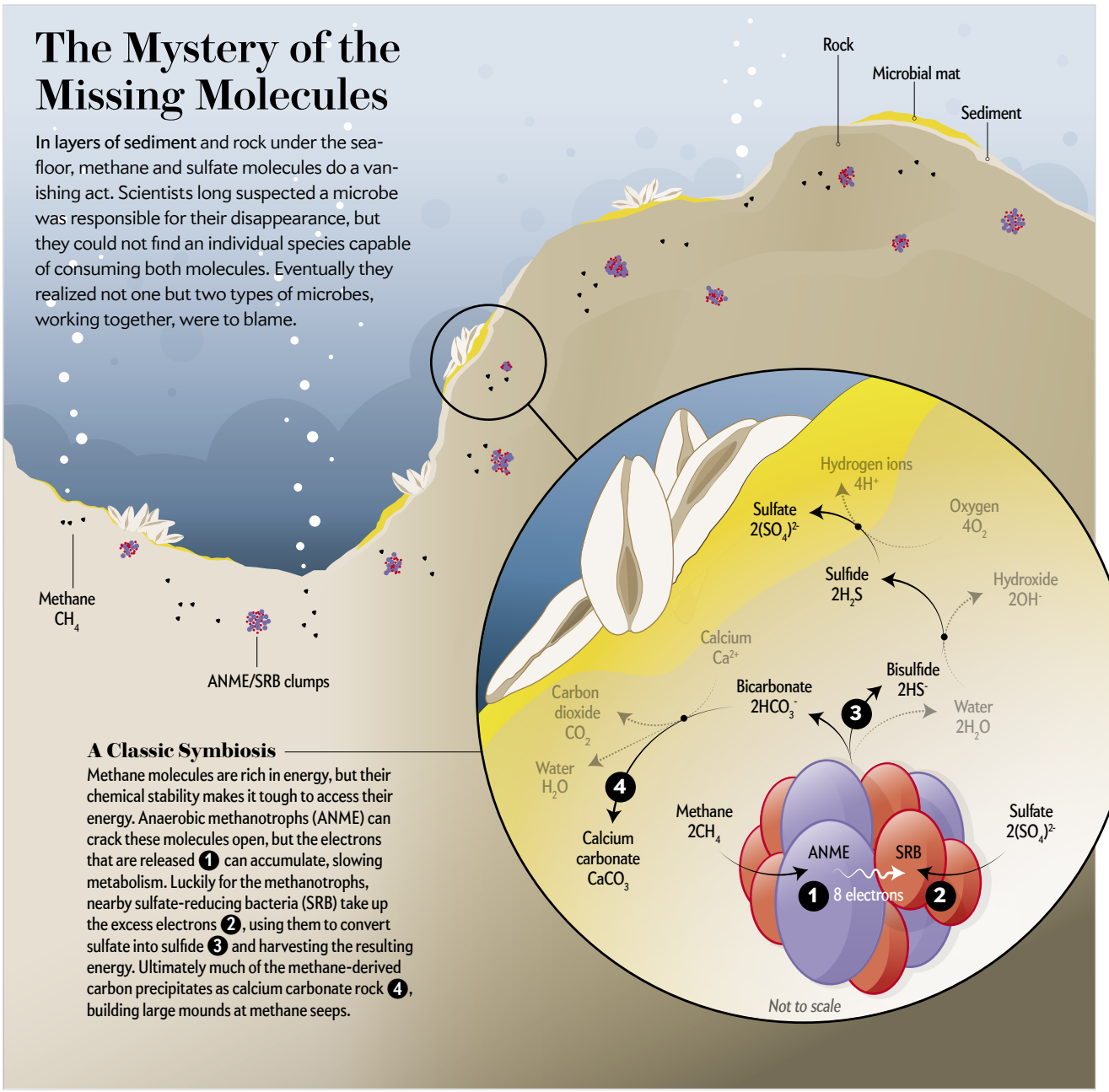
IN BRIEF

Scientists have long known that microbes have been central in shaping Earth's biosphere. The conventional wisdom has been that microbial communities revolve around competition for resources.

But a wealth of new data on microbes that dwell in marine and groundwater settings around the world have revealed that many of these species actually collaborate with one another.

These findings are building a case that interactions and partnerships among microorganisms—not individualistic competition—may be the default mode of life as we know it and the biosphere's animating force.

NERISSA ESCANILAR (*illustration reference for Braakman*)



these species, as well as how cells and biomolecules work in general. When researchers then zoomed out from these studies to understand the biosphere as a whole, stitched together from the constituent species, however, major gaps in their knowledge remained. Only a tiny fraction of microbes seen in the wild could be isolated, suggesting that the species making up complex natural communities are intertwined in ways that cannot easily be replicated in the laboratory. And the very coexistence of many thriving species, which often play complementary roles, seemed to contradict the conventional wisdom that microbial ecosystems revolve around a winner-take-all struggle for resources.

Moreover, metabolic activity rates of individual species measured in the lab—such as how quickly they produce oxygen or consume nitrogen—rarely matched values from real-world environments because species that can be isolated in the lab are often more vigorous than those that cannot be. In other words, the whole was sometimes more, sometimes less, but always different from the sum of the parts.

But a growing body of evidence suggests that these disconnects can be reconciled by considering the vital importance of interactions among organisms. Over the past decade advances in biomolecular sequencing and microscopic imaging, among other technologies, have enabled researchers to study microbial communities more holistically than ever before. The latest findings indicate that collaboration is a critical driver of the biosphere: as individual organisms evolve to share energy, genetic information and metabolic duties, they unlock new ways of life and gain entry to previously inaccessible habitats.

SOURCES: "A MARINE MICROBIAL CONSORTIUM APPARENTLY MEDIATING ANAEROBIC OXIDATION OF METHANE," BY ANTJE BOETIUS ET AL., IN *NATURE*, VOL. 407; OCTOBER 5, 2000; "SINGLE CELL ACTIVITY REVEALS DIRECT ELECTRON TRANSFER IN METHANOTROPHIC CONSORTIA," BY SHAWN E. MCGLYNN ET AL., IN *NATURE*, VOL. 526; OCTOBER 22, 2015; "METHANE-DERIVED CARBONATES AND AUTHIGENIC PYRITE FROM THE NORTHWESTERN BLACK SEA," BY J. PECKMANN ET AL., IN *MARINE GEOLOGY*, VOL. 177, NOS. 1–2; JUNE 30, 2001

Illustration by Tami Tolpa

HIDING IN PLAIN SIGHT

BACK AT HYDRATE RIDGE, *Alvin*'s robotic arm plunges a clear plastic tube with an open bottom into a wispy microbial mat. It slides down easily at first but then catches, the resistance propagating back to the submersible and delivering an unexpected jolt. With a final push, the tube punches through the stubborn layer and obtains a sample, which trails a fine plume of sedimentary dust as *Alvin*'s arm carries it to the sub's quiver of tubes.

Later that afternoon, in the ship's expansive lab, Marlow and his colleagues examine the foot-deep cross section of the seafloor that we recovered. Under the white mat, beige mud transitions into black goo and chunks of rock—the crust that briefly resisted our sampling effort—and finally tapers off to a dark gray mixture. Our microbial quarry inhabits the darkest layer, which reeks of rotten eggs. Previous work in the 1980s had shown that this was the zone where methane produced in deeper horizons and sulfate from the overlying seawater were both being removed from the sediment. Yet efforts to identify individual microbial species in this layer that could simultaneously consume methane and sulfate came up empty again and again. Taking a different tack, other researchers used methane and sulfate as bait to lure the thief out of hiding, tracking the molecules as they disappeared from experimental treatments. Some impressive sleuthing in the early 2000s showed that the culprit was not an "it" but rather a "they": cell clumps made of two types of microbes lit up with telltale signs of metabolic activity. One partner ate methane; the other breathed sulfate.

This process—the anaerobic oxidation of methane—would not be possible without such a close coupling between anaerobic methanotrophs and sulfate-reducing bacteria. Methane is a high-energy but very stable molecule: it is not easy to crack it open to release electrons and power metabolism. Anaerobic methanotrophs can do the job, but they end up releasing an overabundance of electrons as a result, leading to a backlog that would normally cause their metabolism to grind to a halt. One microbe's trash is another's treasure, though. The sulfate-reducing bacteria use the surfeit of electrons to turn sulfate into sulfide (which gives the sediment its putrid smell) and reap the energetic windfall that results. It is a classic symbiosis: the anaerobic methanotrophs enjoy a swift trash collection service, and the sulfate-reducing bacteria bask in an in-house power plant.

Our expedition to Hydrate Ridge showed that symbiotic methane consumption was happening not just in the sediment, where the phenomenon was first discovered, but also inside the carbonate rocks that form enormous mounds around methane seeps the world over. The interaction between the anaerobic methanotrophs and sulfate-reducing bacteria may take place on the microscale, but research in the Black Sea, the Gulf of Mexico and other locations has shown it is a pervasive process, soaking up roughly 80 percent of the methane emerging from the seafloor, building carbonate mounds on global scales.

THE ORIGIN OF TEAMWORK

EARTH'S VAST SUBSURFACE is rife with such examples of microbial interactions, and DNA sequences obtained over the past few years from microbial cells in groundwater and deep-sea sediments reveal just how interconnected these communities really are. As the number of DNA sequences has expanded, two startling conclusions have become increasingly inescapable. First, bacteria and archaea are far more diverse than anyone had imagined—the number of branches on the tree of life has exploded. But perhaps more surprising, their genomes are suspiciously small: many do not have enough information to build a fully functional cell or to complete the metabolic transformations that convert food into energy. "What we see all the time when we go into new environments," says Laura Hug, a professor of environmental microbiology at the University of Waterloo, who was part of a team that discovered a number of previously unknown microbial species, "is that the entire community has the capacity for a certain function, like nitrogen cycling. All the pieces are there, but to identify a single organism that has all the pieces in its own genome—that's really unusual."

If one member takes a hit, the rest of the network of mutually dependent microbes could be left vulnerable to collapse.

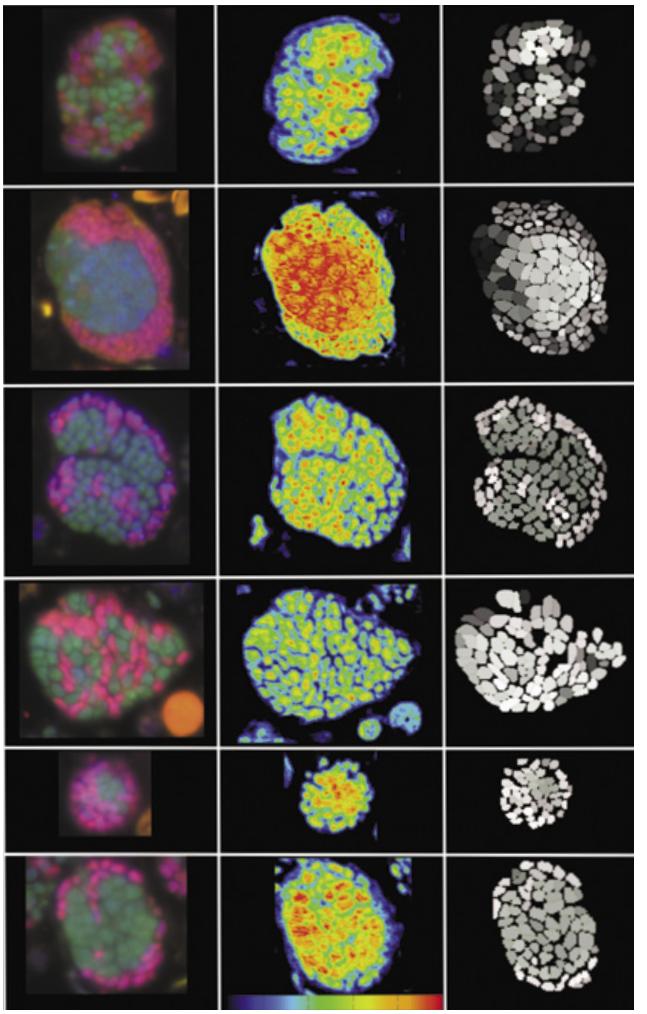
The newly discovered cells' genomes often lack the ability to make all the amino acids needed to build their proteins or the nucleotides for constructing their DNA, suggesting they acquire these building blocks from neighboring cells with a surplus. These communities also appear to extract energy from the environment through a collective process: individual cells perform certain chemical conversions and pass the product down the chain to other cells for subsequent reactions. Sharing cellular building blocks and energetic resources in this way both requires and enables cohabitation among diverse organisms.

Although closely related cells still strive to acquire the same resources, the recent trove of genetic information suggests that at a larger scale, evolution has promoted specialization and collaboration. In much the same way that the global economy capitalizes on local strengths and the exchange of goods, groundwater and deep-sea microbial communities use division of labor to efficiently extract resources from sparse supplies, making harsh environments livable.

How do these vital collaborations arise in the first place? Some scientists believe that physical proximity within dense communities is a pivotal factor. As closely bound organisms reproduce, progeny remain nearby. With proximity comes the benefit of accessing parental resources, like a close-to-home college student taking advantage of laundry facilities. Natural

selection favors the genes that make these shared resources when subsequent generations stay close to one another, but as physical proximity between parents and offspring decreases and genetically divergent cells enter the picture, freeloading mutants gain a selective advantage. They reap the benefits of shared resources without paying the costs of making them, taking over the community and lowering the overall rate of sharing. (This scenario is also called the tragedy of the commons, a term originally invented to describe a group of farmers with shared land; each individual farmer is motivated to have as large a herd as possible, leading to overgrazing and financial ruin for all.) These dynamics show that collaboration and sharing are favored when multiple generations of the same species remain closely co-located, a principle known as group selection.

But is this mechanism of group selection the ultimate explanation for the widespread microbial collaborations found in nature, or might other factors be at work? Clues have come from hundreds of feet above deep-sea methane seeps in the sunlit surface waters of the open ocean, where solar energy is abundant, but life-giving nutrients such as nitrogen and phosphorus are in short supply. Indeed, the tropical and subtropical surface waters were long thought to be ocean "deserts" until the late 1970s and 1980s, when scientists began to take a closer look at these environments and found teeming masses of microbes. Like the more recently detected groundwater and deep-sea sediment microbes, these surface ocean microbes have reduced genomes and cannot be cultivated without adding complex suites of nutrients to their growth media—telltale signs that these species need one another to survive. Yet whereas sedimentary microbes are stuck within dense cages of mineral particles—perfect conditions for group selection—microbes in the surface ocean float freely, constantly churned by their environment. Without reliable proximity to known neighbors, group selection cannot explain their cooperation. Some other force must be at work.



AGGREGATES of the anaerobic methanotrophs and sulfate-reducing bacteria that live in methane seeps are revealed using a variety of imaging techniques.

A LIFE-CHANGING PARTNERSHIP

A SINGLE DROP of water from the surface of the tropical ocean contains about a million microbes. One in 10 is likely a cyanobacterium known as *Prochlorococcus,* the smallest and most abundant photosynthetic organism on the planet. One of us (Braakman) has been peering into the DNA of *Prochlorococcus,* working with colleagues to understand how its metabolism has evolved over hundreds of millions of years. We created a metabolic family tree of this species by mapping variations in its metabolic network—the biochemical reactions that convert nutrient inputs to cellular building blocks—onto a genetic family tree that shows how the various kinds of *Prochlorococcus* are related. By comparing this merged metabolic family tree of *Prochlorococcus* subgroups with the large-scale gradients of light and nutrients where they are found, it became clear that evolution had selected for cells that harvested more solar energy and could best acquire sparse nutrients. At the same time, because more energy harvesting increases the throughput of carbon-based metabolism, cells became saturated with carbon. Energetically juicy molecules, packed with organic carbon, were released as waste—an exhaust valve on the powerful vacuum cleaner that could hoover up increasingly scarce nutrients. *Prochlorococcus* thus emerged as a cellular factory, soaking up sunlight and spitting out organic carbon waste.

This waste stream, in turn, became an attractive resource for microbes that cannot make their own food energy, including *Pelagibacter,* a distinct marine organism that, tellingly, is nearly as abundant as *Prochlorococcus* in the tropical and subtropical surface oceans. To investigate the relation between these two microbial groups, we also created a metabolic family tree for *Pelagibacter* and found an evolutionary path that completed the collaborative loop. Whereas *Prochlorococcus* consumes carbon dioxide and releases organic carbon compounds, *Pelagibacter* takes up those compounds and releases other molecules that *Prochlorococcus* can use for energy when the sun goes down. Both sides of this partnership recycle the waste of the other, extracting otherwise unused energy.

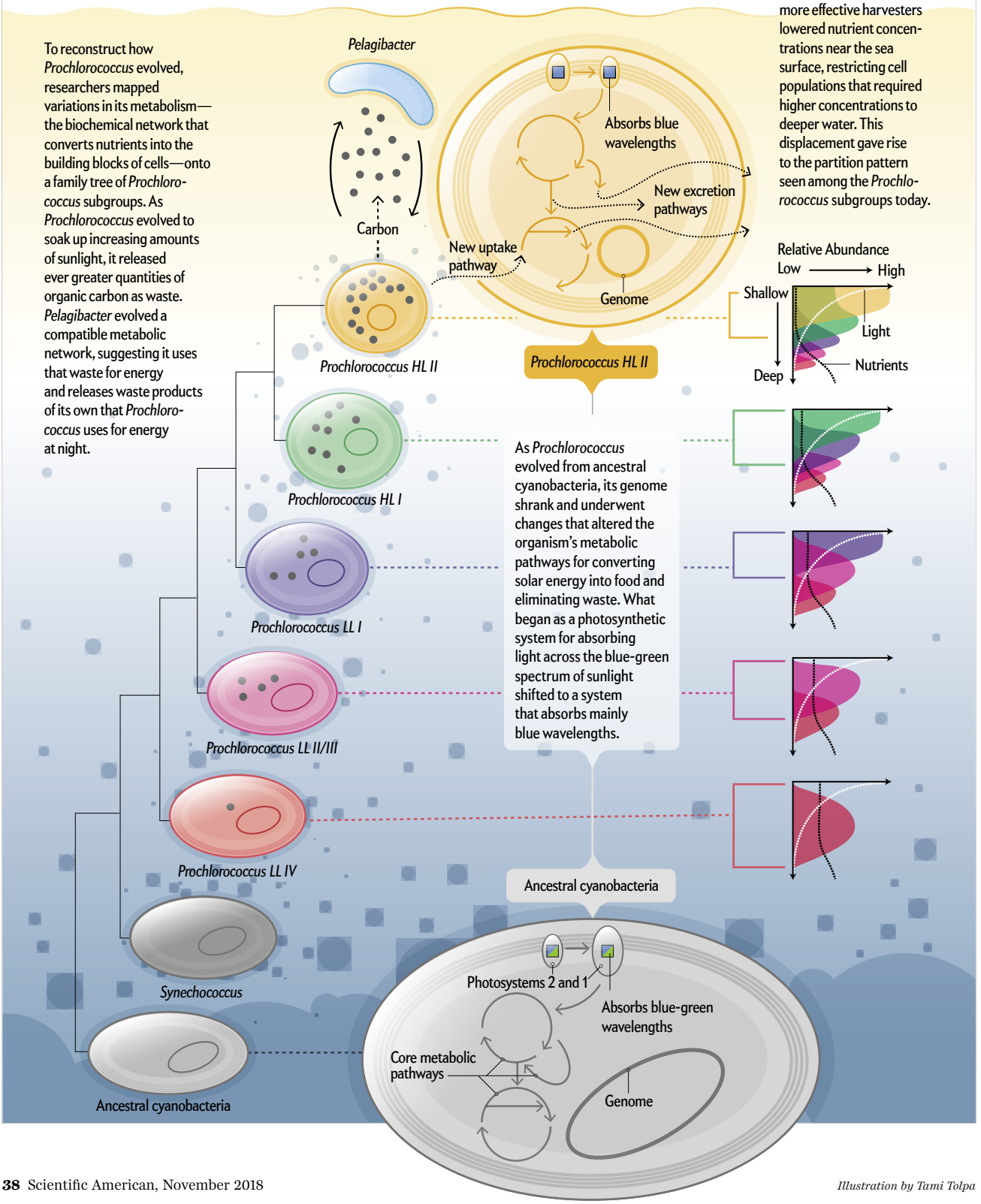
These findings, published in 2017, have important consequences for thinking about how microbial communities evolved in the surface oceans and other habitats. The implication is that as cells got better at collecting scarce nutrients, they drove the

FROM "SINGLE CELL ACTIVITY REVEALS DIRECT ELECTRON TRANSFER IN METHANOTROPHIC CONSORTIA," BY SHAWN E. MCGLYNN ET AL., IN *NATURE*: VOL. 526; OCTOBER 22, 2015

A Collaboration Is Born

Hundreds of millions of years ago two of what are now the most abundant organisms in the sea—the microbes *Prochlorococcus* and *Pelagibacter*—teamed up to exploit each other's waste products. Their collaboration may have laid the groundwork for oxygenating the planet's oceans—a development that revolutionized life on Earth. Recent studies of the metabolic evolution of these two organisms have revealed what drove their partnership and how it came to be.

To reconstruct how *Prochlorococcus* evolved, researchers mapped variations in its metabolism—the biochemical network that converts nutrients into the building blocks of cells—onto a family tree of *Prochlorococcus* subgroups. As *Prochlorococcus* evolved to soak up increasing amounts of sunlight, it released ever greater quantities of organic carbon as waste. *Pelagibacter* evolved a compatible metabolic network, suggesting it uses that waste for energy and releases waste products of its own that *Prochlorococcus* uses for energy at night.



Ancestral populations once occupied much of the sunlight zone (*bottom chart*). Over time natural selection favored those *Prochlorococcus* cells that could harvest more energy from the sun and best obtain scarce nutrients. The ever more effective harvesters lowered nutrient concentrations near the sea surface, restricting cell populations that required higher concentrations to deeper water. This displacement gave rise to the partition pattern seen among the *Prochlorococcus* subgroups today.

Illustration by Tami Tolpa

concentrations of those nutrients ever lower, dictating the terms on which all other organisms can use them. Freeloaders do not stand a chance, because cells that only consume but do not produce organic carbon are less proficient at acquiring other nutrients, such as nitrogen or phosphorus. Nutrient consumption and organic waste production are inextricably linked, strengthening the *Prochlorococcus-Pelagibacter* connection, which is bolstered by natural selection. This powerful arrangement shows that the evolutionary promotion of collaborative interactions does not apply only to tightly associated groups of closely related cells. At least in some cases, this selective drive may simply be a by-product—a self-amplifying feedback loop—of selection acting on individual cells.

The *Prochlorococcus-Pelagibacter* partnership may have emerged out of just a few small genetic changes, but its long-term effects were enormous. When the ancestors of *Prochlorococcus* and *Pelagibacter* colonized the oceans between 600 million and 800 million years ago, the waters were still largely devoid of oxygen and rich in iron. Iron is a requisite component of the photosynthetic proteins that ultimately generate oxygen, but it cannot dissolve and be wrangled into proteins when oxygen is around. This catch-22 would have kept photosynthetic organisms from expanding into the open ocean, where accessible iron would become scarce if they moved in and started making lots of oxygen. But *Prochlorococcus*'s organic carbon waste products—fueled through growth alongside *Pelagibacter*—had a remarkable ability to bind iron, increasing its availability even in the presence of oxygen. Thus, we hypothesized that through the interplay between their organic waste and the critical iron, *Prochlorococcus* and *Pelagibacter* ultimately helped to pave the way for photosynthesis to oxygenate our planet's oceans. Life on Earth would never be the same.

ULTERIOR MOTIVES

MICROBIAL INTERACTIONS may not always be harmonious partnerships, however. Indeed, some scientists believe stable, mutually beneficial relationships may be the exception rather than the rule. "It's a dog-eat-dog world out there," says biologist John McCutcheon of the University of Montana. "Even relationships that are temporarily beneficial in one context can lead to parasitism or competition in another, slightly different circumstance." McCutcheon's Hobbesian worldview comes in part from the phenomenon he studies: endosymbiosis, or the wholesale incorporation of one organism into another. For example, the mitochondria that produce energy inside our cells were once free-living members of a group known as the alphaproteobacteria. Endosymbiosis has led to some of the most important innovations in life's history, generating the hallmark components of complex cells and paving the way for the evolution of plants and animals. Given these positive examples, "it's easy to imagine endosymbioses as a kumbaya kind of thing," McCutcheon warns, "but I think it's a more exploitative interaction." After all, he points out, evolutionary history is likely littered with failed attempts in which endosymbiosis trended toward either predation or parasitism.

Researchers have also found high rates of endosymbiont turnover, where, like a roommate that is just not working out, one incorporated species gets booted and a new one comes in, revealing an uneasy relation for both partners. McCutcheon's research amplifies the sense that interorganism interactions are indeed a dominant force while sounding a note of caution about their motives. "Every organism is looking out for itself," he notes, "and not all interactions are good for everyone."

There may also be a more fundamental downside to intricately connected microbial communities: if one member takes a hit, the rest of the network of mutually dependent microbes could be left vulnerable to collapse. In theory, metabolic linkages could render highly collaborative microbial communities more susceptible to failure than those made up of independent organisms that mind their own business.

Microbiologist Ashley Shade of Michigan State University and her colleagues examined 378 studies of soil, marine, freshwater, bioindustrial and animal gut microbiomes in an effort to develop general principles about community resistance to external disturbance and the ability to return to the baseline state. The researchers found that 56 percent of the investigations reported widespread metabolic changes after a disturbance—for example, exposure to heat prompted one soil-derived community of microbes to stop their usual consumption of nitrogen. Just 10 percent of these disrupted communities eventually resumed normal functioning. (These results should be interpreted with caution, however, because many of the compiled studies that looked at community resistance did not examine their eventual recovery. For those where recovery was examined, it is possible that researchers did not wait long enough to see things get back to normal.) Ultimately the biosphere is incredibly resilient and has always recovered from major disturbances—we would not be around otherwise—but much remains to be understood about how recoveries work, how quick they are and what long-lasting change persists.

We still have much to learn about the microbial communities that underlie the natural world and the role of collaborations. The results to date suggest that close metabolic partnerships drive evolutionary dynamics and open up vast new realms for colonization. But researchers have only just started looking at interactions beyond the microscopic scale, and placing these new findings into context in the real world continues to be a major challenge. How many species can interact in a meaningful way? How do the general principles shaping these interactions change in different environments or at different scales of space and time? A dense web of interacting microbes might mean that human-caused environmental influences could ripple through the entire network and lead to worldwide consequences we cannot yet anticipate. Continuing to decode these microbial networks is crucial as we enter an era of dramatic global change. SA

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IN TIME

Astronomers have found some of the most distant galaxies in the universe, opening a window on a previously unknown period of cosmic history

By Dan Coe

Illustration by Ron Miller

Dan Coe is an astronomer at the Space Telescope Science Institute in Baltimore. He is the principal investigator of RELICS—the Reionization Lensing Cluster Survey.

WE STAND ON THE VERGE OF

WRITING A NEARLY COMPLETE COSMIC HISTORY. ASTRONOMERS have now observed galaxies going back 97 percent of the way to the big bang, which was 13.8 billion years ago.

The light from one such galaxy, named SPT0615-JD, began its journey toward Earth 13.3 billion years ago. In 2017 it arrived at the Hubble Space Telescope, where we were able to glimpse it for the first time through a project I ran called the Reionization Lensing Cluster Survey (RELICS), which aimed to find some of the cosmos's first galaxies. RELICS ran from October 2015 to October 2017, taking up more than 100 hours of Hubble observing time and more than 900 hours on the Spitzer Space Telescope. The project turned up more than 300 galaxy candidates from the universe's first billion years.

IN BRIEF

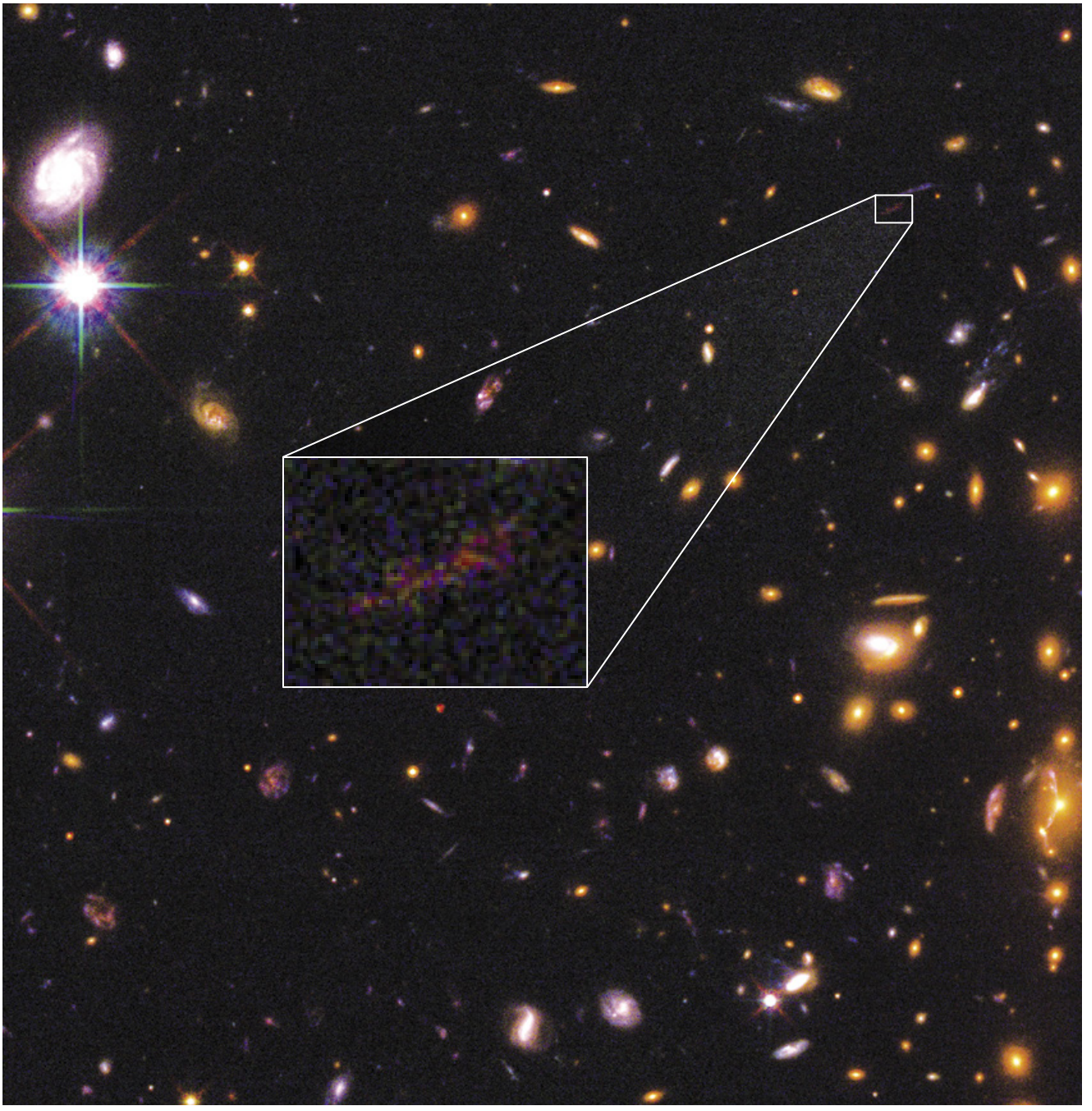
A recent experiment called the Reionization Lensing Cluster Survey (RELICS) aimed to find some of the first galaxies to form in cosmic history.
The project used gravitational lenses—areas where massive cosmic objects bend and magnify distant light.
RELICS discovered more than 300 ancient galaxies, including one around 13.3 billion years old.

These objects are fascinating because they provide a view into a sliver of our history that is still totally unknown. By studying such objects, we hope to learn how the first galaxies formed and influenced the nascent universe. For instance, we believe galaxies such as SPT0615-JD transformed early space by blasting out ultraviolet light that the gas around them absorbed, turning the universe's first neutral atoms back into the lone protons and electrons that they started out as (a process known as reionization). The details of how and when this process occurred are, however, still unclear. With luck, the ancient galaxies we are observing will change that.

THE FIRST GALAXIES

EARLY GALAXIES were not like those we know today. The first galaxies were more pristine, composed primarily of hydrogen and helium gas. Over time their stars would fuse atoms to form heavier elements, and when these stars died in supernova explosions, the heavy elements dispersed throughout the galaxies, enriching them with "star stuff," including the elements needed to create life. The first galaxies had yet to settle into majestic spiral patterns or puffy elliptical balls like the galaxies we see around us now. They were far more disordered and much smaller (making them even harder to find). The earliest galaxies we have seen were about 1 percent the size of our Milky Way, but they were growing rapidly, forming new stars at prodigious rates. Fuel was plentiful back then; early galaxies were bathed in cool streams of flowing hydrogen gas, lured inward by gravity. The galaxies collided with one another and merged frequently, accelerating their growth and triggering new bursts of star formation. As the universe expanded over time, galaxy growth slowed, significant mergers became less frequent and the gas supply thinned out.

This picture is our basic understanding of cosmic history. We are still working to fill in the details, and many questions remain, especially surrounding the earliest times. When did the first galaxies form? How small were they? What did they look like? Were they "building blocks" of galaxies to come, with single large regions of star formation, or were they more fragmented and clumpy? Were they all bursting with intense star formation, or were some more relaxed, like most galaxies today? Did any early galaxies have time to settle into disks like the Milky Way did, or were they merging too frequently to do so? Will we ever find any filled with pristine hydrogen and helium gas, or did the first supernovae enrich them too quickly with heavier elements? How rapidly did early galaxies build up in mass and numbers? And were they, in fact, responsible for reionizing the universe? With the re-



NASA, ESA, STScI AND B. SALMON

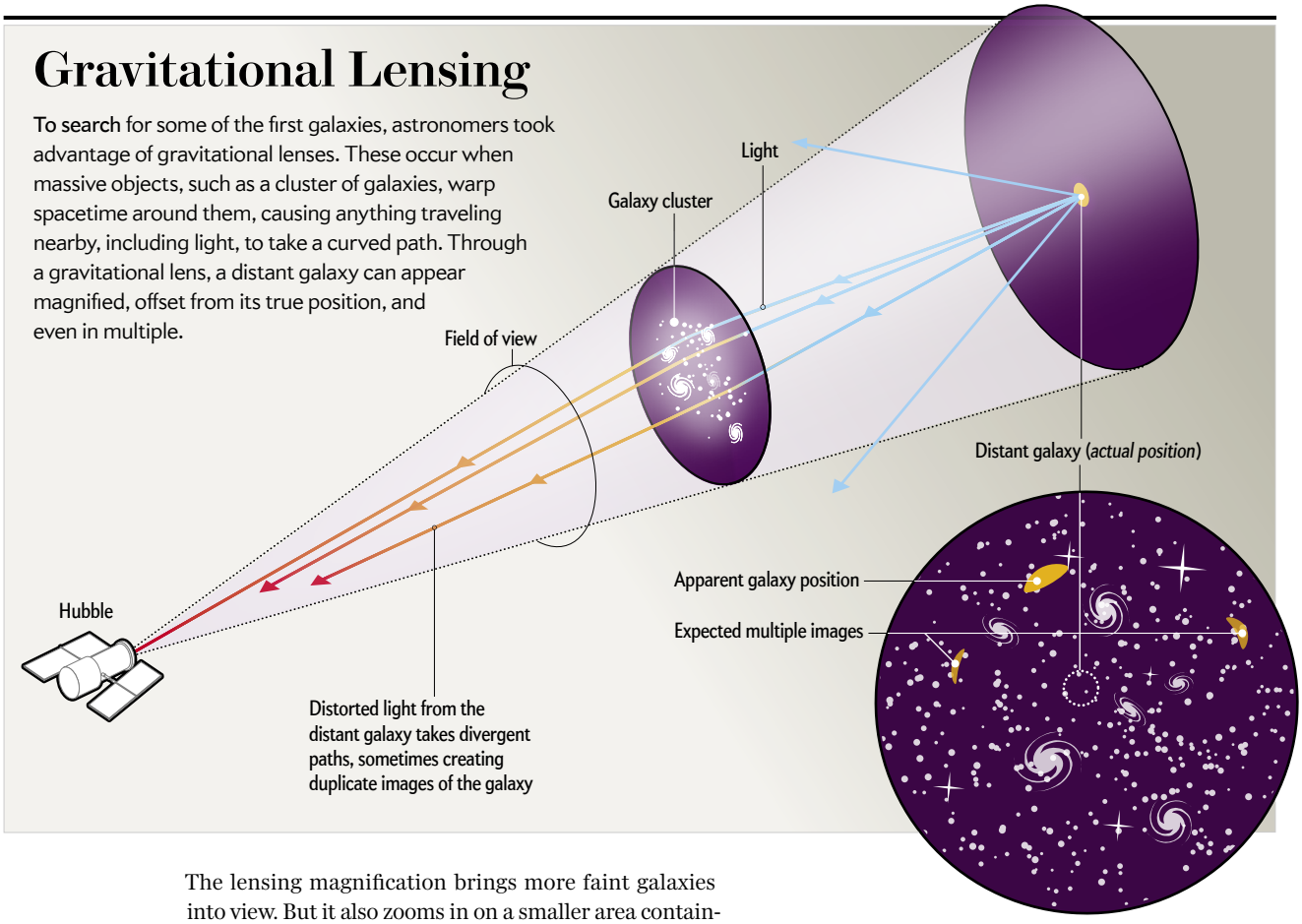
sults from RELICS, we will take another step toward answering these questions.

COSMIC MAGNIFYING GLASSES

RELICS RELIED on a technique called gravitational lensing to glimpse far back into the past. We took advantage of nature's own magnifying glasses in the form of massive galaxy clusters. These groups of galaxies have so much mass combined that their gravity bends space and time, according to Einstein's general theory of relativity. As light from a more distant object travels through the universe, it follows the bent spacetime around the cluster, becoming magnified along the way. When it reaches Earth, the distant object looks warped and stretched, and sometimes multiple images of it appear. If this effect seems abstract, you can find a similar example as close as your next glass of wine. Look at a lit candle through the base of the wine glass, and you will see multiple images of the flame magnified.

Magnified galaxies are brighter and resolved in more detail than normal, allowing us to better study their properties. Another advantage to observing strongly lensed regions of the sky is that we discover distant galaxies more efficiently than by observing "blank" patches such as the famous Hubble Deep Fields. This outcome is not obvious, and actually there is a trade-off.

RED BLUR: A faint streak in a Hubble Space Telescope image represents SPT0615-JD, one of the most distant known galaxies.



The lensing magnification brings more faint galaxies into view. But it also zooms in on a smaller area containing fewer galaxies. Which effect wins out? Lensing does when there are many faint galaxies brought into view by magnification, compensating for the loss of area. In the early universe small, faint galaxies were plentiful, meaning we detect many more distant galaxies by searching in images strongly lensed by galaxy clusters.

Three of the largest Hubble programs carried out in the past seven years have used galaxy-cluster gravitational lensing to search for distant galaxies. These programs also partnered with Spitzer, which observes in infrared light at longer wavelengths than Hubble. The first, the Cluster Lensing and Supernova Survey with Hubble (CLASH), was a three-year program led by Marc Postman of the Space Telescope Science Institute (STScI) in Baltimore to observe 25 galaxy clusters. I helped write the proposal and analyze the images, and in 2012 I discovered MACS0647-JD, a galaxy observed at just 420 million years after the big bang. This is a strong candidate for the most distant galaxy known, surpassed only in 2016, when Pascal Oesch of Yale University discovered a galaxy from 20 million years earlier, this time with the Cosmic Assembly Near-Infrared Deep Extragalactic Legacy Survey (CANDELS), a large Hubble scan of relatively blank patches of sky, unaided by strong lensing.

After the successes of CLASH, I helped to convince Hubble's director at the time, Matt Mountain, to include galaxy clusters in the next big Hubble program: the Frontier Fields, led by Jennifer Lotz of STScI. This project followed in the footsteps of the previous Hubble Deep Fields programs, which stared at small patches of sky for many days. These earlier projects targeted the emptiest areas of sky scientists could find, devoid of relatively bright "close" galaxies (within mere billions of light-years away) that would block our views of the more distant universe. The first Hubble Deep Field image, which combined 342 exposures taken over 10 days in 1995, was a revelation: in a blank bit of sky the size of a grain of sand held at arm's length, some 3,000 galaxies appeared. The subsequent Hubble Deep Field South and Ultra Deep Field were similarly careful to avoid nearby galaxies. The Frontier Fields boldly broke from that tradition by obtaining deep images of six regions containing some of the densest concentrations of galaxies three billion to five billion light-years away. The project also observed six relatively blank areas nearby, more in the tradition of the previous deep-field programs. By boosting the power of Hubble and Spitzer with gravitational lensing, the Frontier Fields revealed the smallest and faintest distant galaxies ever observed.

RELICS FROM THE PAST

AFTER CLASH and with the Frontier Fields under way, it was not clear that astronomers would approve another large Hubble proposal to observe galaxy clusters. But I

Illustrations by Nigel Hawtin

found that many massive clusters had never been observed by Hubble at near-infrared wavelengths, in which distant galaxies would appear. (As the universe expands, light from faraway objects gets stretched and shifted toward longer, redder wavelengths—an effect called redshift.) I had uncovered a set of natural telescopes that we had yet to look through in our search for galaxies in the first billion years.

I tracked down these clusters in a catalog produced in 2015 by the European Space Agency's Planck space telescope. Planck is more famous for its detailed all-sky images of the cosmic microwave background (CMB)—the earliest observed radiation in the universe. But it was also able to catalog more than 1,000 massive galaxy clusters by noting their distortion effect on the CMB light. Most of these clusters were well known, but many were new discoveries. I found that the most massive cluster in the catalog, Abell 2163, had been observed by Hubble only in visible wavelengths, not near-infrared wavelengths. The second most massive cluster—PLCK G287.0+32.9, one of Planck's recent finds—had shown itself to be an excellent lens in ground-based imaging, but Hubble had yet to take a peek at it.

I compiled a list of 41 massive clusters lacking Hubble near-infrared imaging and assembled a team of astronomers to help write a large proposal to observe them. We requested the use of Hubble during 190 of its orbits around Earth—roughly 5 percent of the observing time available for proposals that year, amounting to more than 100 hours of observations. Once all the Hubble proposals were submitted, astronomers from around the world convened in Baltimore to deliberate over them. Our team was fortunate to learn in June 2015 that our proposal was accepted as the largest General Observer program in Hubble's 23rd full year of science operations.

RELICS observed all 41 clusters with Hubble's Wide Field Camera 3 infrared channel (WFC3/IR). We also observed them at red, green and blue visible wavelengths (if they had not been observed already) with the telescope's Advanced Camera for Surveys (ACS). The higher-resolution ACS images help us to measure the lensing properties of the cluster and to estimate the magnifications of the distant galaxies discovered in the WFC3/IR images. We observed at seven different wavelengths spanning 0.4 to 1.7 microns, enabling us to separate the light from each galaxy into its constituent colors. By looking at known light features, such as the specific wavelength that neutral hydrogen absorbs, we can estimate how much the galaxy's light has been redshifted and therefore how distant it is.

We have also been awarded 945 hours of observing time with Spitzer in proposals led by Maruša Bradač of the University of California, Davis, with important contributions from Spitzer's director, Tom Soifer. Spitzer's wavelengths deliver a more complete census of the stars in early galaxies, enabling us to measure their stellar mass and whether they are truly as far as they appear in the Hubble images.

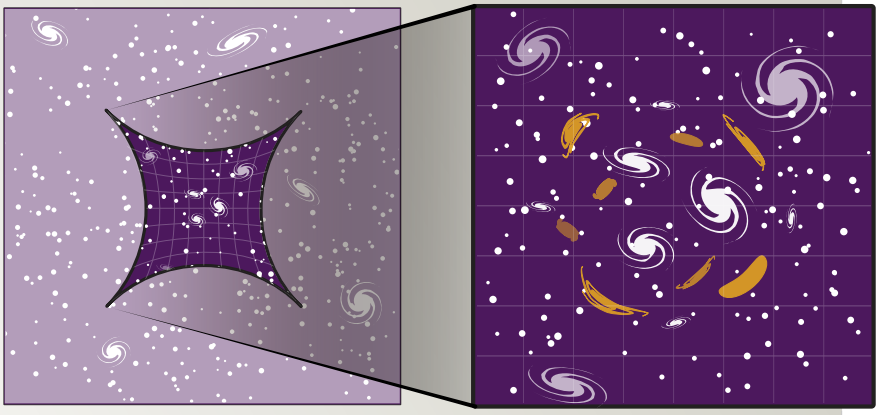
DISCOVERY

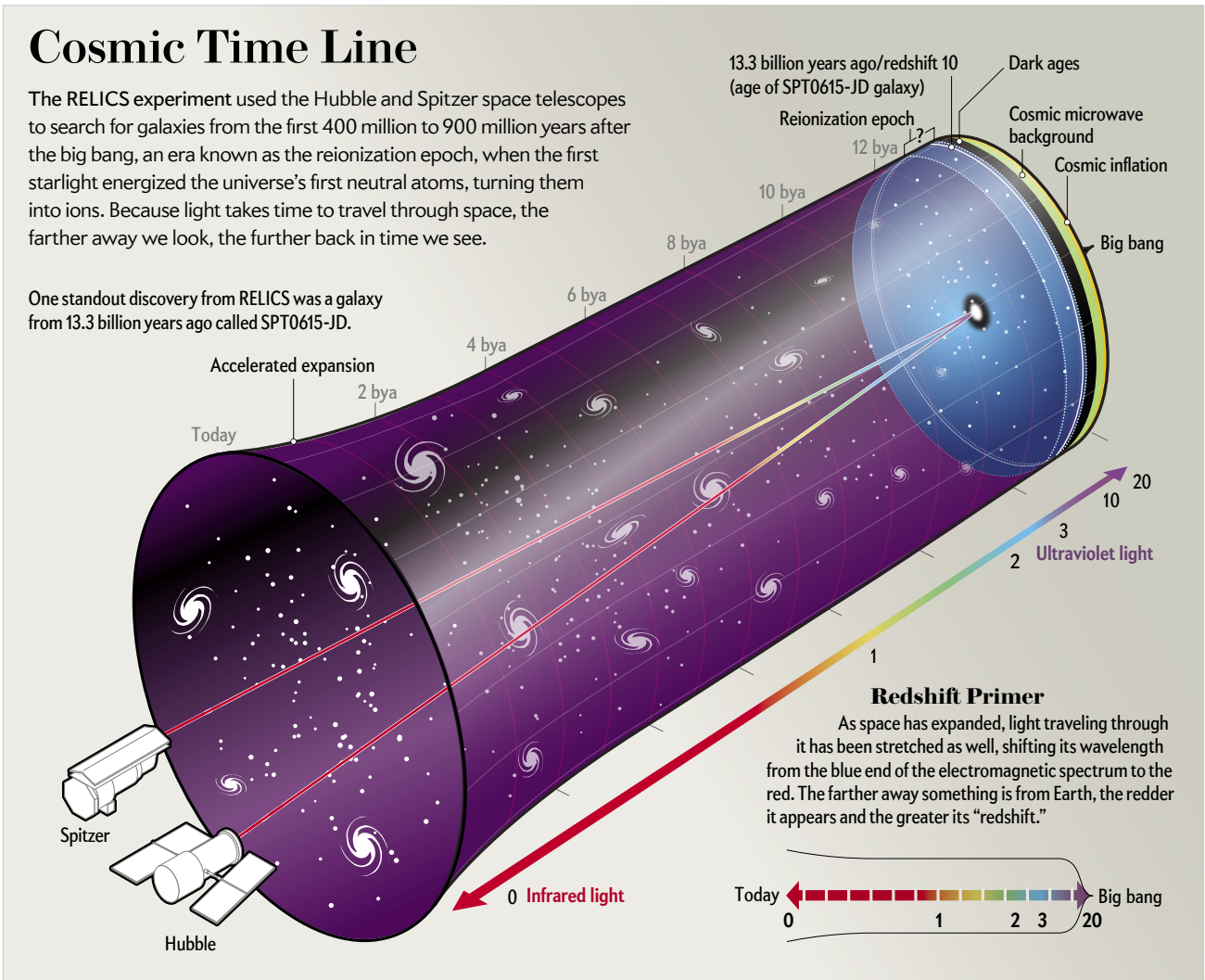
SPT0615-JD REVEALED itself in 2017 to a postdoctoral astronomer named Brett Salmon hired by myself with RELICS deputy principal investigator Larry Bradley of STScI. It did not pop out of the Hubble images right away as the unique object that it is. Galaxies can appear red to us for different reasons. Some are highly redshifted, such as SPT0615-JD. Others are enshrouded in dust, which absorbs bluer light and then reemits it as infrared light, making the galaxies appear redder than they are. Still other red galaxies are simply older—they have not formed many new stars in a while, and the stars that remain are longer-lived redder ones. Red galaxies may also be any combination of these: redshifted, dusty and old.

Spitzer's observations at three to five microns are critical in helping us to distinguish distant redshifted galaxies from less distant galaxies that are intrinsically red and would appear even brighter in Spitzer's

Two Strategies

Astronomers can take two approaches to search for galaxies. One is to look at an apparently "blank" patch of sky. Another option, employed by the Reionization Lensing Cluster Survey (RELICS), is to observe areas that include a massive galaxy cluster to capitalize on its gravitational lensing. This strategy takes in a smaller, oddly shaped field of view (because lensing magnifies the sky), but it reveals galaxies that would otherwise be too faint to see.





wavelengths. In fact, we originally discovered three candidate galaxies (including SPT0615-JD) in our Hubble images that appeared to be at a redshift, or "*z*," of about 10, dating from when the universe was less than 500 million years old, more than 13 billion years ago. Analysis of the Spitzer observations, however, revealed that two of them were more likely to lie at a redshift of around two, when the universe was "only" 10 billion years old (nearly three quarters of its current age). SPT0615-JD survived the Spitzer analysis as a more likely redshift 10 candidate.

Combining Salmon's Hubble analysis with a Spitzer analysis by Victoria Strait of U.C. Davis, we found the light from SPT0615-JD drops off at around 1.34 microns, with all the light of smaller wavelengths missing. This light was absorbed as it excited hydrogen gas in the infant universe, or reionized it, turning atoms back into ions. The hard break in SPT0615-JD's spectrum is very useful because it allows us to measure its distance. Although we see the break at around 1.34 microns, we know that neutral hydrogen absorbs extreme ultraviolet light at wavelengths of less than 0.1216 micron. The ratio between the original and observed breaks in SPT0615-JD's spectrum reveals just how much the universe has expanded and its light has been redshifted and therefore just how far away it is.

We are seeing SPT0615-JD at a redshift of 10, when the universe was just 3.5 percent of its present age. This dating makes SPT0615-JD one of the oldest galaxies we are aware of. Two other galaxies are known to be a bit more distant, at a redshift of 11, observed when the universe was 400 million years old. But Hubble reveals those galaxies as simply infrared dots, too small for us to discern any details about their inner structure. SPT0615-JD is special. Its light has been stretched and magnified by gravitational lensing, giving us our most detailed look at such an early galaxy.

It may not look like much in our current observations, but we hope to take deeper Hubble images to reveal more details and uncover the fainter lensed multiple images of this galaxy predicted by Rachel Paterno-Mahler of the University of California, Irvine.

Illustration by Nigel Hawtin

We also have an accepted observing program with the Atacama Large Millimeter Array (ALMA), which we expect to confirm our distance measurement and to reveal oxygen, which would be the earliest detection yet of such a heavy element. And we will propose observations with NASA's next flagship observatory, the James Webb Space Telescope (JWST), which could provide detailed images of the galaxy's inner workings, measure its contribution to reionization, and reveal its chemical makeup, whether it be of pristine hydrogen and helium or enriched heavier elements.

SPT0615-JD was RELICS's most noteworthy discovery, but we also found more than 300 ancient-galaxy candidates (still to be confirmed) in the universe's first billion years. Among them are the brightest galaxies known dating back to these early times, which will allow us to study them in great detail. At first, I found this surprising because ground-based telescopes had observed many times more of the sky's area. But after crunching the numbers, the results are as expected. By using Hubble, Spitzer and the advantage of lensing, RELICS was able to uncover brighter galaxies at these distances.

THE GAP IN OUR STORY

THE ANCIENT GALAXIES we are finding through RELICS are helping to fill in a missing chunk of the cosmology history books. Scientists have a basic theory about the first moments of time, when the big bang initiated the universe, and space ballooned rapidly in a period called inflation. Around 380,000 years after the birth of space and time, the universe had cooled enough for the first atoms to form and for light to stream free. We see that afterglow today as the CMB.

After that snapshot, what follows is a 400-million-year gap in our story. We have yet to observe a single object as it existed during that time. That 3 percent of cosmic history is unknown to us. But we do know it was eventful. The first stars formed perhaps 100 million years after the big bang. Then, we think, stars began to cluster, eventually forming the first galaxies. Light from these galaxies streamed out and scattered off hydrogen atoms, ionizing them and liberating their electrons.

Understanding how this process happened by studying these galaxies is crucial for filling in the missing pages in our origin story. RELICS and projects that came before it—such as CLASH, CANDELS and the Frontier Fields—are taking big strides, but we expect an even bigger leap when JWST launches. This observatory, due to fly in 2021, will be humanity's most powerful tool ever for looking back at the earliest times. Observing with a larger mirror at longer wavelengths than previous telescopes, it will be able to see fainter, more distant galaxies with better resolution than any observatory before it. And it should be able to determine those galaxies' masses and compositions and how they contributed to reionization.

As much as gravitational lensing has helped us discover distant galaxies with current telescopes, I expect this advantage to be even greater at higher redshifts with JWST. As we look back in time, we find that smaller galaxies make up more and more of the overall census. If this trend continues into the first 400 million years, the lensing advantage will multiply further. Based on the current estimates, I predict that lensing will be the key to discovering the very first galaxies with JWST.

JWST will almost certainly see galaxies 300 million years after the big bang, and I strongly suspect that lensing will allow us to see galaxies within the first 200 million years, shrinking our historical gap in half—that is, if galaxies even formed that early.

We need to hit the ground running as soon as JWST launches because we may have a mere five to 10 years to work with it. Although Hubble is operating strongly 28 years after its launch, JWST will have only enough fuel to maintain its orbit for a decade. It is due to fly about a million miles from Earth, much too far for astronauts to service, repair or add new instruments to it, as they did several times for Hubble. RELICS is crucial to making the most use of JWST while we have it because it has already identified some of the best ancient galaxies for the new telescope to observe in detail, as well as the most gravitationally lensed areas of sky in which JWST can search for new galaxies.

LOOKING BACK

OUR MILKY WAY is probably as old as SPT0615-JD. The difference is that we see our galaxy as it is now and have no insight into how it looked in the very early universe. Because SPT0615-JD's light has taken so long to get here, we are seeing a fossilized version of its younger self.

But SPT0615-JD and our galaxy may have had similar histories, building up in size over the past 13 billion years. Planets probably formed around stars in the SPT0615-JD galaxy. Perhaps on some of those planets, life formed. And just maybe some of that life developed intelligence, culture, technology and telescopes in space. If so, they may be looking back at us now, through the same galaxy cluster, seeing a similarly magnified image of our galaxy as a pale red dot, the Milky Way as it was shortly after it was born.

Such possibilities are why we explore the frontiers of our universe: to discover our origins and, ultimately, to find ourselves. SA

MORE TO EXPLORE

RELICS: A Candidate z~10 Galaxy Strongly Lensed into a Spatially Resolved Arc. Brett Salmon et al. in *Astrophysical Journal Letters,* Vol. 864, No. 1, Article No. L22; September 1, 2018. http://iopscience.iop.org/article/10.3847/2041-8213/aadc10

RELICS Web site: https://relics.stsci.edu

FROM OUR ARCHIVES

The First Starlight. Michael D. Lemonick; April 2014.

scientificamerican.com/magazine/sa

MATHEMATICS

MATHEMATICIANS ARE DEVELOPING FORENSICS TO IDENTIFY POLITICAL MAPS THAT DISENFRANCHISE VOTERS

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GEOMETRY V. GERRYMANDERING

By Moon Duchin

Illustration by Hanna Barczyk

IN BRIEF

Attempts to shape voting districts in ways that unfairly favor a political party have provoked legal challenges across the country. But courts lack a practical standard for identifying these so-called gerrymanders.

In recent years mathematicians have stepped into the fray to develop statistical methods that courts can use to spot manipulative districting and to act as experts inside and outside of courtrooms.

There are so many ways to district a state that evaluation has become a massive data challenge for even the fastest computers. Courts, however, seem amenable to a tool called Markov chain Monte Carlo that stands up to the task.

GERRYMANDERING IS CLAWING ACROSS courtrooms and headlines nationwide. The U.S. Supreme Court recently heard cases on the constitutionality of voting districts that allegedly entrenched a strong advantage for Republicans in Wisconsin and Democrats in Maryland but dodged direct rulings in both. Another partisan gerrymandering case from North Carolina is winding its way up with a boost from an emphatic lower court opinion in August. But so far it has been impossible to satisfy the justices with a legal framework for partisan gerrymandering. Part of the problem, as former justice Anthony Kennedy noted in a 2004 case, is that courts high and low have yet to settle on a "workable standard" for identifying a partisan gerrymander in the first place. That is where a growing number of mathematicians around the country think we can help.

Moon Duchin is an associate professor of mathematics and a senior fellow at the Jonathan M. Tisch College of Civic Life at Tufts University. Her research is in geometric group theory, low-dimensional topology, and dynamics. She formed the Metric Geometry and Gerrymandering Group in the fall of 2016 to focus mathematical attention on redistricting.

Two years ago, with a few friends, I founded a working group to study the applications of geometry and computing to redistricting in the U.S. Since then, the Metric Geometry and Gerrymandering Group has expanded its scope and mission, becoming deeply engaged in research, outreach, training and consulting. More than 1,200 people have attended our workshops around the country, and many of them have become intensely involved in redistricting projects. We think the time is right to make a computational intervention. The mathematics of gerrymandering is surprisingly rich—enough to launch its own subfield—and computing power is arguably just catching up with the scale and complexity of the redistricting problem. Despite our group's technical orientation, our central goal is to reinforce and protect civil rights, and we are working closely with lawyers, political scientists, geographers and community groups to build tools and ideas in advance of the next U.S. Census and the round of redistricting to follow it.

In a country that vests power in elected representatives, there will always be skirmishes for control of the electoral process. And in a system such as that of our House of Representatives—where winner takes all within each geographical district—the delineation of voting districts is a natural battleground. American history is chock-full of egregious line-drawing schemes, from stuffing a district with an incumbent's loyalists to slicing a long-standing district three ways to suppress the political power of black voters. Many varieties of these so-called packing and cracking strategies continue today, and in the big data moment, they have grown enormously more sophisticated. Now more than ever, abusive redistricting is stubbornly difficult to even identify definitively. People think they know gerrymandering by two hallmarks—bizarre shapes and disproportionate electoral outcomes—yet neither one is reliable. So how do we determine when the scales are unfairly tipped?

THE EYEBALL TEST

THE 1812 EPISODE that gave us the word "gerrymander" sprang from the intuition that oddly shaped districts betray an illegitimate agenda. It is named for Elbridge Gerry, who was governor of Massachusetts at the time. Gerry had quite a Founding Father pedigree—signer of the Declaration of Independence, major player at the U.S. Constitutional Convention, member of Congress, James Madison's vice president—so it is amusing to consider that his enduring fame comes from nefarious redistricting. "Gerry-mander," or Gerry's salamander, was the satirical name given to a curvy district in Boston's North Shore that was thought to favor the governor's Democratic-Republican party over the rival Federalists. A woodcut political cartoon ran in the *Salem Gazette* in 1813; in it, wings, claws and fangs were suggestively added to the district's contours to heighten its appearance of reptilian contortions.

So the idea that erratic districts tip us off to wrongdoing goes a long way back, and the converse notion that close-knit districts promote democratic ideals is as old as the republic. In 1787 Madison wrote in *The Federalist Papers* that "the natural limit of a democracy is that distance from the central point which will just permit the most remote citizens to assemble as often as their public functions demand." In other words, districts should be transitable. In 1901 a federal apportionment act marked the first appearance in U.S. law of the vague desideratum that districts should be composed of "compact territory." The word "compact" then proliferated throughout the legal landscape of redistricting but almost always without a definition.

For instance, at a 2017 meeting of the National Conference of State Legislatures, I learned that after the last Census, Utah's lawmakers took the commendable time and effort to set up a Web site, Redistrict Utah, to solicit proposed districting maps from everyday citizens. To be considered, maps were required to be "reasonably compact." I jumped at the opportunity to find out how exactly that quality was being tested and enforced, only to learn that it was handled by just tossing the funny-looking maps. If that sounds bad, Utah is far from alone. Thirty-seven states have some kind of shape regulation on the books, and in almost every case, the eyeball test is king.

The problem is that the outline of a district tells a very partial and often misleading story. On one hand there can certainly be benign reasons for ugly shapes. Physical geography or reasonable attempts to follow county lines or unite communities of interest can influence a boundary, although just as often, legitimate priorities such as these are merely scapegoated in an attempt to defend the worst-offending districts. On the other hand districts that are plump, squat and symmetrical offer no meaningful seal of quality. Just this year a congressional redistricting plan in Pennsylvania drafted by Republicans in the state legislature achieved strong compactness scores under all five formulas specified by Pennsyl-

vania's supreme court. Yet mathematical analysis revealed that the plan would nonetheless lock in the same extreme partisan skew as the contorted plan, enacted in 2011, that it was meant to replace. So the justices opted for the extraordinary measure of adopting an independent outsider's plan.

LOPSIDED OUTCOMES

IF SHAPE IS NOT a reliable indicator of gerrymandering, what about studying the extent to which elected representatives match the voting patterns of the electorate? Surely lopsided outcomes provide prima facie evidence of abuse. But not so fast. Take Republicans in my home state of Massachusetts. In the 13 federal elections for president and Senate since 2000, GOP candidates have averaged more than one third of the votes statewide. That is six times the level needed to win a seat in one of Massachusetts's nine congressional districts because a candidate in a two-way race needs a simple majority to win. Yet no Republican has won a seat in the House since 1994.

We must be looking at a gerrymander that denies Republicans their rightful opportunity districts, right? Except the mathematics here is completely exonerating. Let us look at a statewide race so that we can put uncontested seats and other confounding variables to the side. Take Kenneth Chase, the Republican challenger to Ted Kennedy for the U.S. Senate in 2006, who cracked 30 percent of the statewide vote. Proportionally, you would expect Chase to beat Kennedy in nearly three out of nine congressional districts. But the numbers do not shake out. As it turns out, it is mathematically impossible to select a single district-sized grouping of towns or precincts, even scattered around the state, that preferred Chase. His voters simply were not clustered enough. Instead most precincts went for Chase at levels close to the state average, so there were too few Chase-favoring building blocks to go around.

Any voting minority needs a certain level of nonuniformity in how its votes are distributed for our districting system to offer even a theoretical opportunity to secure representation. And the type of analysis applied to the Chase-Kennedy race does not even consider spatial factors, such as the standard requirement that each district be one connected piece. One may rightfully wonder how we can ever hold district architects accountable when the landscape of possibilities can hold so many surprises.

RANDOM WALKS TO THE RESCUE

THE ONLY REASONABLE WAY to assess the fairness of a districting plan is to compare it with other valid plans for cutting up the same jurisdiction because you must control for aspects of electoral outcomes that were forced by the state's laws, demographics and geography. The catch is that studying the universe of possible plans becomes an intractably big problem.

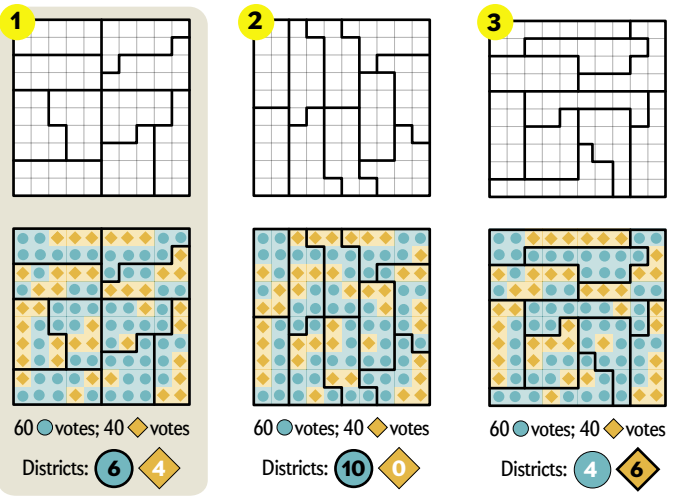
Think of a simple four-by-four grid and suppose you want to divide it into four contiguous districts of equal size, with four squares each. If we imagine the grid as part of a chessboard, and we interpret contiguity to mean that a rook should be able to visit the entire district, then there are exactly 117 ways to do it. If corner adjacency is permitted—so-called queen contiguity—then there are 2,620 ways. And they are not so straightforward to count. As my colleague Jim Propp, a professor at the University of Massachusetts Lowell and a leader in the field of combinatorial enumeration, puts it, "In one dimension, you can split paths along the way to divide and conquer, but in two dimensions, suddenly there are many, many ways to get from point A to point B."

The issue is that the best counting techniques often rely on recursion—that is, solving a problem using a similar problem that is a step smaller—but two-dimensional spatial counting problems just do not recurse well without some extra structure. So complete enumerations must rely on brute force. Whereas a cleverly programmed laptop can classify partitions of small grids nearly instantly, we see huge jumps in complexity as the grid size grows, and the task quickly zooms out of reach. By the time you get to a grid of nine-by-nine, there are more than 700 trillion solutions for equinumerous rook partitions, and even a high-performance computer needs a week to count them all. This seems like a hopeless state of affairs. We are trying to assess one way of cutting up a state without any ability to enumerate—let alone meaningfully compare it against—the universe of alternatives. This situation sounds like groping around in a dark, infinite wilderness.

The good news is that there is an industry standard used across scientific domains for just such a colossal task: Markov chain Monte Carlo (MCMC). Markov chains are random walks in which where you go next is governed by probability, depending only on

The Power of the Pen

Gerrymandering relies on carefully drawn lines that dilute the voting power of one population to favor another by clustering one side's voters into a few districts with excessively high numbers (packing), by dispersing them across several districts so that they fall short of electing a preferred candidate (cracking), or by using a combination of the two schemes.



A grid is districted to produce an electoral outcome proportional to the share of votes for each party (1). The same grid can be districted using combinations of packing and cracking to produce extreme outcomes (2), (3)—one in which the Blue party wins all districts and one in which it wins only four of 10. In this particular case, the geometry of the layout turns out to favor the Blue party. Statistical analysis using Markov chain Monte Carlo reveals that the Orange party is far more likely to get two or three seats, rather than its proportional share of four, in the universe of possible plans.

Illustrations by Jen Christiansen

Dimensions; Districts	Equal-size districts	District sizes can be unequal (+/- 1)
2×2 grid; 2 districts	2	6
3×3 grid; 3 districts	10	58
4×4 grid; 2 districts	70	206
4×4 grid; 4 districts	117	1,953
4×4 grid; 8 districts	36	34,524
5×5 grid; 5 districts	4,006	193,152
6×6 grid; 2 districts	80,518	?*
6×6 grid; 3 districts	264,500	?
6×6 grid; 4 districts	442,791	?
6×6 grid; 6 districts	451,206	?
6×6 grid; 9 districts	128,939	?
6×6 grid; 12 districts	80,092	?
6×6 grid; 18 districts	6,728	?
7×7 grid; 7 districts	158,753,814	?
8×8 grid; 8 districts	187,497,290,034	?
9×9 grid; 9 districts	706,152,947,468,301	?

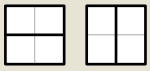
How to Compare Countless Districting Plans

Markov chains are random walks around a graph or network in which the next destination is determined by a probability, like a roll of the dice, depending on the current position. Monte Carlo methods use random sampling to estimate a distribution of probabilities. Combined, Markov chain Monte Carlo (MCMC) is a powerful tool for searching and sampling from a vast space of scenarios, such as all the possible districting plans in a state. Attempts to use computational analysis to spot devious districting go back several decades, but efforts to apply MCMC to the problem are much more recent.

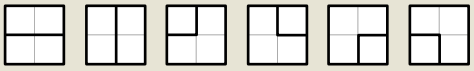
SIMPLE CASE

It is easy to enumerate all the ways to partition a small grid into equal-size districts. For a two-by-two grid with two districts of equal size, there are only two solutions. But if districts can vary in size, the number of solutions jumps to six.

Equal-size districts:
2 solutions



District size can be +/-1:
6 solutions



**Mathematicians have not yet enumerated these solutions, which can require a week of computing or more. To find out more about the hunt for these numbers, visit www.mggg.org*

where you are now (at every position, you roll the dice to choose a neighboring space to move to). Monte Carlo methods are just estimation by random sampling. Put them together, and you get a powerful tool for searching vast spaces of possibilities. MCMC has been successfully used to decode prison messages, probe the properties and phase transitions of liquids, find provably accurate fast approximations for hard computational problems, and much more. A 2009 survey by the eminent statistician Persi Diaconis estimated that MCMC drives 10 to 15 percent of the statistical work in science, engineering and business, and the number has probably only gone up since then. Although computational analysis in redistricting goes back several decades, serious attempts to apply MCMC in that effort only started to appear publicly around 2014.

Imagine that officials in the state of Gridlandia hire you to decide if their legislature's districting plan is reasonable. If Gridlandia is a four-by-four grid of squares, and its state constitution calls for rook-contiguous districts, then you are in luck: there are exactly 117 ways to produce a compliant plan, and you can examine them all. You can set up a perfectly faithful model of this universe of districting plans by using 117 nodes to represent the valid plans and adding edges between the nodes to represent simple moves in which two squares in the grid swap their district assignments. The edges give you a way of conceptualizing how similar two plans are by simply counting the number of swaps needed to transform one to the other. (I call this structure a "metagraph" because it is a graph of ways to cut up another graph.) Now suppose that the state legislature is controlled by the Diamond party, and its rivals suspect that it has rigged the seats in its favor. To determine if that is true, one may turn to the election data. If the Diamond plan would have produced more seats for the party in the last election than, say, 114 out of 117 alternatives and if the same is true for several previous elections, the plan is clearly a statistical outlier. This is persuasive evidence of a partisan gerrymander—and you do not need MCMC for such an analysis.

The MCMC method kicks in when you have a full-sized problem in place of this small toy problem. As soon as you get past 100 or so nodes, there is a similar metagraph, but you cannot completely build it because of its forbidding complexity. That is no deal breaker, though. From any single plan, it is still easy to build out the local neighborhood by performing all possible moves. Now you can take a million, billion or trillion steps and see what you find. There is mathematics in the background (ergodic theory, to be precise) guaranteeing that if you random-walk for long enough, the ensemble of maps you collect will have properties representative of the overall universe, typically long before you have visited even a modest fraction of nodes in your state space. This lets you determine if the map you are evaluating is an extreme outlier according to various partisan metrics.

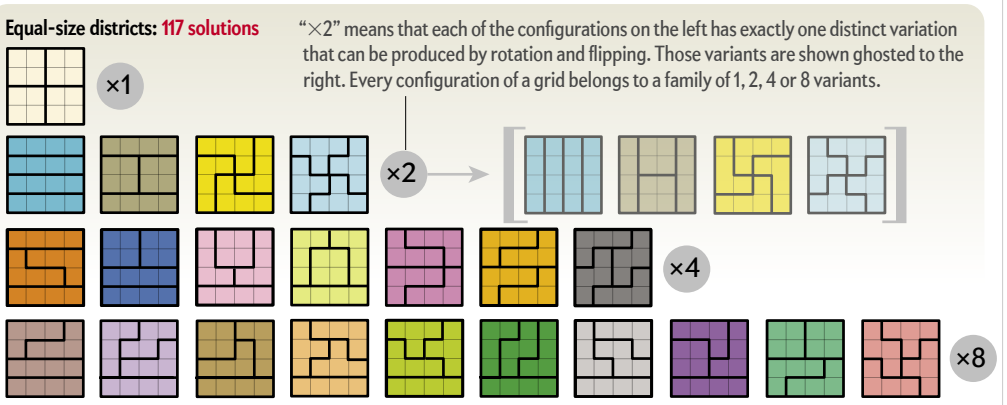
The cutting edge of scientific inquiry is to build more powerful algorithms and, at the same time, to devise new theorems that certify that we are sampling well enough to draw robust conclusions. There is an emerging scientific consensus around this method but also many directions of ongoing research.

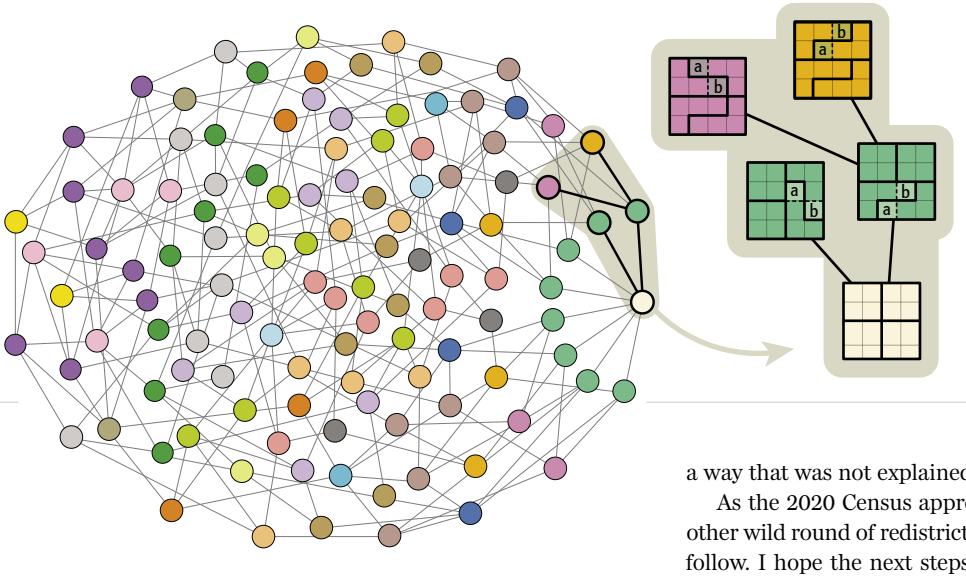
R.I.P. GOVERNOR GERRY

SO FAR COURTS seem to be smiling on this approach. Two mathematicians—Duke University's Jonathan Mattingly and Carnegie Mellon University's Wes Pegden—have recently testified about

BIGGER CASE

As the size of the grid grows, the number of possibilities for carving it up skyrockets. Dividing a four-by-four grid into four districts of equal size has 117 solutions. If the districts can vary in size by even one unit, there are 1,953 solutions. It does not take long before even the most powerful computers struggle to enumerate the possibilities for more complex grids. That presents a problem for anyone trying to detect manipulative maps by comparing the myriad ways to district a U.S. state. But MCMC can help.





We can efficiently explore valid districting plans by traveling randomly around a "metagraph," defined by moves such as the unit swaps pictured. In the highlighted inset, each pattern has squares marked a and b whose district assignments are exchanged to arrive at the configuration of the pattern shown. The edges in the network represent these simple swap moves. The metagraph models the space of all valid districting plans and can be used to sample many billions of plans. Geometers are trying to understand the shape and structure of that universe of plans.

MCMC approaches for the federal case in North Carolina and the state-level case in Pennsylvania, respectively.

Mattingly used MCMC to characterize the reasonable range one might observe for various metrics, such as seats won, across ensembles of districting plans. His random walk was weighted to favor plans that were deemed closer to ideal, along the lines of North Carolina state law. Using his ensembles, he argued that the enacted plan was an extreme partisan outlier. Pegden used a different kind of test, appealing to a rigorous theorem that quantifies how unlikely it is that a neutral plan would score much worse than other plans visited by a random walk. His method produces *p*-values, which constrain how improbable it is to find such anomalous bias by chance. Judges found both arguments credible and cited them favorably in their respective decisions.

For my part, Pennsylvania governor Tom Wolf brought me on earlier this year as a consulting expert for the state's scramble to draw new district lines following its supreme court's decision to strike down the 2011 Republican plan. My contribution was to use the MCMC framework to evaluate new plans as they were proposed, harnessing the power of statistical outliers while adding new ways to take into account more of the varied districting principles in play, from compactness to county splits to community structure. My analysis agreed with Pegden's in flagging the 2011 plan as an extreme partisan outlier—and I found the new plan floated by the legislature to be just as extreme, in a way that was not explained away by its improved appearances.

As the 2020 Census approaches, the nation is bracing for another wild round of redistricting, with the promise of litigation to follow. I hope the next steps will play out not just in the courtrooms but also in reform measures that require a big ensemble of maps made with open-source tools to be examined before any plan gets signed into law. In that way, the legislatures preserve their traditional prerogatives to commission and approve district boundaries, but they have to produce some guarantees that they are not putting too meaty a thumb on the scale.

Computing will never make tough redistricting decisions for us and cannot produce an optimally fair plan. But it can certify that a plan behaves as though selected just from the stated rules. That alone can rein in the worst abuses and start to restore trust in the system. SA

SOURCE: ZACHARY I. SCHUTZMAN AND FLOOR VAN DE VELDE

MORE TO EXPLORE

A Formula Goes to Court: Partisan Gerrymandering and the Efficiency Gap. Mira Bernstein and Moon Duchin in *Notices of the American Mathematical Society*, Vol. 64, No. 9, pages 1020–1024; October 2017. www.ams.org/journals/notices/201709/rnoti-p1020.pdf

Gerrymandering Metrics: How to Measure? What's the Baseline? Moon Duchin in *Bulletin of the American Academy of Arts & Sciences*, Vol. 71, No. 2, pages 54–58; Winter 2018.

FROM OUR ARCHIVES

Election Security Is a Matter of National Security. David L. Dill; Guest blog, ScientificAmerican.com, November 30, 2016.

The Science of Elections. Michael Latner; Observations blog, ScientificAmerican.com, June 14, 2018.

scientificamerican.com/magazine/sa

SPECIAL REPORT

THE SCIENCE OF INEQUALITY

HIGH ECONOMIC INEQUALITY NEGATIVELY IMPACTS NEARLY EVERY ASPECT OF HUMAN well-being—as well as the health of the biosphere. Contrary to intuition, it affects the wealthy and the middle classes, not just the poor. Here several leading researchers discuss these wide-ranging effects. Economist Joseph E. Stiglitz explains the origins of U.S. inequality and suggests measures to alleviate it. Political scientist Virginia Eubanks describes how digital systems often hurt, rather than help, the most vulnerable members of society. Neuroscientist Robert M. Sapolsky details the mechanisms by which inequality damages mental and physical health. And economist James K. Boyce describes how imbalances in economic and political power injure the environment—and how communities are coming together to combat such harm.

INSIDE

Illustration by Andrea Ucini

A RIGGED ECONOMY

And what we can do about it *By Joseph E. Stiglitz*

AMERICANS ARE USED TO THINKING THAT THEIR NATION IS special. In many ways, it is: the U.S. has by far the most Nobel Prize winners, the largest defense expenditures (almost equal to the next 10 or so countries put together) and the most billionaires (twice as many as China, the closest competitor). But some examples of American Exceptionalism should not make us proud. By most accounts, the U.S. has the highest level of economic inequality among developed countries. It has the world's greatest per capita health expenditures yet the lowest life expectancy among comparable countries. It is also one of a few developed countries jostling for the dubious distinction of having the lowest measures of equality of opportunity.

The notion of the American Dream—that, unlike old Europe, we are a land of opportunity—is part of our essence. Yet the numbers say otherwise. The life prospects of a young American depend more on the income and education of his or her parents than in almost any other advanced country. When poor-boy-makes-good anecdotes get passed around in the media, that is precisely because such stories are so rare.

Things appear to be getting worse, partly as a result of forces, such as technology and globalization, that seem beyond our control, but most disturbingly because of those within our command. It is not the laws of nature that have led to this dire situation: it is the laws of humankind. Markets do not exist in a vacuum: they are shaped by rules and regulations, which can be designed to favor one group over another. President Donald Trump was right in saying that the system is rigged—by those in the inherited plutocracy of which he himself is a member. And he is making it much, much worse.

America has long outdone others in its level of inequality, but in the past 40 years it has reached new heights. Whereas the income share of the top 0.1 percent has more than quadrupled and that of the top 1 percent has almost doubled, that of the bottom 90 percent has declined. Wages at the bottom, adjusted for inflation, are about the same as they were some 60 years ago! In fact, for those with a high school education or less, incomes have fallen over recent decades. Males have been particularly hard hit, as the U.S. has moved away from manufacturing industries into an economy based on services.

DEATHS OF DESPAIR

WEALTH IS even less equally distributed, with just three Americans having as much as the bottom 50 percent—testimony to how much money there is at the top and how little there is at the bottom. Families in the bottom 50 percent hardly have the cash reserves to meet an emergency. Newspapers are replete with stories of those for whom the breakdown of a car or an illness starts a downward spiral from which they never recover.

In significant part because of high inequality [see "The Health-

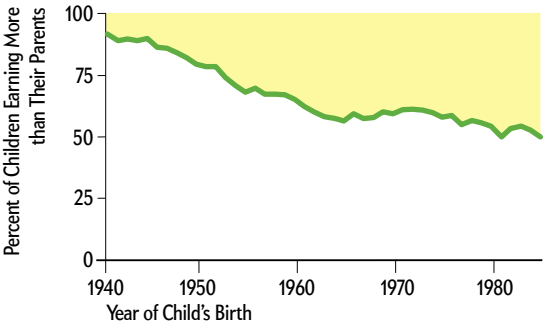
Joseph E. Stiglitz is a University Professor at Columbia University and Chief Economist at the Roosevelt Institute. He received the Nobel prize in economics in 2001. Stiglitz chaired the Council of Economic Advisers from 1995–1997, during the Clinton administration, and served as the chief economist and senior vice president of the World Bank from 1997–2000. He chaired the United Nations commission on reforms of the international financial system in 2008–2009. His latest authored book is *Globalization and Its Discontents Revisited* (2017).

Illustration by Andrea Ucini

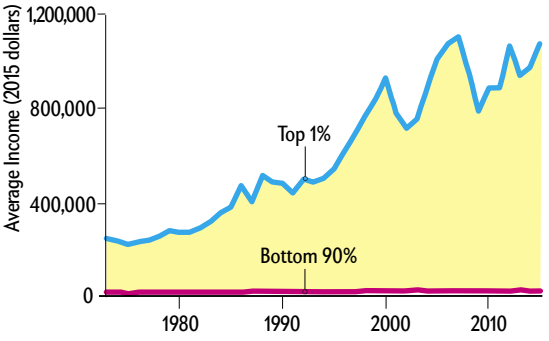
FADING OF THE AMERICAN DREAM

Contrary to popular belief, equality of opportunity in the U.S. is lower than in most advanced countries—and it is declining. A 2017 report by economist Raj Chetty and others indicates that an American born in 1940 was almost certain to become more prosperous than his or her parents. Someone born in 1980 is just as likely to be worse off, however. Declining equality of opportunity stems in large part from the high cost of higher education, coupled with spiraling economic inequality. Statistics from the World Inequality Database show that since about 1970 the income of the top 1 percent, corrected for inflation, has quadrupled, whereas that of the bottom 90 percent has stagnated. Men with only high school degrees have seen their incomes drop.

The American Dream Is Fading for Many …



… as the Income Gap Widens in the U.S.



Wealth Gap," by Robert M. Sapolsky, on page 62], U.S. life expectancy, exceptionally low to begin with, is experiencing sustained declines. This in spite of the marvels of medical science, many advances of which occur right here in America and which are made readily available to the rich. Economist Ann Case and 2015 Nobel laureate in economics Angus Deaton describe one of the main causes of rising morbidity—the increase in alcoholism, drug overdoses and suicides—as "deaths of despair" by those who have given up hope.

Defenders of America's inequality have a pat explanation. They refer to the workings of a competitive market, where the laws of supply and demand determine wages, prices and even interest rates—a mechanical system, much like that describing the physical universe. Those with scarce assets or skills are amply rewarded, they argue, because of the larger contributions they make to the economy. What they get merely represents what they have contributed. Often they take out less than they contributed, so what is left over for the rest is that much more.

This fictional narrative may at one time have assuaged the guilt of those at the top and persuaded everyone else to accept this sorry state of affairs. Perhaps the defining moment exposing the lie was the 2008 financial crisis, when the bankers who brought the global economy to the brink of ruin with predatory lending, market manipulation and various other antisocial practices walked away with millions of dollars in bonuses just as millions of Americans lost their jobs and homes and tens of millions more worldwide suffered on their account. Virtually none of these bankers were ever held to account for their misdeeds.

I became aware of the fantastical nature of this narrative as a schoolboy, when I thought of the wealth of the plantation owners, built on the backs of slaves. At the time of the Civil War, the market value of the slaves in the South was approximately half of the region's total wealth, including the value of the land and the physical capital—the factories and equipment. The wealth of at least this part of this nation was not based on industry, innovation and commerce but rather on exploitation. Today we have replaced this open exploitation with more insidious forms, which have intensified since the Reagan-Thatcher revolution of the 1980s. This exploitation, I will argue, is largely to blame for the escalating inequality in the U.S.

After the New Deal of the 1930s, American inequality went into decline. By the 1950s inequality had receded to such an extent that another Nobel laureate in economics, Simon Kuznets, formulated what came to be called Kuznets's law. In the early stages of development, as some parts of a country seize new opportunities, inequalities grow, he postulated; in the later stages, they shrink. The theory long fit the data—but then, around the early 1980s, the trend abruptly reversed.

EXPLAINING INEQUALITY

ECONOMISTS HAVE put forward a range of explanations for why inequality has in fact been increasing in many developed countries. Some argue that advances in technology have spurred the demand for skilled labor relative to unskilled labor, thereby depressing the wages of the latter. Yet that alone cannot explain why even skilled labor has done so poorly over the past two decades, why average wages have done so badly and why matters are so much worse in the U.S. than in other developed nations. Changes in technology are global and should affect all advanced economies in the same way. Other economists blame globalization itself, which has weakened the power of workers. Firms can and do move abroad unless demands for higher wages are curtailed. But again, globalization has been integral to all advanced economies. Why is its impact so much worse in the U.S.?

The shift from a manufacturing to a service-based economy is partly to blame. At its extreme—a firm of one person—the service economy is a winner-takes-all system. A movie star makes millions, for example, whereas most actors make a pittance. Overall, wages are likely to be far more widely dispersed in a service economy than in one based on manufacturing, so the transition contributes to greater inequality. This fact does not explain, however, why the average wage has not improved for decades. Moreover, the shift to the service sector is happening in most other advanced countries: Why are matters so much worse in the U.S.?

Again, because services are often provided locally, firms have more market power: the ability to

SOURCES: "THE FADING AMERICAN DREAM: TRENDS IN ABSOLUTE INCOME MOBILITY SINCE 1940," BY RAJ CHETTY ET AL., IN *SCIENCE*, VOL. 356; APRIL 28, 2017 (*child-parent wealth comparison*); WORLD INEQUALITY DATABASE (*90% versus 1% wealth trend data*)

Graphics by Jen Christiansen

raise prices above what would prevail in a competitive market. A small town in rural America may have only one authorized Toyota repair shop, which virtually every Toyota owner is forced to patronize. The providers of these local services can raise prices over costs, increasing their profits and the share of income going to owners and managers. This, too, increases inequality. But again, why is U.S. inequality practically unique?

In his celebrated 2013 treatise *Capital in the Twenty-First Century,* French economist Thomas Piketty shifts the gaze to capitalists. He suggests that the few who own much of a country's capital save so much that, given the stable and high return to capital (relative to the growth rate of the economy), their share of the national income has been increasing. His theory has, however, been questioned on many grounds. For instance, the savings rate of even the rich in the U.S. is so low, compared with the rich in other countries, that the increase in inequality should be lower here, not greater.

An alternative theory is far more consonant with the facts. Since the mid-1970s the rules of the economic game have been rewritten, both globally and nationally, in ways that advantage the rich and disadvantage the rest. And they have been rewritten further in this perverse direction in the U.S. than in other developed countries—even though the rules in the U.S. were already less favorable to workers. From this perspective, increasing inequality is a matter of choice: a consequence of our policies, laws and regulations.

In the U.S., the market power of large corporations, which was greater than in most other advanced countries to begin with, has increased even more than elsewhere. On the other hand, the market power of workers, which started out less than in most other advanced countries, has fallen further than elsewhere. This is not only because of the shift to a service-sector economy—it is because of the rigged rules of the game, rules set in a political system that is itself rigged through gerrymandering, voter suppression and the influence of money. A vicious spiral has formed: economic inequality translates into political inequality, which leads to rules that favor the wealthy, which in turn reinforces economic inequality.

FEEDBACK LOOP

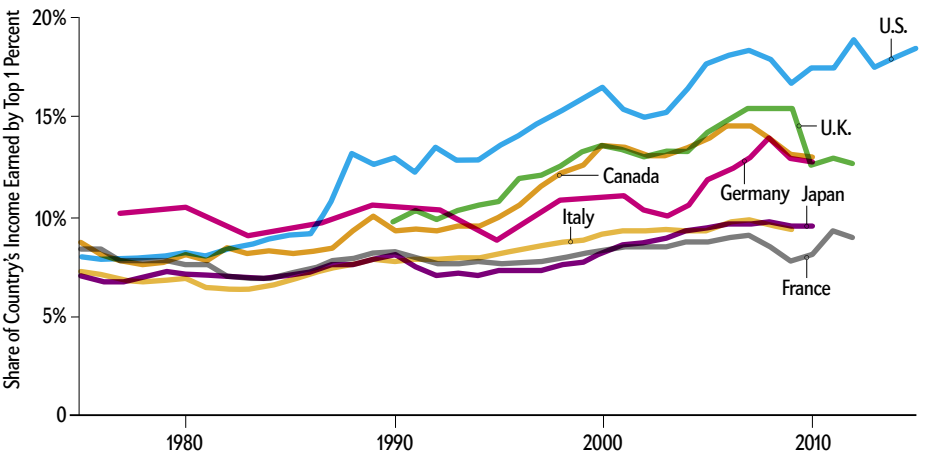
POLITICAL SCIENTISTS have documented the ways in which money influences politics in certain political systems, converting higher economic inequality into greater political inequality. Political inequality, in its turn, gives rise to more economic inequality as the rich use their political power to shape the rules of the game in ways that favor them—for instance, by softening antitrust laws and weakening unions. Using mathematical models, economists such as myself have shown that this two-way feedback loop between money and regulations leads to at least two stable points. If an economy starts out with lower inequality, the political system generates rules that sustain it, leading to one equilibrium situation. The American system is the other equilibrium—and will continue to be unless there is a democratic political awakening.

An account of how the rules have been shaped must begin with antitrust laws, first enacted 128 years ago in the U.S. to prevent the agglomeration of market power. Their enforcement has weakened—at a time when, if anything, the laws themselves should have been strengthened. Technological changes have concentrated market power in the hands of a few global players, in part because of so-called network effects: you are far more likely to join a particular social network or use a certain word processor if everyone you know is already using it. Once established, a firm such as Facebook or Microsoft is hard to dislodge. Moreover, fixed costs, such as that of developing a piece of software, have increased as compared with marginal costs—that of duplicating the software. A new entrant has to bear all these fixed costs up front, and if it does enter, the rich incumbent can respond by lowering prices drastically. The cost of making an additional e-book or photo-editing program is essentially zero.

In short, entry is hard and risky, which gives established firms with deep war chests enormous power

GLOBAL INEQUALITY TRENDS

Inequality has increased in most advanced countries because of factors such as globalization, technological change and the shift to a service-based economy. It has grown fastest in the U.S., however, according to the World Inequality Database. That is because rules have been rewritten to make them more favorable for the rich, while being disadvantageous to everyone else. Large companies have been allowed to accrue more power over the market, whereas the influence of workers has shrunk. Taxation and other policies have consistently favored the wealthy.



SOURCES: *ECONOMIC REPORT OF THE PRESIDENT*, JANUARY 2017; WORLD INEQUALITY DATABASE

to crush competitors and ultimately raise prices. Making matters worse, U.S. firms have been innovative not only in the products they make but in thinking of ways to extend and amplify their market power. The European Commission has imposed fines of billions of dollars on Microsoft and Google and ordered them to stop their anticompetitive practices (such as Google privileging its own comparison shopping service). In the U.S., we have done too little to control concentrations of market power, so it is not a surprise that it has increased in many sectors.

Rigged rules also explain why the impact of globalization may have been worse in the U.S. A concerted attack on unions has almost halved the fraction of unionized workers in the nation, to about 11 percent. (In Scandinavia, it is roughly 70 percent.) Weaker unions provide workers less protection against the efforts of firms to drive down wages or worsen working conditions. Moreover, U.S. investment treaties such as the North Atlantic Free Trade Agreement—treaties that were sold as a way of preventing foreign countries from discriminating against American firms—also protect investors against a tightening of environmental and health regulations abroad. For instance, they enable corporations to sue nations in private international arbitration panels for passing laws that protect citizens and the environment but threaten the multinational company's bottom line. Firms like these provisions, which enhance the credibility of a company's threat to move abroad if workers do not temper their demands. In short, these investment agreements weaken U.S. workers' bargaining power even further.

LIBERATED FINANCE

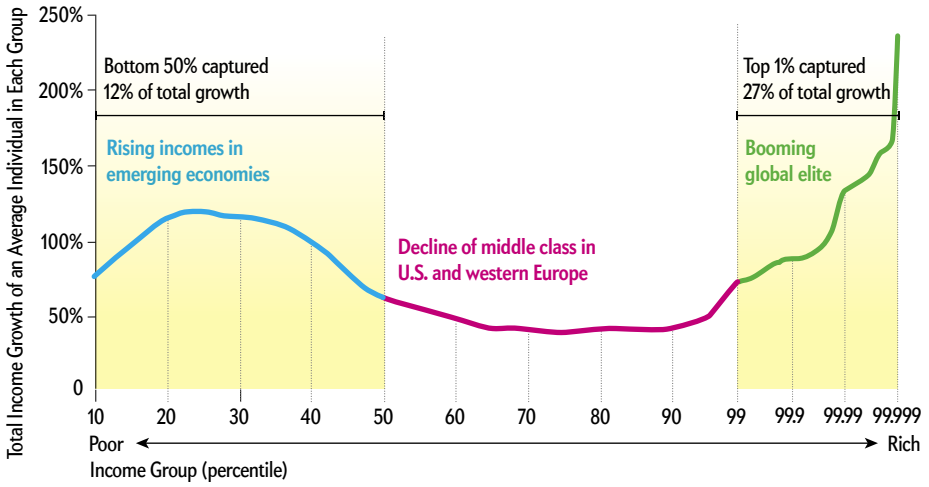
MANY OTHER changes to our norms, laws, rules and regulations have contributed to inequality. Weak corporate governance laws have allowed chief executives in the U.S. to compensate themselves 361 times more than the average worker, far more than in other developed countries. Financial liberalization—the stripping away of regulations designed to prevent the financial sector from imposing harms, such as the 2008 economic crisis, on the rest of society—has enabled the finance industry to grow in size and profitability and has increased its opportunities to exploit everyone else. Banks routinely indulge in practices that are legal but should not be, such as imposing usurious interest rates on borrowers or exorbitant fees on merchants for credit and debit cards and creating securities that are designed to fail. They also frequently do things that are illegal, including market manipulation and insider trading. In all of this, the financial sector has moved money away from ordinary Americans to rich bankers and the banks' shareholders. This redistribution of wealth is an important contributor to American inequality.

Other means of so-called rent extraction—the withdrawal of income from the national pie that is incommensurate with societal contribution—abound. For example, a legal provision enacted in 2003 prohibited the government from negotiating drug prices for Medicare—a gift of some $50 billion a year or more to the pharmaceutical industry. Special favors, such as extractive industries' obtaining public resources such as oil at below fair-market value or banks' getting funds from the Federal Reserve at near-zero interest rates (which they relend at high interest rates), also amount to rent extraction. Further exacerbating inequality is favorable tax treatment for the rich. In the U.S., those at the top pay a smaller fraction of their income in taxes than those who are much poorer—a form of largesse that the Trump administration has just worsened with the 2017 tax bill.

Some economists have argued that we can lessen inequality only by giving up on growth and efficiency. But recent research, such as work done by Jonathan Ostry and others at the International Monetary Fund, suggests that economies with greater equality perform better, with higher growth, better average standards of living and greater stability. Inequality in the extremes observed in the U.S. and in the manner generated there actually damages the economy. The ex-

UNEVEN DISTRIBUTION OF GLOBAL GROWTH

Globalization has benefited millions of the poor in emerging economies, particularly in China. Data compiled by economist Branko Milanovic and displayed in the *World Inequality Report 2018* demonstrate, however, that between 1980 and 2016, the steepest gains went to the world's top 1 percent, which captured more than a quarter of the growth in the global economy. In early 2018 Oxfam International reported that just 42 individuals have as much wealth as the bottom 50 percent put together. The middle classes in the U.S. and western Europe have benefited the least from global growth, as have the world's poorest.



SOURCES: *WORLD INEQUALITY REPORT 2018*. WORLD INEQUALITY LAB, 2017; BRANKO MILANOVIC

ploitation of market power and the variety of other distortions I have described, for instance, makes markets less efficient, leading to underproduction of valuable goods such as basic research and overproduction of others, such as exploitative financial products.

Moreover, because the rich typically spend a smaller fraction of their income on consumption than the poor, total or "aggregate" demand in countries with higher inequality is weaker. Societies could make up for this gap by increasing government spending—on infrastructure, education and health, for instance, all of which are investments necessary for long-term growth. But the politics of unequal societies typically puts the burden on monetary policy: interest rates are lowered to stimulate spending. Artificially low interest rates, especially if coupled with inadequate financial market regulation, often give rise to bubbles, which is what happened with the 2008 housing crisis.

It is no surprise that, on average, people living in unequal societies have less equality of opportunity: those at the bottom never get the education that would enable them to live up to their potential. This fact, in turn, exacerbates inequality while wasting the country's most valuable resource: Americans themselves.

RESTORING JUSTICE

MORALE IS LOWER in unequal societies, especially when inequality is seen as unjust, and the feeling of being used or cheated leads to lower productivity. When those who run gambling casinos or bankers suffering from moral turpitude make a zillion times more than the scientists and inventors who brought us lasers, transistors and an understanding of DNA, it is clear that something is wrong. Then again, the children of the rich come to think of themselves as a class apart, entitled to their good fortune, and accordingly more likely to break the rules necessary for making society function. All of this contributes to a breakdown of trust, with its attendant impact on social cohesion and economic performance.

There is no magic bullet to remedy a problem as deep-rooted as America's inequality. Its origins are largely political, so it is hard to imagine meaningful change without a concerted effort to take money out of politics—through, for instance, campaign finance reform. Blocking the revolving doors by which regulators and other government officials come from and return to the same industries they regulate and work with is also essential.

Beyond that, we need more progressive taxation and high-quality federally funded public education, including affordable access to universities for all, no ruinous loans required. We need modern competition laws to deal with the problems posed by 21st-century market power and stronger enforcement of the laws we do have. We need labor laws that protect workers and their rights to unionize. We need corporate governance laws that curb exorbitant salaries bestowed on chief executives, and we need stronger financial regulations that will prevent banks from engaging in the exploitative practices that have become their hallmark. We need better enforcement of antidiscrimination laws: it is unconscionable that women and minorities get paid a mere fraction of what their white male counterparts receive. We also need more sensible inheritance laws that will reduce the intergenerational transmission of advantage and disadvantage.

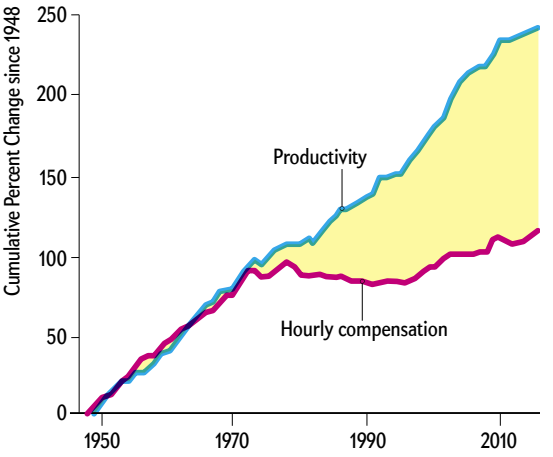
The basic perquisites of a middle-class life, including a secure old age, are no longer attainable for most Americans. We need to guarantee access to health care. We need to strengthen and reform retirement programs, which have put an increasing burden of risk management on workers (who are expected to manage their portfolios to guard simultaneously against the risks of inflation and market collapse) and opened them up to exploitation by our financial sector (which sells them products designed to maximize bank fees rather than retirement security). Our mortgage system was our Achilles' heel, and we have not really fixed it. With such a large fraction of Americans living in cities, we have to have urban housing policies that ensure affordable housing for all.

It is a long agenda—but a doable one. When skeptics say it is nice but not affordable, I reply: We cannot afford to *not* do these things. We are already paying a high price for inequality, but it is just a down payment on what we will have to pay if we do not do something—and quickly. It is not just our economy that is at stake; we are risking our democracy.

As more of our citizens come to understand why the fruits of economic progress have been so unequally shared, there is a real danger that they will become open to a demagogue blaming the country's problems on others and making false promises of rectifying "a rigged system." We are already experiencing a foretaste of what might happen. It could get much worse.

WIDENING WAGE GAP

Since about 1980 the productivity of American workers has doubled, according to Josh Bivens and others at the Economic Policy Institute. But wages for production and nonsupervisory workers have stagnated, with virtually all the gains from increased productivity going to investors and owners. Salaries for the top 1 percent, including corporate executives and finance professionals, have, however, gone up—by more than 150 percent between 1979 and 2012. The increasing wage gap plays a significant role in spiraling inequality.



SOURCES: *RAISING AMERICA'S PAY: WHY IT'S OUR CENTRAL ECONOMIC POLICY CHALLENGE*, BY JOSH BIVENS ET AL. ECONOMIC POLICY INSTITUTE, JUNE 4, 2014; *THE STATE OF WORKING AMERICA*, BY LAWRENCE MISHEL, JOSH BIVENS, ELISE GOULD AND HEIDI SHIERHOLZ. 12TH EDITION. ILR PRESS, 2012

THE HEALTH-WEALTH GAP

The growing gulf between rich and poor inflicts biological damage on bodies and brains *By Robert M. Sapolsky*

WESTERN CULTURES HAVE LONG CHERISHED THE NOTION that all people are created equal. But in the real world, our lives are not balanced with equal opportunities and resources. This distinction was noted mordantly in 1894 by author Anatole France, who wrote that "the law, in its majestic equality, forbids the rich as well as the poor to sleep under bridges, to beg in the streets, and to steal bread." The rich, of course, need none of these things, whereas the poor often have little choice. And economic disparity has only gotten worse during the past several decades, particularly in the U.S. In 1976 the richest 1 percent of U.S. citizens owned 9 percent of the country's wealth; today they own nearly 24 percent. This trend echoes around the globe.

One of the consequences for the growing poor is worsening health, and the reasons are not as obvious as you might think. Yes, lower socioeconomic status (SES) means less access to health care and living in more disease-prone neighborhoods. And, yes, as the SES ladder's lower rungs have become more populated, the number of people with medical problems has climbed. This is not merely an issue of poor health for the poor and some version of better health for everyone else. Starting with Jeff Bezos at the top, every step down the ladder is associated with worse health.

But the link between socioeconomic inequality and poor health goes beyond simple access to care and living with more dangers. Less than half of the health changes along this SES/health ladder can be explained away by risks such as smoking, alcohol consumption and reliance on fast food or protective factors such as insurance and health club memberships. The large Whitehall Studies of risks in specific groups, led by epidemiologist Michael Marmot, demonstrated this clearly. Further, this ladder, or gradient, exists in countries with universal health care; if care availability was truly responsible, universal access should make the gradient vanish. Something else,

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Illustration by Andrea Ucini

something quite powerful, must be associated with inequities and be able to cause health problems.

That factor seems to be the stressful psychosocial consequences of low SES. Psychologist Nancy Adler of the University of California, San Francisco, and her colleagues have demonstrated that how people rate how they are doing, relative to others, is at least as predictive of health or illness as are any objective measures such as actual income level. The research indicates that poor health is not so much about being poor as feeling poor. Epidemiologists Richard Wilkinson and Kate Pickett of the University of Nottingham and the University of York in England, respectively, have filled out this picture in detail, showing that while poverty is bad for your health, poverty amid plenty—inequality—can be worse by just about any measure: infant mortality, overall life expectancy, obesity, murder rates, and more. Health is particularly corroded by your nose constantly being rubbed in what you do not have.

Basically, more unequal societies have worse quality of life. Across countries and among U.S. states, more inequality, independent of absolute levels of income, predicts higher rates of crime, including homicide, and higher incarceration rates. Add in higher rates of kids being bullied at schools, more teen pregnancies and lower literacy. There are more psychiatric problems, alcoholism and drug abuse, lower levels of happiness and less social mobility. And there is less social support—a steep hierarchy is the antithesis of the equality and symmetry that nourish friendship. This grim collective picture helps to explain the immensely important fact that when inequality increases, everyone's health suffers.

This is where the problem affects the rich, the haves as well as the have-nots. With increasing inequality, they typically expend more resources insulating themselves from the world underneath the bridges. I have heard economist Robert Evans of the University of British Columbia call this the "secession of the wealthy." They spend more of their own resources on gated communities, private schools, bottled water and expensive organic food. And they give lots of money to politicians who help them maintain their status. It is stressful to construct thick walls to keep everything stressful out.

Knowing that these psychological and social factors influence the biology of disease is one thing. Demonstrating just how these stressors do their dirty work inside the body is something else. How do SES and inequality "get under the skin"? It turns out that researchers have made significant strides toward an answer. We have learned a lot about how poverty affects biology, and the part of the growing inequality gap that worries people is the poverty end. Scientists have been able to trace physiological connections from external inequality to three key inner areas: chronic inflammation, chromosomal aging and brain function.

A HEAVY LOAD

THINKING about the biology of disease was revolutionized in the 1990s, when Bruce McEwen of the Rockefeller University introduced the concept of allostatic load. Our bodies are constantly challenged by our environment, and we stay healthy when we meet those challenges and return to a baseline state, or homeostasis. Traditionally this view led scientists to focus on specific organs that solve specific challenges. Allostasis has a different perspective: physiological challenges provoke far-flung adaptations throughout the body. An infected toe, for instance, will produce not only inflammation at the tip of the foot but also wider changes in everything from energy taken from abdominal fat to the brain chemistry of sleepiness. As this biological grind continues, it leads to an array of body parts functioning less than optimally, which can be as damaging to health as a single organ gone very wrong.

Teresa Seeman of the University of California, Los Angeles, took this idea and followed it through the body, measuring various biomarkers of wear and tear, including increases in blood pressure, cholesterol, blood lipids, body mass index, molecular indicators of chronic hyperglycemia, and levels of stress hormones. She showed that this group of disparate measures powerfully predicts physical health and mortality.

Recent research by Seeman and others links low SES with heavy allostatic load because the body is in a constant and futile battle to return to a normal, nonstressed state. These findings highlight an important theme: whereas an adult's SES predicts allostatic wear and tear, childhood SES leaves a stronger lifelong mark. Low SES predisposes youngsters' bodies toward earlier "aging." The scientists also found protective factors. Although growing up in an impoverished neighborhood worsens the low SES/allostatic load link, lucking out with a mother who has the time and energy to be highly nurturing reduces the ill effects.

Stress in any form can produce these effects. It does not have to be related to money, but it is usually related to social situations. My own work with baboons living freely on the East African savanna has shown this effect. In baboon groups, an animal's place in the social hierarchy produces more or less stress. If you are a low-ranking baboon—a socially stressful situation—your body has unhealthy abnormalities in its secretion of glucocorticoids, which are stress hormones such as cortisol. The body also shows unhealthy changes in the gonadal, cardiovascular and immune systems.

In animal and human hierarchies, these stress-induced changes affect health through a key process: chronic inflammation. Few things are better examples of a double-edged biological sword than inflammation. After tissue injury, inflammation contains damage and initiates cell repair. Chronic widespread inflammation, however, causes molecular damage through-

out the body, and studies have demonstrated that it contributes to diseases ranging from atherosclerosis to Alzheimer's. Recent work (including my own focusing on inflammation of the nervous system) indicates that chronic high stress levels can promote chronic inflammation. In people, childhood poverty upregulates the adult body's pro-inflammatory set point, with increased expression of inflammatory genes and increased levels of inflammatory markers such as C-reactive protein, which is associated with a higher risk of heart attacks.

These are long-term effects: more financial losses in the Great Recession predict higher C-reactive protein levels six years later. Humans share such vulnerabilities with other primates that live in unequal circumstances. Work by Jenny Tung of Duke University shows more markers of chronic inflammation in low-ranking rhesus monkeys versus the socially dominant animals in a group. Studies such as this one highlight the directness of the link between social stress factors and unhealthy biology because it occurs in a species that lacks changes in lifestyle risk factors, such as increased rates of smoking and drinking that we often see in humans who are stuck in low-status situations.

PREMATURE DNA AGING

PROGRESS in understanding the routes into the body taken by the SES/health gradient has also come through a very sensitive measure of aging: the condition of telomeres, which are the stretches of DNA at the very tips of chromosomes.

Telomeres help to keep our chromosomes stable—molecular biologists like to say that they resemble the plastic caps at the ends of shoelaces that prevent fraying. Every time chromosomes are duplicated for cell division, the telomeres shorten; when they get too short, cells can no longer divide, and they lose many of their healthy functions. Telomere shortening is countered by the enzyme telomerase, which rebuilds these tips. Thus, the state of a cell's telomeres tells much about its biological "age," and shortened telomeres that produce frayed, vulnerable chromosomes seem to be a molecular version of wear and tear.

Telomere biology met stress physiology in a 2004 study by health psychologist Elissa Epel of U.C.S.F. and Elizabeth Blackburn of the Salk Institute for Biological Studies; Blackburn won the Nobel Prize for her pioneering work on telomeres. They examined 39 people who live with severe stress every day: women who are caregivers for chronically ill children. The landmark finding was that white blood cells in these caregivers had shortened telomeres, decreased telomerase activity, and elevated oxidative damage to proteins and enzymes. (Oxidation can disable telomerase.) The longer a child's

INSIDE INEQUALITY

Life in societies with wide gaps between rich and poor creates ongoing social and psychological stresses. These grind down the body in a host of unhealthy ways, affecting our brains, our immune systems and our DNA, according to a broad range of research. Here are some effects that can lead to serious physical illnesses and mental problems.

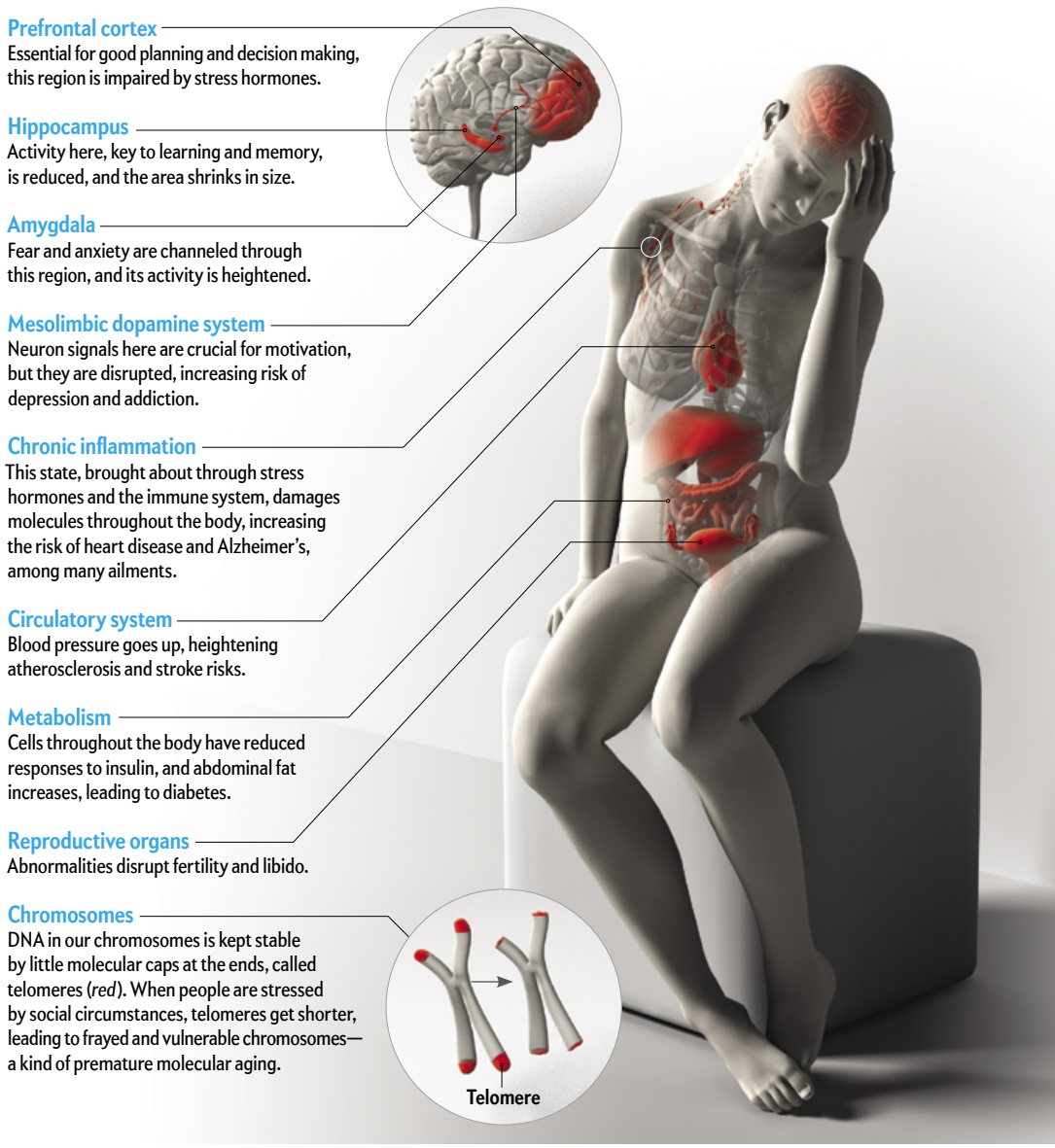
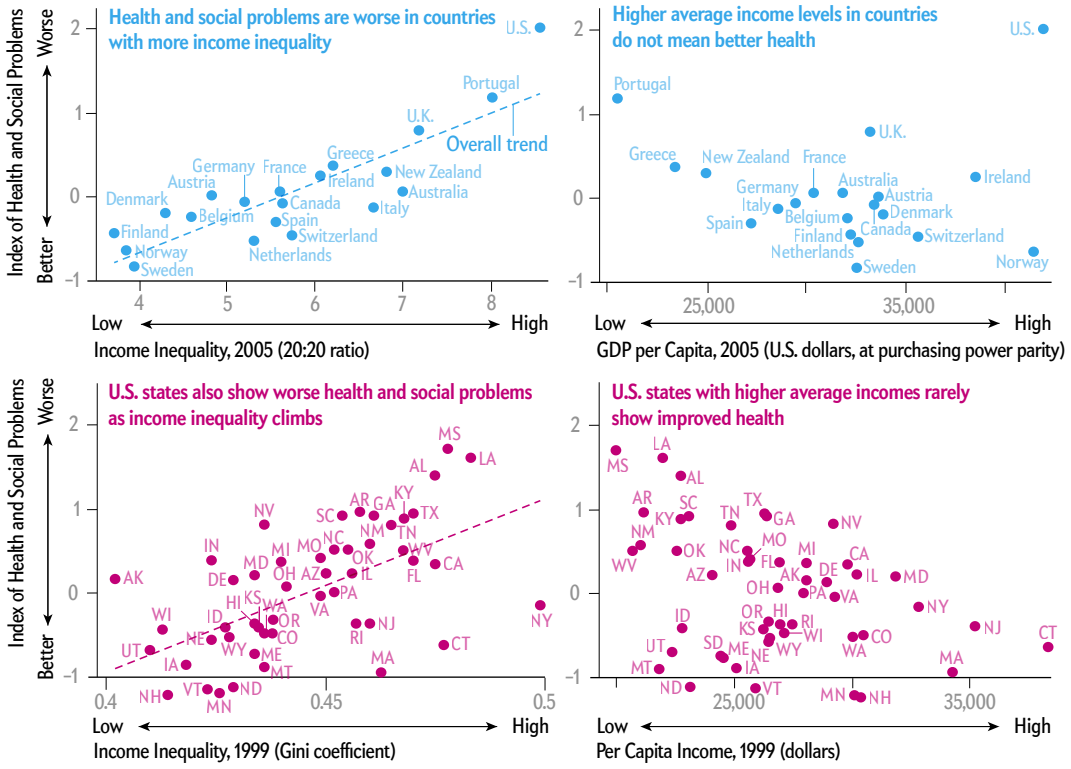


Illustration by Bryan Christie Design

THE HEALTH OF NATIONS AND STATES

Around the world, health and social problems grow as income disparities widen within societies. Epidemiologists Richard Wilkinson and Kate Pickett demonstrated this connection in their 2009 book *The Spirit Level*. They ranked countries by an economic measure from the United Nations called the 20:20 ratio, which compares how much richer the top 20 percent of people are than the bottom 20 percent. As the gap widened, a combined index of life expectancy, infant mortality, mental health issues, obesity and other problems got worse. Average income in these countries does not explain this trend. In U.S. states, researchers found a similar effect. They ranked states using a U.S. Census Bureau measure called the Gini coefficient, which compares incomes among all population members, not just select groups. Again, the trend of bad health effects strongly followed inequality and could not be explained by average income in a state.



Index of Health and Social Problems includes these components:

- Life expectancy
- Teenage births
- Obesity
- Mental health
- Homicides
- Imprisonment
- Trust/mistrust
- Education
- Infant mortality rate
- Social mobility (for country level only)

illness, the more stress the women reported and the shorter their telomeres were, even after the researchers accounted for potentially confounding factors such as diet and smoking. Telomeres normally shorten at a more or less constant rate in people, and calculations showed that these women's telomeres had aged roughly an additional decade—and sometimes more—past those in the low-stress group.

This discovery triggered a flood of supporting studies showing that stressors that included major depression, post-traumatic stress disorder and the experience of racial discrimination can all accelerate telomere shortening. Unsurprisingly, lower childhood SES also predicts shorter telomeres in adulthood; perceived poor neighborhood quality, witnessing or experiencing violence, family instability (such as divorce, death or incarceration of a parent), and other features of poor status early on are tied to these shrunken chromosome tips later in life. Spend your childhood in poverty, and by middle age your telomeres will probably be about a decade older than those with more fortunate childhoods.

Thus, from the macro level of entire body systems to the micro level of individual chromosomes, poverty finds a way to produce wear and tear. Most studies of telomere length compare "poor" with "non-poor," as do the studies comparing allostatic load, but the few studies that examine the whole spectrum of inequality, step by low-status step, show that every rung down the SES ladder most likely worsens these biological markers of aging.

OUT OF CONTROL

SLIPPING DOWN these rungs also changes the brain and behavior, according to a slew of recent neurobiological studies. My laboratory has devoted a quarter of a century to studying what ongoing stress does to the brain in rodents, monkeys and humans. Along with other labs, we have learned that one hotspot is the hippocampus, a region critical to learning and memory. Sustained stress or exposure to excessive glucocorticoids impairs memory by lowering hippocampal excitability, retracting connections between neurons and suppressing the birth of new neurons. In the amygdala, a different brain area that is central to fear and anxiety,

THE SPIRIT LEVEL: WHY GREATER EQUALITY MAKES SOCIETIES STRONGER. KATE PICKETT AND RICHARD WILKINSON. BLOOMSBURY, 2009; BUREAU OF ECONOMIC ANALYSIS, U.S. DEPARTMENT OF COMMERCE (*U.S. income per capita data*); *HUMAN DEVELOPMENT REPORT 2007/2008: FIGHTING CLIMATE CHANGE: HUMAN SOLIDARITY IN A DIVIDED WORLD.* UNITED NATIONS DEVELOPMENT PROGRAMME, 2007 (*GDP per capita data*)

Graphics by Jen Christiansen

stress and glucocorticoids heighten those two reactions. Instead of damping things down as they do in the hippocampus, in this fear-promoting region they increase excitability and expand neuronal connections. Together these findings help to explain why post-traumatic stress disorder atrophies the hippocampus and enlarges the amygdala. Another affected area is the mesolimbic dopamine system, which is crucial to reward, anticipation and motivation. Chronic stress disrupts that system, and the result is a predisposition toward the anhedonia of depression and vulnerability to addiction.

Bombardment by glucocorticoids also affects the prefrontal cortex (PFC), key to long-term planning, executive function and impulse control. In the PFC, social stress and elevated glucocorticoids weaken connections between neurons, making it harder for them to communicate. Myelination, the process that insulates cables between neurons and thus helps them pass signals faster, is impaired. Total cell volume in the region declines, and chronic inflammation is activated.

What happens when the PFC is impaired in this way? Lousy, impulsive decisions happen. Consider "temporal discounting": when choosing between an immediate reward and a bigger one if you wait, the appeal of waiting goes down as the time you have to wait goes up. The PFC is normally good at combating this shortsightedness. But stress steepens temporal discounting; the more cumulative stress, the less PFC activation in experiments that call for gratification postponement. For people sliding further into inequality, the less active PFC makes it harder for the brain to choose long-term health over immediate pleasure. That neurological effect can explain why people with more total life stress gain more weight and smoke and drink more than people with fewer stressors.

These changes in the PFC happen in children, too. In separate studies, Martha Farah of the University of Pennsylvania and W. Thomas Boyce, now at U.C.S.F., observed that lower-SES kindergartners typically have elevated glucocorticoid levels, a thinner and less active PFC, and poor PFC-dependent impulse control and executive function. These effects increase as kids get older. By adolescence, lower SES predicts smaller PFC volume. By adulthood, low SES predicts steeper temporally discounted decisions.

Some of these observations present a tricky chicken-and-egg question. The brain changes could lead to poor choices, which in turn lead to deeper poverty, rather than the other way around. But the research suggests that causes and effects run in the other direction, with SES and inequality first influencing PFC function, and then other bad things happen.

For example, kindergartners' SES predicted their PFC function; few five-year-olds plummet into poverty by squandering their paychecks on drink and horses. Further evidence comes from a 2013 study by Jiaying Zhao of the University of British Columbia and his colleagues. They examined Indian farmers whose economic fortunes vary seasonably. As individuals' SES went from being poorest during planting season to wealthiest after harvest, improvements in PFC function followed.

To me, the most important evidence comes from research in which people's sense of their SES was lowered by the design of the experiment. Afterward these individuals did heavier temporal discounting. In one 2012 study, subjects played a game of chance against one another, with differing amounts of starting resources. "Poor" subjects became more likely to borrow against future earnings and less attuned to helpful clues about game strategy.

In another study, subjects prompted to imagine scenarios of financial loss (versus neutral or advantageous ones) did steeper temporal discounting in an unrelated task. In still other research, subjects were primed to imagine their financial burdens by contemplating an expensive car repair; cognitive function was unchanged in high-SES subjects but declined in poorer individuals.

Why should a transient sense of lower SES induce cognitive changes typical of lower SES in the real world? One explanation is that it is a rational response because it is hard to think about squirreling away money for old age if you can barely buy groceries. Poverty makes the future a less relevant place.

But there is also a powerful stress-related explanation: long-term planning and impulse control tires out the PFC. Increase subjects' cognitive "load" with taxing PFC-dependent tasks, and they become more likely to cheat on their diet. Or you can—and scientists have done this—increase cognitive load by tempting dieting subjects with snacks, and then they do worse on PFC-dependent tests. How much this represents literal "depletion" of the PFC metabolically versus declining motivation is unclear.

Either way, lower SES creates chronic financial worry that distracts and exhausts. It is hard to ace a psychological task of, say, subtracting a series of numbers or a more important task of reining in your drinking when you are worrying about paying your rent. One finding in the car-repair study supports this interpretation. When subjects contemplated a repair of negligible cost, low- and high-SES subjects performed equally well on cognitive tasks.

Of course, we need to better understand the biological consequences of inequality and learn better ways to heal its health scars. But frankly, right now we know quite a bit. We know enough to prompt moral outrage at the situation. It is outrageous that if children are born into the wrong family, they will be predisposed toward poor health by the time they start to learn the alphabet. It should not require us to measure inflammation or the length of chromosomes to prove this is wrong, but if it does, more power to this science.

AUTOMATING BIAS

How algorithms designed to alleviate poverty can perpetuate it instead

By Virginia Eubanks

NEAR THE END OF 2006 MITCH DANIELS, THEN GOVERNOR of Indiana, announced a plan to give the state's "neediest people a better chance to escape welfare for the world of work and dignity." He signed a $1.16-billion contract with a consortium of companies, including IBM, that would automate and privatize eligibility processes for Indiana's welfare programs.

Rather than visiting their county office to fill out applications for assistance, members of the public were encouraged to apply through a new online system. About 1,500 state employees were "transitioned" to private positions at regional call centers. Caseworkers who had been responsible for dockets of families in local welfare offices now responded to a list of tasks dropped into a queue in their workflow management system. Cases could come from anywhere in the state; every call went to the next available worker. This move toward electronic communication, the administration insisted, would improve access to services for needy, elderly and disabled people, all while saving taxpayers money.

From the ledger books of the county poorhouse to the photographic slides of the Eugenics Record Office, the U.S. has long collected and analyzed voluminous information about poor and working-class families. Like Daniels, today's politicians, policy makers and program administrators often look to automation to remake social assistance. This trend is sometimes called poverty analytics, the digital regulation of the poor through data collection, sharing and analysis. It takes myriad forms, from predicting child maltreatment using statistical models to mapping the movement of refugees with high-definition satellite imagery. The contemporary resurgence of poverty analytics is reaching an apogee, with breathless assessments of the power of big data and artificial intelligence to improve welfare, policing, criminal sentencing, homeless services and more.

The central faith that seems to animate these projects is that poverty is primarily a systems engineering problem. Information is simply not getting where it needs to go, meaning resources are being used inefficiently, perhaps even counterproductively. The rise of automated eligibility systems, algorithmic decision making and predictive analytics is often hailed as a revolution in public administration. But it may just be a digitized return to the pseudoscience-backed economic rationing of the past.

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Illustration by Andrea Ucini

A SCIENCE OF THE POOR

IN 1884 Josephine Shaw Lowell published *Public Relief and Private Charity,* urging governments to stop providing poor relief to families struggling with the lingering impacts of the 1873–1879 depression. Lowell, a founder of the Charity Organization Society of New York City, wrote that providing even modest support without prior moral investigation created poverty instead of relieving it, encouraging idleness and vice. She promised that "private charity can and will provide for every case that should be kept from resorting to public sources of relief." But how could the country's wealthy philanthropists take over the government's responsibility for protecting its citizens from economic shocks? Her solution was simple: make charity more scientific.

Lowell and other proponents of so-called scientific charity believed that evidence-based, data-driven methods could separate the deserving from the undeserving poor, making social assistance more cost-efficient and effective. The movement pioneered methods that would become known as casework, whereby police officers scrutinized all areas of relief seekers' lives and verified their stories through interviews with neighbors, shopkeepers, doctors and clergy. This bred a culture of prediction and profiling, investigation and moral classification, unleashing a flood of data about poor and working-class families that still flows today.

Contemporary proponents of poverty analytics believe that public services will improve if we use these data to create "actionable intelligence" about fraud and waste. Daniels, for example, promised that Indiana would save $500 million in administrative costs and another $500 million by identifying fraud and ineligibility over the 10 years of the contract.

In reality, the private call-center system severed the relationship between caseworkers and the people they served, making it difficult to ensure that families received all the benefits they were entitled to. Prioritizing online applications over in-person procedures was a problem for low-income families, nearly half of whom lacked Internet access. The state failed to digitize decades of paperwork, requiring recipients to resubmit all their documentation. The rigid automated system was unable to differentiate between an honest mistake, a bureaucratic error and an applicant's attempt to commit fraud. Every glitch, whether a forgotten signature or software error, was interpreted as a potential crime.

The result of Indiana's experiment with automated eligibility was one million benefits denials in three years, a 54 percent increase from the previous three years. Under pressure from angry citizens, legislators from both parties and overburdened local governments, Daniels canceled the IBM contract in 2009, resulting in an expensive, taxpayer-funded legal battle that lasted for eight years.

THE BIAS IN SURVEILLANCE

POVERTY ANALYTICS is not just driven by a desire for cost saving and efficiency. Its proponents also have a laudable goal to eliminate bias. After all, insidious racial discrimination in social service programs has deep historical roots.

In the child welfare system, the problem has not traditionally been exclusion of people of color; it has been their disproportionate *inclusion* in programs that increase state scrutiny of their families. According to the National Council of Juvenile and Family Court Judges, in 47 states, African-American children are removed from their homes at rates that exceed their representation in the general population. That was certainly true in Pennsylvania's Allegheny County: In 2016, 38 percent of children in foster care there were African-American, although they made up less than 19 percent of the county's young people.

In August 2016 the Allegheny County Department of Human Services (DHS) launched a statistical modeling tool it believes can predict which children are most likely to be abused or neglected in the future. The Allegheny Family Screening Tool (AFST) was designed by an international team led by economist Rhema Vaithianathan of the Auckland University of Technology in New Zealand and including Emily Putnam-Hornstein, director of the Children's Data Network at the University of Southern California. It draws on information collected in a county data warehouse that receives regular extracts from dozens of public programs, including jails, probation, county mental health services, and the office of income maintenance and public schools. By mining two decades' worth of data, the DHS hopes that the AFST can help subjective human screeners make better recommendations for which families should be referred for child protective investigations.

Scientific charity reformers of the 19th century also argued that more objective decision making could transform public programs, which they saw as corrupted by patronage, machine politics and ethnic parochialism. But they viewed bias through a narrow lens: discrimination was episodic and intentional, driven by self-interest. What the movement failed to recognize was how it built systemic, structural bias into its supposedly objective, scientific tools and practices.

If one strand of scientific charity's DNA was austerity, the other was white supremacy. While touting itself as evidence-based and value-neutral, scientific charity refused aid to newly liberated African-Americans and supported immigration restriction. It also exerted enormous energy protecting white elites from threats it believed were lurking from *within* the race: low intelligence, criminality and unrestricted sexuality. It was at heart a eugenic exercise: trying to slow the growth of poverty by slowing the growth of poor families.

Undoubtedly, tools such as the AFST have grown out of a desire to mitigate this kind of bigotry. But human bias is a built-in feature of predictive risk models, too. The

AFST primarily relies on data collected only on people who reach out to public services for family support. Wealthier families might hire a nanny to help with child care or work with a doctor to recover from an addiction. But because they pay out of pocket or with private insurance, their data are not collected in the warehouse. Therefore, the AFST may miss abuse or neglect in professional middle-class households. Oversurveillance of the poor shapes the model's predictions in systemic ways, interpreting the use of public benefits as a risk to children. Simply, the model confuses parenting while poor with poor parenting.

Because there are thankfully not enough child fatalities and near fatalities in Allegheny County to produce the volume of data needed for reliable modeling, the Vaithianathan team used a related variable to stand in for child maltreatment. After some experimentation, the researchers decided to use *child placement*—when a report made on a child is "screened in" for investigation and results in him or her being placed in foster care within two years—as a proxy for child harm. The outcome the model is predicting, therefore, is a decision made by the agency and the legal system to remove the child from his or her home, *not* the actual occurrence of maltreatment. Although this is a design choice made of necessity, not ill intention, child well-being is innately subjective, making it a poor candidate for predictive modeling.

Further, while the AFST might uncover patterns of bias in intake screening, this is not where the majority of racial disproportionality enters the system. In fact, the county's own research shows that most racial bias enters through referral, not screening. The community reports African-American and biracial families for child abuse and neglect three and four times more often, respectively, than it reports white families. Once children are referred, screener discretion does not make much difference: a 2010 study showed that intake workers screen in 69 percent of cases involving African-American and biracial children and 65 percent of those involving white children. Ironically, attenuating screener discretion may amplify racial injustice by removing clinical judgment at a point where it can override community prejudice.

Heightening the danger of harm is a human inclination to trust that technology is more objective than our own decision making. But economists and data scientists are just as likely as call screeners to hold mistaken cultural beliefs about poor white families and families of color. When systems designers program their assumptions into these tools, they hide consequential political choices behind a math-washed facade of technological neutrality.

MODELING JUSTICE

ADMINISTRATORS and data scientists working in public services often share a basic preconception: poverty analytics are a system for triage, for making hard choices about how to use limited resources to address enormous needs. But the decision to accept that some people will be granted access to their basic human needs and others will not is itself a political choice. Poverty is not a natural disaster; it is created by structural exploitation and bad policy.

Data science can indeed play a role in addressing deep inequities. Progressive critics of algorithmic decision making suggest focusing on transparency, accountability and human-centered design to push big data toward social justice. Of course, any digital system used to make decisions in a democracy should be grounded in these values. But the field of poverty analytics has limited itself to, at best, incrementally improving the accuracy and fairness of systems with questionable social benefit. We first need to rethink basic principles. This means acknowledging that in the context of austerity, structural racism and the criminalization of poverty, unfettered analytics will supercharge discrimination and worsen economic suffering.

We should begin by testing for self-fulfilling models that produce the very effects they are supposed to predict. For example, if a fear of being scored as high risk by the AFST leads parents to avoid public services, it may create the kind of stress that can result in abuse and neglect. We also need to install policy levers capable of arresting systems with negative or unintended impacts. Data collected by these systems should be secure, but more important, they should be obtained in noncoercive ways, without making families feel they have to trade one basic human right—privacy, safety or family integrity—for another, such as food or shelter.

Finally, for those who are harmed by poverty analytics, clear mechanisms for remedy need to be put in place. As a 2018 World Economic Forum white paper on discrimination in machine learning points out, those designing and implementing automated decision-making systems have a duty to establish protocols "for the timely redress of any discriminatory outputs" and make them easy to find and use.

Poverty analytics will not fundamentally change until we rewrite the false stories we tell. Despite popular belief, poverty is not an aberration in the U.S. According to research from sociologists Mark R. Rank and Thomas Hirschl, 51 percent of Americans will fall below the poverty line at some point between the ages of 20 and 64, and nearly two thirds of us will access means-tested public assistance programs such as Temporary Assistance for Needy Families and Medicaid. So instead of designing sophisticated moral thermometers, we need to build universal floors under us all. That means fully funding public programs, guaranteeing good pay and safe working conditions, supporting caregiving, fostering health, and protecting dignity and self-determination for everyone. Until we do that, we are not modernizing triage. We are automating injustice.

THE ENVIRONMENTAL COST OF INEQUALITY

Power imbalances facilitate environmental degradation—and the poor suffer the consequences

By James K. Boyce

IN THE FALL OF 2016 AN ENVIRONMENTAL STRUGGLE IN RURAL North Dakota made headlines worldwide. The local Standing Rock Sioux Tribe and climate activists were pitted against the corporate and government backers of the Dakota Access Pipeline, which was being built to carry oil from the state's Bakken shale fields to a terminal in Illinois. Private security guards unleashed attack dogs on protesters, and the police blasted them with water cannons in freezing weather.

The tribe feared that a leak in the pipeline as it crossed under a reservoir along the Missouri River would contaminate its water supply. Climate activists joined the protest to fight ramped-up extraction of fossil fuels. Supporters of the $3.8-billion project argued that it would save the oil industry money, being less costly than the alternative of oil shipment by rail, and that its construction would bring jobs with multiplier effects to the local economy. Because the price of oil is set on world markets, the cost saving would not mean lower prices for consumers—but it would bring higher profits to producers.

By December 2016 the U.S. Army Corps of Engineers announced that it would deny approval for the pipeline crossing, a decision greeted with whoops of joy at the protesters' encampment. But four days after taking office in January, President Donald Trump overturned the ruling, and a few months later the oil began to flow.

The battle reflected what seems to be a basic reality: When people who could benefit from using or abusing the environment are economically and politically more powerful than those who could be harmed, the imbalance facilitates environmental degradation. And the wider the inequality, the more the damage. Furthermore, those with less power end up bearing a disproportionate share of the environmental injury.

We see these situations all around us. Polluting power plants and hazardous waste dumps are located in poor neighborhoods. Drinking water impurities afflict minority communities. But is this relation between power and environmental degradation consistently true? If so, why? And what can we do about it? At Standing Rock, the balance between the opposing sides was close; Trump's election tipped the scales. But the experience, along with some recent shifts in power balances, offers lessons—and even hope—that efforts to reduce economic and social inequal-

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Illustration by Andrea Ucini

ity will be good not only for people but also for the environment.

GREATER INEQUALITY, GREATER HARM

RESEARCH on the connection between social power and environmental degradation began in earnest in the 1990s. Economists reported that they had found an inverted U-shaped relation between pollution and per capita income. They plotted air and water pollution on the y-axis of a graph and average income on the x-axis, comparing dozens of countries. Pollution initially increased as income went from $0 to a turning point of up to about $8,000 a year. But after that, pollution decreased as income rose further. This became known as the environmental Kuznets curve because of its similarity to the relation between inequality and average income found in a famous 1955 study by economist Simon Kuznets.

The environmental Kuznets curve appeared to offer respite from the bleak assumption that rising production and consumption necessarily lead to more environmental damage. Maybe humans were not, as environmental historian Roderick Nash once put it, a "cancerous" species whose growth "endangers the larger whole." A spirited debate ensued among analysts who saw economic growth as the solution to environmental woes and those who still saw it as the crux of the problem.

I was not convinced by either side. Maybe that was because in my 20s, I had lived among some of the world's poorest people in a Bangladesh village. That experience left me with the indelible understanding that human societies cannot be neatly summed up by population or per capita data. Many Bangladeshis went hungry but not because the country had too many people or too little food per person. There was enough food for everyone, yet communities starved because the poor lacked the purchasing power to buy it in the market or the political power to obtain it by other means. In his 1981 book *Poverty and Famines,* economist Amartya Sen explains that famines typically arise from similar realities. Inequality in the distribution of wealth and power seems to be central to how societies function and malfunction.

In thinking about the original and environmental Kuznets curves, it occurred to me that inequality, not per capita income, might underlie environmental degradation: the two seemed to rise and fall together. When then Ph.D. student Mariano Torras and I reanalyzed the environmental Kuznets curve data in 1998, we found that countries with lower rates of adult literacy, fewer political rights and civil liberties, and higher income inequality—which we considered to be indicators of more unequal distributions of power—tended to have more polluted air and water. After controlling for these indicators, the apparent effect of per capita income weakened, and for some pollutants, it disappeared entirely. We also found that greater inequality was associated with less access to clean drinking water and sanitation facilities, both crucial to the environment and human well-being.

In a 1999 follow-up study, my co-authors and I examined the 50 U.S. states. We analyzed the relation between the strength of state environmental policies and the distribution of power, using as proxies the rate of voter participation, the percentage of adults completing high school, tax fairness and Medicaid access. We found that wider inequality was associated with weaker environmental policies and that weaker policies were associated with more environmental stress and poorer public health. These results suggested that the pathways by which inequality adversely affects health include not only physiological stress, violence and reduced access to health care—all of which had been documented by public health researchers—but also impacts on the environment.

The initial reactions to our findings were decidedly cool. In the 1990s, when free markets and deregulation were all the rage, concerns about inequality were brushed aside as passé, maybe even soft-headed. One reviewer claimed that I was "beating a dead horse."

In the 2000s, however, inequality reemerged as a central political issue. The growing gap between the "1 percent" and everyone else, the terrible toll of Hurricane Katrina on low-income residents in New Orleans and the economic dislocations that followed the 2008 financial crisis all helped to put it back on the agenda. At the same time, evidence mounted that more concentrated wealth and political power leads to worse environmental performance—and not just in terms of air and water pollution. Researchers found that the proportion of plants and animals threatened with extirpation or extinction is higher in countries with more unequal income distributions. Rates of deforestation are higher in countries with greater corruption. Public expenditure on environmental research and development and patents on environmental innovations are lower in industrial nations with greater income inequality. More inequality has also been linked to higher carbon emissions per person and per unit of gross domestic product.

These findings make sense when we consider that with less inequality, people are better able to defend the air, water and natural resources on which their health and well-being depend. Protecting the environment and reducing inequality go hand in hand.

POWER RULES

ANY ACTIVITY that causes environmental degradation generates winners as well as losers. The activity benefits some people—otherwise no one would pursue it. And some people bear the costs—otherwise the degradation would not be seen as a problem. This poses a basic question: Why can those who benefit from such activities impose environmental costs on others?

There are three possible answers, all of them related to power disparities. One is that the costs are deferred, borne by future generations, who are not here today to defend themselves. In such cases, as when we think of the long-term impacts of climate change, the only way to safeguard the environment is for those of us who are alive to take responsibility toward those "whose faces are yet beneath the surface of the ground—the unborn of the future Nation," in the words of the Iroquois Constitution.

A second possibility is that people who are harmed are unaware of being hurt or do not know where the harm comes from. They may realize, for example, that their children are getting sick but not that the illness can be traced to emissions from a nearby refinery or power plant. In such cases, the solution lies in greater access to knowledge and, in particular, in policies that guarantee the public's right to know about environmental hazards and their sources.

The final possibility is that even when people are well aware that they are bearing the brunt of environmental costs and know the sources, they lack sufficient economic and political power to prevail in social decisions about the use and abuse of the environment. Standing Rock is an example. The solution in such cases is to change the balances of power.

Government decisions affecting the environment often invoke a cost-benefit analysis: How much benefit can be gained and at what cost? In this calculation, economic power (also known as purchasing power) plays a key role. People with more dollars effectively wield more "votes."

When the people who could be harmed have little or no political power, decision makers can minimize or ignore the costs. An extreme example is the cost-benefit case the U.S. Environmental Protection Agency recently made for repealing the Clean Power Plan. It assigned a value of zero to all climate impacts outside the U.S., reasoning that harms to people not in the country should not be considered in the making of U.S. climate policy.

Purchasing power and political power tend to be correlated: those with more dollars often have more political influence, and vice versa. Their joint effect can be described by a concept I call the power-weighted social decision rule. It means that the weight assigned to the costs and benefits from environmentally degrading activities depends on the power of the people to whom those accrue. When those who benefit from environmentally degrading activities are wealthy and powerful, compared with those who are harmed, social decisions favor the winners over the losers. The greater the inequality between rich and poor and between the more powerful and the less powerful, the greater the extent of environmental degradation.

Power inequality also exacerbates the neglect of future generations and lack of knowledge about environmental costs. When inequalities are wide, the imperatives of day-to-day survival for the very poor may overshadow worries about tomorrow; among the very rich, fear that their sway will eventually end can foster a cut-and-run attitude toward natural resources (exemplified by the rapacious deforestation of Southeast Asia in the 1960s and 1970s under such dictators as the Philippines' Ferdinand Marcos and Indonesia's Suharto). And when inequalities are wide, the poor are more likely to lack access to information, including about the nature and causes of the environmental harms to which they are subjected.

HEADS I WIN, TAILS YOU LOSE

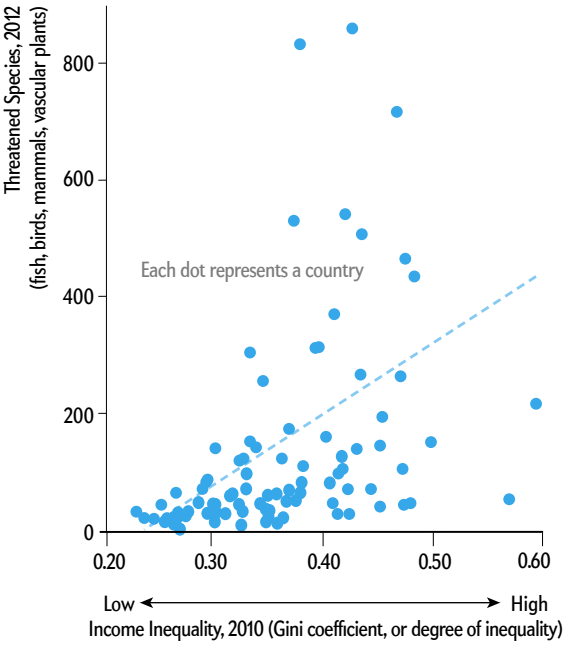
THE POWER-WEIGHTED social decision rule predicts not only that greater inequality will lead to greater environmental harm but also that the harm will be concentrated in communities at the lower end of the wealth-and-power spectrum. In those places, environmental costs carry less weight in the eyes of decision makers. Racial and ethnic minorities and low-income communities are at greatest risk. The Standing Rock reservation, where 40 percent of residents fall below the federal poverty line (triple the national rate), was vulnerable on both counts.

At the same time, the benefits from environmentally degrading

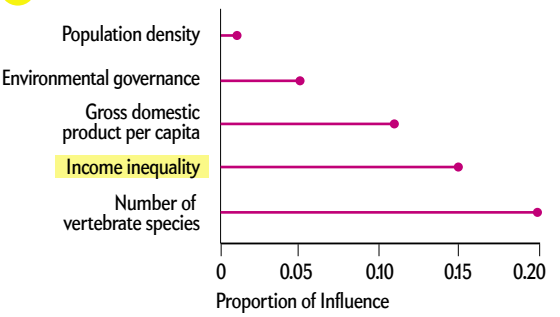
MORE INEQUALITY, FEWER SPECIES

Many studies show that as the gap between rich and poor people widens, the extent of environmental damage increases. For example, one analysis found that countries with higher income inequality also have higher rates of species classified as threatened by the International Union for Conservation of Nature (1). A separate report determined that income inequality is more strongly correlated with species loss than other major factors such as population density and even environmental policies (2). Only the total number of species had greater influence.

1 Species Threatened in Countries Worldwide



2 Factors Linked to Species Loss



SOURCES: "INEQUALITY AND ENVIRONMENTAL SUSTAINABILITY," BY S. NAZRUL ISLAM, UNITED NATIONS DEPARTMENT OF ECONOMIC AND SOCIAL AFFAIRS WORKING PAPER NO. 145, UNITED NATIONS, AUGUST 2015 (*number of species threatened*); "A CROSS-NATIONAL ANALYSIS OF HOW ECONOMIC INEQUALITY PREDICTS BIODIVERSITY LOSS," BY TIM G. HOLLAND, GARRY D. PETERSON AND ANDREW GONZALEZ, IN *CONSERVATION BIOLOGY*, VOL. 23, NO. 5, OCTOBER 2009 (*factors linked to species loss*)

Graphics by Jen Christiansen

OBJECTION to the Dakota Access Pipeline in North Dakota by local Native Americans concerned about contaminated water supplies grew to a larger protest nationwide against corporations and politicians having more power than underserved communities.

activities—higher profits for producers and lower prices for consumers—are concentrated at the upper end of the economic spectrum. Profits flow to shareholders and corporate executives, who generally are relatively well off. And the more that consumers spend, the more they benefit from lower prices, again bestowing greater benefits on the well-to-do.

This is not to say that affluent people do not want a clean and safe environment. But to a substantial extent, environmental quality is what economists call an impure public good. It is not equally available to everyone. Well-off people can afford to live in cleaner places, buy bottled water and air conditioners, and get better medical care. They can also more effectively oppose having environmental hazards placed in their neighborhoods. By being further removed from environmental harms, they can more easily afford to ignore them. Even when they cannot altogether escape the consequences of environmental degradation, they weigh a relatively small share of the costs against a relatively large share of the benefits.

ENVIRONMENTAL INJUSTICE

SINCE THE 1980S researchers have systematically documented the disproportionate exposure of racial and ethnic minorities and low-income communities to environmental hazards in the U.S. One of the earliest studies, by sociologist Robert Bullard, examined the spatial distribution of hazardous-waste sites in Houston and found them to be located primarily in African-American neighborhoods.

Subsequent studies have revealed similar patterns in many parts of the country: race and ethnicity correlate strongly with proximity and exposure to environmental harms. Researchers have also investigated how the correlations can be explained. One controversy that arose was about timing: Are hazardous facilities sited from the outset in communities with less wealth and power? Or, after a facility is sited, do wealthier residents move out, property values decline and poorer people move in? Few studies have explored this question directly, but those that do have found strong evidence that such toxic facilities are sited from the start in communities with less power. The evidence also indicates that in cases where more well-to-do people leave after a facility is built, the trend had already begun before the siting, suggesting that communities in transition are more vulnerable to having environmental hazards imposed on them.

Disproportionate pollution exposure hurts children in particular, resulting in higher rates of infant mortality, lower birth weights, a higher incidence of neurodevelopmental disabilities, more frequent and intense asthma attacks, and lower school test scores. Among adults, exposure is linked to work days lost to illnesses and the need to care for sick children. Over time, these health effects reinforce the disparities that make communities more vulnerable to environmental harm in the first place.

Although the effects are most severe for at-risk communities, they often spill over to wider populations. For example, U.S. metropolitan areas with more residential segregation along racial and ethnic lines tend to have higher cancer risks from air pollution for everyone, not only for people of color. In cities that rank in the top 5 percent nationally for racial and ethnic disparities in industrial air pollution exposure, the average exposure for non-Hispanic whites is significantly higher than in those where pollution disparities are smaller. Environmental justice is good for everyone.

Environmental inequalities can be found everywhere. In England and the Netherlands, poorer and more nonwhite neighborhoods

JIM WATSON Getty Images

have higher air concentrations of particulate matter and nitrogen oxides, which aggravate respiratory problems. In Delhi, whose residents breathe some of the world's dirtiest air, the poor live in more polluted neighborhoods. They also spend more time working outdoors, including along roadways, where air pollution loads are most extreme. They cannot afford air conditioning or air purifiers. At the same time, they obtain fewer benefits from the power generation, transportation and other industries that cause the pollution.

The power-weighted social decision rule operates at the international scale, too. Environmental harm is unduly inflicted on the poorest countries. In a 1991 memorandum, Lawrence Summers, then chief economist at the World Bank, wrote that "the economic logic behind dumping a load of toxic waste in the lowest-wage country is impeccable" because the foregone earnings from illnesses and deaths there will be lowest. His statement may have been tongue-in-cheek, but environmental practice often follows this script. Every year millions of tons of toxic waste are shipped from advanced industrial countries to low-income nations in Africa, Asia and Latin America.

The Basel Convention on the Control of Transboundary Movement of Hazardous Wastes and Their Disposal, an international environmental agreement that took effect in 1992, has proved inadequate to halt this flow. The distance between people who benefit from the economic activities that generate the waste and those who bear the costs of its disposal gives a painful new twist to the adage "out of sight, out of mind."

THE NEW ENVIRONMENTALISM

SO WHAT CAN WE DO to lessen social and environmental inequality, thereby reducing harm to people and the planet?

The relation between inequality and the environment is a two-way street. Reducing inequality in the distribution of wealth and power helps to bring about a greener environment. And efforts to advance the right to a clean and safe environment help to bring about greater equality. The key to both is active mobilization for change.

U.S. environmentalism in the 20th century aimed to protect nature from people. Enlightened elites often saw themselves as defenders of nature from the irresponsible masses. From there, it was a short step to assume an inexorable trade-off between environmental protection and broad-based economic well-being.

In the 21st century we are witnessing the ascendance of a new environmentalism. The aim is to protect individuals who face harm from people who profit from degradation. The balance of power between these two sides can and does change over time. When climate activists from across the country joined Native Americans at Standing Rock, defending their right to a clean and safe environment, the power-balance scales began to move. The protesters, building on past achievements of movements across the country for equal rights and environmental protection, came close to halting a multibillion-dollar enterprise.

In other, less widely covered cases, the new environmentalism has scored significant victories. In Washington State, for instance, activists succeeded in blocking a proposed coal export terminal that would have been the largest in the country, protecting lands and waters of tribal communities. Another coal terminal had initially been blocked in Oakland, Calif., by a coalition of environmental, labor and economic justice advocates, but legal challenges continue. In Montana, the Blackfeet Nation won the cancellation of energy leases on 23,000 acres, the culmination of a 30-year struggle.

The intimate links between inequality and the environment have led to growing recognition that if we want to rebalance human relationships with nature, we also need to rebalance our relationships with one another. SA

For more on the "Science of Inequality," visit scientificamerican.com/inequality

MORE TO EXPLORE

STIGLITZ

The Price of Inequality: How Today's Divided Society Endangers Our Future. Joseph E. Stiglitz. W. W. Norton, 2012.

The Great Divide: Unequal Societies and What We Can Do about Them. Joseph E. Stiglitz. W. W. Norton, 2015.

Rewriting the Rules of the American Economy: An Agenda for Growth and Shared Prosperity. Joseph E. Stiglitz. W. W. Norton, 2015.

Globalization and Its Discontents Revisited: Anti-globalization in the Era of Trump. Joseph E. Stiglitz. W. W. Norton, 2017.

SAPOLSKY

Why Zebras Don't Get Ulcers: The Acclaimed Guide to Stress, Stress-Related Diseases, and Coping. Third edition. Robert M. Sapolsky. Holt Paperbacks, 2004.

The Spirit Level: Why Greater Equality Makes Societies Stronger. Richard Wilkinson and Kate Pickett. Bloomsbury Press, 2010.

Behave: The Biology of Humans at Our Best and Worst. Robert M. Sapolsky. Penguin Press, 2017.

EUBANKS

Automating Inequality: How High-Tech Tools Profile, Police, and Punish the Poor. Virginia Eubanks. St. Martin's Press, 2018.

BOYCE

Inequality and Environmental Protection. James K. Boyce in *Inequality, Cooperation, and Environmental Sustainability.* Edited by Jean-Marie Baland, Pranab Bardhan and Samuel Bowles. Princeton University Press, 2006.

The Haves, the Have-Nots, and the Health of Everyone: The Relationship between Social Inequality and Environmental Quality. Lara Cushing et al. in *Annual Review of Public Health,* Vol. 36, pages 193–209; March 2015.

Economic Inequality and the Value of Nature. Moritz A. Drupp et al. in *Ecological Economics,* Vol. 150, pages 340–345; August 2018.

FROM OUR ARCHIVES

The Disease of Poverty. Michael Marmot; The Science of Health, March 2016.

The Threat of Inequality. Angus Deaton; September 2016.

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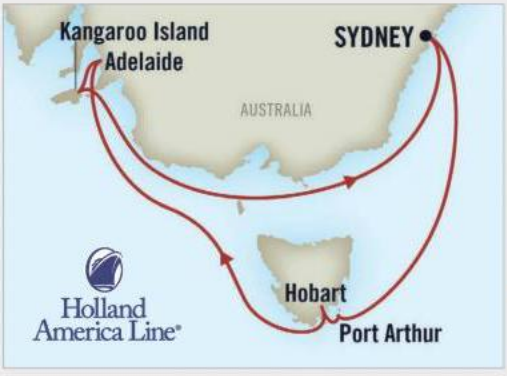

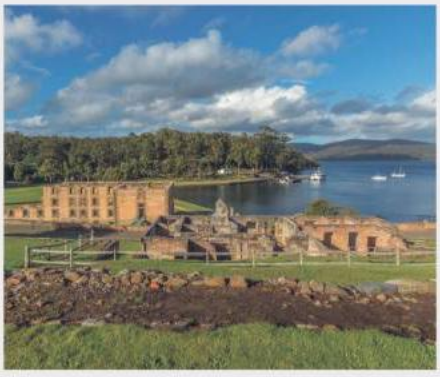

SPEAKERS:

Alex Filippenko, Ph.D.

Alex Filippenko is an elected member of both the National Academy of Sciences and the American Academy of Arts & Sciences, is one of the world's most highly cited astronomers and the recipient of numerous prizes for his scientific research. He was the only person to have been a member of both teams that revealed the accelerating expansion of the Universe, an amazing discovery that was honored with the 2011 Nobel Prize in Physics to the teams' leaders and the 2015 Breakthrough Prize in Fundamental Physics to all team members. Winner of the most prestigious teaching awards at UC Berkeley and voted the "Best Professor" on campus a record nine times, he was named the National Professor of the Year in 2006. He has produced five astronomy video courses with The Great Courses, coauthored an award-winning astronomy textbook, and appears in more than 100 television documentaries. In 2004, he was awarded the Carl Sagan Prize for Science Popularization. He was recently selected as one of only two recipients of the 2017 Caltech Distinguished Alumni Award.

Martin Green, Ph.D.

Martin Green is Scientia Professor at the University of New South Wales, Sydney and Director of the Australian Centre for Advanced Photovoltaics, involving several other Australian Universities and research groups. His group's contributions to photovoltaics are well known and include holding the record for silicon solar cell efficiency for 30 of the last 34 years, described as one of the "Top Ten" Milestones in the history of solar photovoltaics. Major international awards include the 1999 Australia Prize, the 2002 Right Livelihood Award, also known as the Alternative Nobel Prize the 2007, SolarWorld Einstein Award, and, most recently, the 2016 Ian Wark Medal from the Australian Academy of Science.

Angela Moles, Ph.D., F.R.S.N.

Angela Moles is a plant ecologist at UNSW Sydney. Angela studies global patterns in the ways plants grow. One of Angela's studies, known as "The World Herbivory Project" took her to 75 ecosystems around the world, including arctic tundra in Greenland and Alaska; deserts in Arizona; Central Australia and Israel; tropical rainforests in the Republic of Congo, Panama, China, Mexico and Peru; shrublands in Mexico and California; temperate forests in Argentina, Sweden, Tasmania, Norway, and Oregon; and savannas in South Africa, Australia, and Zambia. At each site, Angela and her team measured how well defended the plants were, and how much of their leaf area was eaten by animals. This study overturned the long-held idea that plants are better defended in the tropics (they are actually better-defended at higher latitudes), and the idea that plants suffer greater losses to animals in tropical ecosystems (plants get eaten a lot everywhere).

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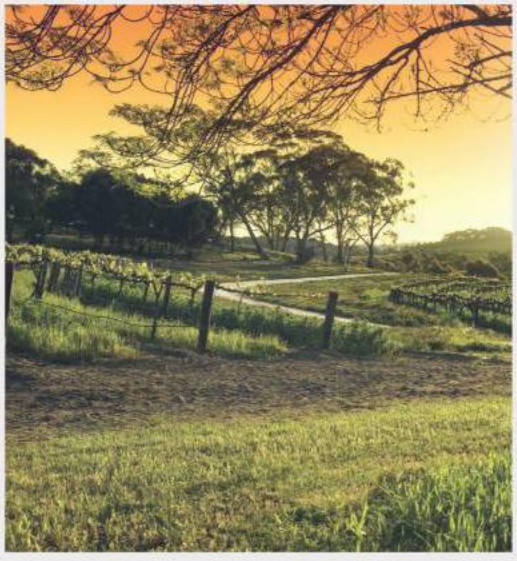

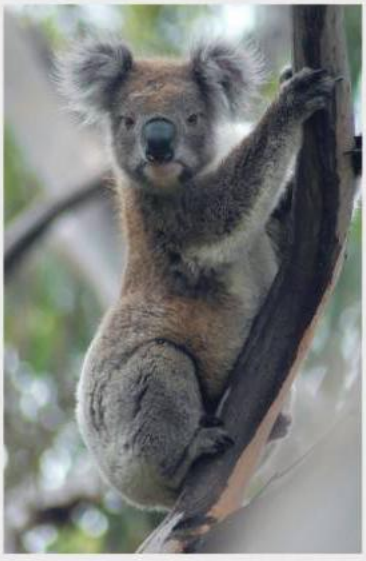

Since having children, Angela has stopped travelling so much and started working on introduced species. Angela's group has shown that 70% of the annual plant species introduced to Australia in the last 100 years have changed significantly since their arrival from overseas. A glasshouse study on a beach daisy introduced to Australia from South Africa in the 1930s has revealed substantial differences in growth form, flower size and photosynthetic rate between the South African and Australian forms of this plant, and the two populations do not cross to form strong offspring.

Veena Sahajwalla, Ph.D., F.T.S.E.

Australian Research Council (ARC) Laureate Professor Veena Sahajwalla is revolutionizing recycling science to unlock the wealth of resources in the many complex and toxic wastes currently destined for landfill. As a materials scientist and engineer and founding Director of the Centre for Sustainable Materials Research and Technology (SMaRT) at the University of New South Wales, Sydney, she is producing a new generation of green materials, products and resources made entirely, or primarily, from waste.

Veena Sahajwalla is an internationally respected scientist and engineer. Her research focuses on the sustainability of materials and processes with an emphasis on environmental and community benefits. One of her most celebrated achievements is the invention of a process of recycling plastics and rubber tires in steelmaking, now known around the world as green steel. Veena has published around 300 peer-reviewed papers and delivers keynote and invited speeches across Australia and worldwide.

She continues her community engagement through regular school visits and public talks, her mentoring program for girls in science (Science 50:50) and regular media commentary. In 2017, Veena Sahajwalla received the 2017 PLuS Alliance Prize for Research Innovation category and became the first woman to be awarded the prestigious Jubilee Professorship by the Indian Academy of Sciences.

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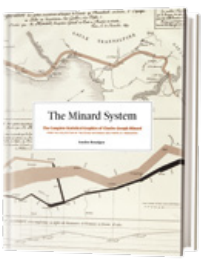
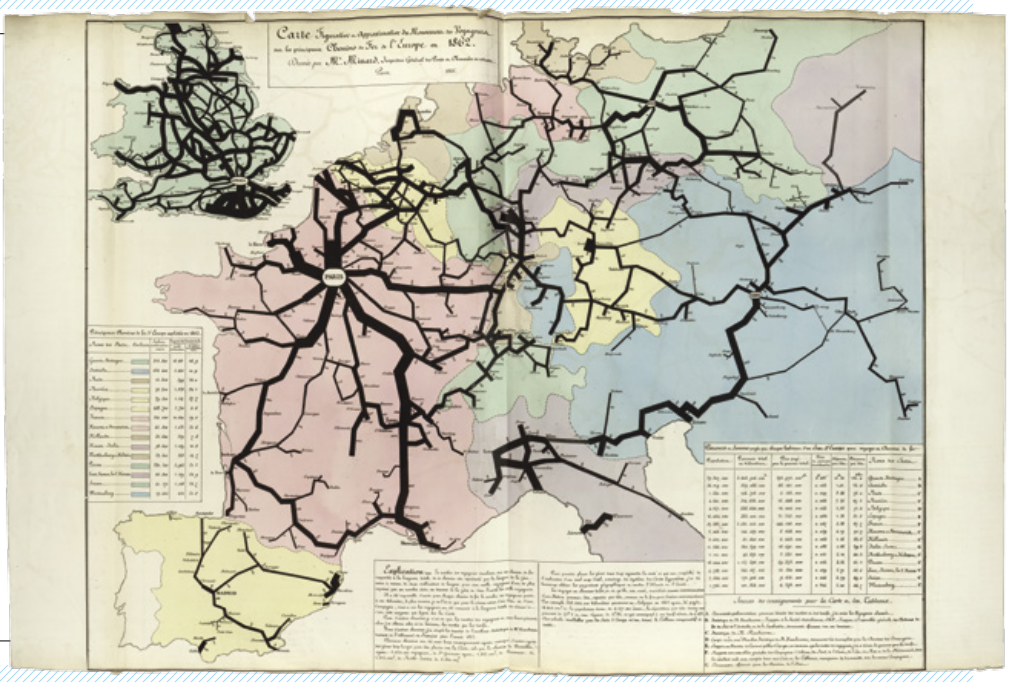
RECOMMENDED

By Andrea Gawrylewski

The Minard System: The Complete Statistical Graphics of Charles-Joseph Minard

by Sandra Rendgen. Princeton Architectural Press, 2018 ($60)

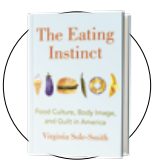




French civil engineer Charles-Joseph Minard became famous in the 19th century for the "flow map," which represents the movement and quantity of something over space or time. His most recognized map was among his last: the charting of Napoleon's disastrous 1812 campaign into Russia, in which hundreds of thousands of troops were lost. A forefather of modern information visualization, as writer and editor Rendgen calls him, Minard created more than 60 statistical graphics that capture the economic and social changes of the industrial revolution in Europe and around the globe. He meticulously interpreted the data for each topic and created a narrative intended to shine through each map. This stunning collection includes them all—from visual depictions of the transport of mineral fuels in France in 1856 to a series on the European import of cotton over eight years. The flow map above shows the number of railroad passengers in Europe in 1862.

The Eating Instinct: Food Culture, Body Image, and Guilt in America

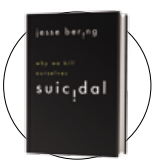
by Virginia Sole-Smith. Henry Holt, 2018 ($28)



When journalist Sole-Smith's daughter was an infant, she had to be tube-fed because of a heart surgery. After her recovery, she refused to drink milk and, later, to eat solid food. It took two years for the author and her husband to painstakingly teach their child to feel safe and interested in eating. Although their example is extreme, Sole-Smith investigates the varied ways many people's relationships with food are fraught. In this engrossing tale, she interviews doctors, nutritionists, chefs and many individuals who are all striving to figure out what it means to "eat well." Sole-Smith reveals the lack of science behind many diets and detox plans claiming to improve health and wonders, "Why is it so hard to feel good about food?" *—Clara Moskowitz*

Suicidal: Why We Kill Ourselves

by Jesse Bering. University of Chicago Press, 2018 ($27.50)



By age 35 psychologist and writer Bering had accomplished most of his career ambitions. He was respected in academia, having scored large research grants and published in prestigious journals. He also was a successful freelance writer. Outwardly he seemed to be thriving, but internally he suffered from suicidal thoughts. Why do people in their prime have the impulse to kill themselves? Bering takes us through the science behind ending one's life. Bering says research shows, for instance, that susceptibility to suicide is about 43 percent dependent on genetics and 57 percent on environmental factors. He weaves together personal stories, delves into whether nonhuman animals die by suicide, and examines the relation of religion and self-killing. These angles offer a critical perspective on a devastating problem. *—Sunya Bhutta*

Gene Machine: The Race to Decipher the Secrets of the Ribosome

by Venki Ramakrishnan. Basic Books, 2018 ($18.99)

Many people know what DNA is and how it works. Most, however, would struggle to describe the ribosome, the molecular machine that synthesizes proteins according to the genetic code. "Virtually every molecule in every cell in every form of life is either made by the ribosome or made by enzymes that are themselves made by the ribosome," writes Ramakrishnan, co-winner of the 2009 Nobel Prize in Chemistry for illuminating the ribosome's structure. As he relates in this absorbing account, his team raced others for decades to decipher the structure; its nonuniform crystal pattern does not lend itself to x-ray crystallography and defied years of coaxing. With each try, Ramakrishnan got a slightly clearer picture of this ancient machinery—paving the way for discoveries in antibiotics and other fields. *—Kacper Ksieski*

Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com) and a Presidential Fellow at Chapman University. His new book is *Heavens on Earth: The Scientific Search for the Afterlife, Immortality, and Utopia.* Follow him on Twitter @michaelshermer

The Fallacy of Excluded Exceptions

Why the singular of "data" is not "anecdote"

By Michael Shermer

For a documentary on horror movies that seem cursed, I was recently asked to explain the allegedly spooky coincidences associated with some famous films. Months after the release of *Poltergeist,* for example, its 22-year-old star, Dominique Dunne, was murdered by her abusive ex-boyfriend; Julian Beck, who played the preacher "beast," succumbed to stomach cancer before *Poltergeist II*'s release; and 12-year-old Heather O'Rourke died months before the release of what would be her last starring role in *Poltergeist III.*

The Exorcist star Linda Blair hurt her back when she was thrown around on her bed when a piece of rigging broke; Ellen Burstyn was injured on the set when flung to the ground; and actors Jack MacGowran and Vasiliki Maliaros both died while the film was in postproduction (their characters died in the film).

When Gregory Peck was on his way to London to make *The Omen,* his plane was struck by lightning, as was producer Mace Neufeld's plane a few weeks later; Peck avoided aerial disaster again when he canceled another flight at the last moment (that plane crashed, killing everyone onboard); and two weeks after filming, an animal handler who worked on the set was eaten alive by a lion.

During the making of *The Crow,* star Brandon Lee was accidentally shot to death by a stage gun with blanks; he was the son of Bruce Lee, who also died mysteriously at a young age, possibly from a drug reaction. While filming *Twilight Zone: The Movie,* star Vic Morrow was killed in a freak helicopter accident.

For some people, such eerie coincidences suggest evil supernatural forces at work. But that conclusion is not warranted. As I explained on camera, picture a 2×2 square with four cells. Cell 1 contains Cursed Horror Movies (*Poltergeist, The Exorcist, The Omen, The Crow, Twilight Zone: The Movie*). Cell 2 contains Cursed Nonhorror Movies (*Superman, The Wizard of Oz, Rebel Without a Cause, Apocalypse Now*). Cell 3 contains Noncursed Horror Movies (*It, The Ring, The Sixth Sense, The Shining*). Cell 4 contains Noncursed, Nonhorror Movies (*The Godfather, Star Wars, Casablanca, Citizen Kane*). When they are put into this perspective, it is clear that those seeing supernatural intervention are remembering only the horror movies that seemed cursed and forgetting all the other possibilities.

Call it the Fallacy of Excluded Exceptions, or the failure to note instances that do not support the generalization. In cell 1, for example, *Halloween* is not included, because there are no "curse" stories associated with it; its star, Jamie Lee Curtis, went on to a successful motion picture career, and the film launched a franchise in the horror genre. In cell 2, no one attributes evil forces at work on the California highway where James Dean lost his life after making *Rebel Without a Cause.* In cell 3, a spine-chilling film like *The Shining* should be loaded with curses, but it isn't.

The psychology underlying the Fallacy of Excluded Exceptions is confirmation bias, where once one commits to a belief, the tendency is to look for and find only confirming examples while ignoring those that disconfirm. This is very common with paranormal claims. People grasp at predictions by psychics or astrologers when they come true, but what about all the predictions that did not come true or major events that nobody predicted? In the realm of faith, cancers that go into remission after intercessory prayer are often considered religious miracles, but what about the cancers that disappeared without faith-based intervention or the cancer patients who were prayed for but died? Divine providence is often adduced when a few faithful people survive a disaster, but all the religious folks who died and atheists who lived are expediently ignored.

The problem is rampant not just with paranormal and supernatural claims. Claims of medical cures associated with this or that alternative treatment modality typically exclude cases where treated patients were not cured or were cured but possibly by other means. Crime waves are often linked to economic downturns, but this hypothesis is gainsaid by counterexamples, such as the relatively low crime rates during the 1930s depression and the 2008–2010 recession.

Excluded exceptions test the rule. Without them, science reverts to subjective speculation. 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.

Pets Gone Wild

People dump their exotic animals for logical, if not good, reasons

By Steve Mirsky

Slough slog. Wet walk. Swamp tromp. Whatever you call it, it's a hike in the knee-deep to waist-deep water of the Everglades or other aqueous environments. A slough, pronounced "sloo," is stagnant or slow-moving water. Slough, pronounced "sluff," is a snake's shed skin. And the sloughs in the slough is why I won't slog.

Oh, I did a few slough slogs in my younger days. We would range from hammock to hammock, some of which might even let you hang a hammock. A hammock, pronounced "hammock," is a stand of trees that forms a small island. A hammock, pronounced "lazy man's nap station," is a sling you can attach to two trees within the hammock.

Anyway, my slough-slog days were when the Everglades included alligators (which ordinarily shy away from people), disease-causing mosquitoes, rattlesnakes and various other critters that could do me harm. But now the Everglades is home to thousands—perhaps hundreds of thousands—of Burmese pythons. And some pythons are big enough to at least try to eat an adult alligator—a famous 2005 photograph shows the remains of a death match in which a python was split asunder after swallowing all or most of a similarly sized gator. So, I'm not slogging through any sloughs that contain enormous, potentially me-eating snakes that properly belong 10,000 miles away in Southeast Asia.

The founders of this predatory serpent population were possibly some snakes that escaped from a local breeding center damaged during Hurricane Andrew in 1992, as well as pets released into the wild. But why would people toss their adored animal buddy into the swamp?

"Despite the importance releases play in the invasion process for the pet trade pathway, most of the research to date has focused on the factors influencing the establishment of exotic pet populations and not on the factors related to their initial introduction (or release ...)," write Rutgers University researchers Oliver C. Stringham and Julie L. Lockwood in their paper "Pet Problems: Biological and Economic Factors That Influence the Release of Alien Reptiles and Amphibians by Pet Owners," published online in August in the *Journal of Applied Ecology*. Therefore, "we set out to identify broadscale and easily measured biological and economic factors that influence the release of these exotic pets by their owners."

Stringham and Lockwood analyzed databases of animals available for sale as pets and information on life-history traits—that is, how fast various species grow, how big they get, how many offspring they can have. What they discovered is what you would probably suspect, but which until their research, nobody could say for sure: chances that somebody will relocate their pet to the great outdoors depend on how many of the beasties were available to be sold in the first place, how cheap they were and how much damn bigger they'll grow in their relatively long lives than when they were cute little babies.

These factors are independent of the likelihood of the swamp thing establishing itself in its new environment. Thus, in some cases, abandoned creatures live their lives without consequence. But some species take over and bust up the joint. For example, a 2012 study in the *Proceedings of the National Academy of Sciences USA* found that where the Florida pythons slither, observations of native populations of raccoons were down 99.3 percent, possum sightings plummeted by 98.9 percent, and rabbits were either gone completely or were hiding deep in their holes as they'd done (while called "wabbits") during the Elmer Fudd incursion of 1940.

The Rutgers authors note that "integrating the release stage into risk management can result in a more robust and accurate assessment of invasion risk.... Such risk assessments have been used to guide legislation aimed at curbing invasions through import bans of high risk species." The research team also writes that "our results can be used to craft legislation targeted at reducing the probability of release of species. For example, our results can be used to target taxing and licensing efforts towards high-release risk species.... Regardless of the approach, a data-driven effort to document factors that result in exotic pet releases can advance a more comprehensive, evidence-based approach to risk management and policy implementation."

One day, when evidence-based approaches, data-driven efforts, and reasonable taxation and legislation are back in vogue, the information in this study could come in handy. SA

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Illustration by Matt Collins

Show us your quantum vision of reality

The Quantum Shorts contest calls for films up to five minutes long that take inspiration from quantum physics. Enter to be in the running for international screenings, subscriptions to *Scientific American* and cash prizes of up to US$1500.

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NOVEMBER

1968 Riddle of Steel

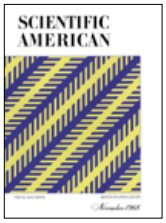
"Can hard steels ever be made tough and ductile? One of the properties of materials that are of greatest concern to engineers and scientists concerned with materials is fracture. The scope of fracture problems is wide, ranging from catastrophic failures of bridges, tanks, pipelines and machine parts to basic considerations such as how atoms become separated when single crystals of a metal are broken. Both calculations and experiments have shown that the metals used by engineers should be about 10 times stronger than the engineer actually finds they are. The story of modern steels is an example of the kind of investigation that is helping to reveal and define the upper boundaries of strength and ductility that practical materials may reasonably be expected to reach within the next decade."

1918 Peace Arrives

"The wave of hysterical rejoicing that swept over the United States when our President announced the signing of a truce had many impulses; but none was more strong than the conviction that, with the death of German militarism, there had died also the ever-present threat of war and the ever-accumulating burden of naval and military armaments. With the surrender of the German fleet and the passing of Germany as a first-class naval power, the United States moves up again to its former position as the second great naval power of the world. Furthermore, it finds itself committed, through its administrative head, to the noble concept of perpetuating our alliance for war as an alliance for peace, by the formation of a great League of Nations, one of the first fruits of which will be that limitation of armaments to which the war-mad German was formerly the unsurmountable obstacle."

Influenza Invades

"In the recent epidemic of influenza the United States Public Health Service was called upon for a far greater measure of service to the nation than it was able to render. This onslaught of the Grim Reaper (to borrow a phrase from the fledgling reporter's vocabulary) found the country unprepared. The Health Service did well, under the circumstances. An emergency appropriation of a million dollars was rushed through Congress. The Volunteer Medical Service Corps furnished a list of a thousand physicians, to whom temporary appointments were offered by telegraph. Some nurses, though far too few, were obtained with the aid of the American Red Cross. All these measures, however, savor of improvisation; and a newly arrived Martian would certainly gain the impression from the recent occurrence that no great epidemic of disease had ever before visited our nation. Otherwise (we may suppose the enlightened stranger saying to himself) these Earthians would have had the defensive machinery all ready to set in motion."



1968

1918


1868


1918: Troops, with a newly invented "Whippet" tank, are seen crossing the Canal du Nord in France. The final push to end the First World War was on.

1868 Midge Meal

"Dr. Livingstone, relating his adventures on Lake Nyassa [also called Lake Malawi], thus tells one curiosity which he fell in with: 'During a portion of the year, the northern dwellers on the lake have a harvest which furnishes a singular kind of food. As we approached our limit in that direction, clouds, as of smoke arising from miles of burning grass, were observed bending in a southeasterly direction. We sailed through one of the clouds, and discovered that it was neither smoke nor haze, but countless millions of minute midges called *kungo* (a cloud of fog). They filled the air to an immense height, and swarm upon the water too light to sink in it. The people gathered these insects by night and boiled them into thick cakes to be used as a relish—millions of midges in a cake. It tasted not unlike caviare or salted locusts.'"

Modesty and Mania

"The velocipede mania is beginning to set in, and with the opening of the spring months we may expect to see our parks and highways thronged with this cheap and agreeable substitute for the horse. The two-wheeled velocipede is not exactly the thing wanted for general use, as it will be somewhat difficult for novices to keep upright upon it. A nicely adjusted vehicle with a double hind wheel would be most desirable for all classes. The ladies will need something of the kind, and for obvious reasons; unless they don the Bloomer costume, they will not be able to ride on the two-wheeled machine."

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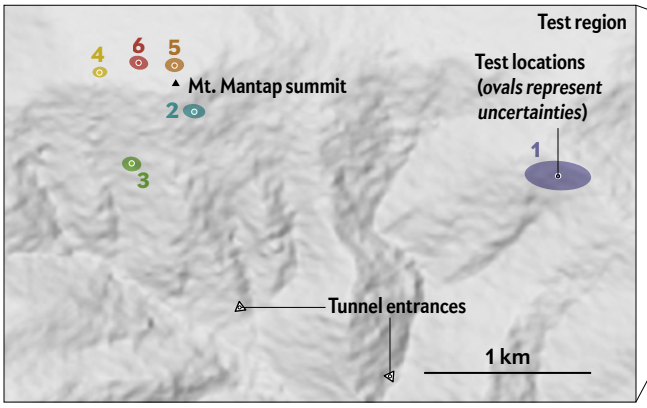
Text and Graphic by Katie Peek

Watching North Korea

Illicit nuclear detonations are anything but secret

In September 2017 North Korea tested its largest nuclear bomb yet. It was 10 times the blast strength of any of the five previous underground detonations (*map*). How do we know? A global network of more than 300 earthquake-monitoring stations stands sentry. After an explosion, seismometers pick up two types of shock waves within minutes and alert intelligence officers. Scientists learn even more afterward. Since the last blast, they have combined the seismic signals with satellite images and other data to pinpoint more details, recently published, such as the precise location and bomb size (*chart*). Should North Korea—or any other nation—try another bomb, the world will know.

Six Nuclear Bomb Tests Compared



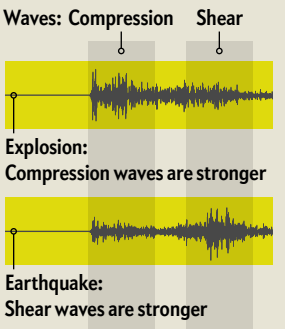
Test date	Seismogram	Bomb size	Blast depth
1 October 9, 2006	Magnitude 4.3	1.1–2.1 kilotons	340–480 meters
2 May 25, 2009	4.7	4.6–10.4 kt	340–500 m
3 February 12, 2013	5.1	8–27 kt	270–450 m
4 January 6, 2016	5.1	8–19 kt	480–670 m
5 September 9, 2016	5.3	20–87 kt	440–630 m
6 September 3, 2017	6.3	104–150 kt	530–670 m

Test locations
North Korea's six explosions were conducted at the Punggye-ri test site, located underneath Mount Mantap. In each case, seismometers around the world picked up the shock waves. Researchers compared the arrival times of the waves at multiple stations to determine where the blast originated.

Bomb sizes
The 2017 test created the equivalent of a magnitude 6.3 earthquake. Seismologists initially used a standard relation, based on old French and Russian detonations, to estimate the bomb's strength, or yield, as equivalent to 100 to 200 kilotons of TNT. The most recent estimate, based on a more detailed analysis, puts the blast at 125 kilotons. The 1945 blast at Hiroshima was 13 to 18 kilotons.

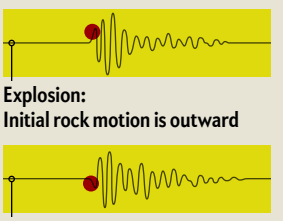
Blast depths
Scientists determine whether an explosion was shallow or deep by modeling the test site design and simulating a range of strengths and depths.

How to Tell a Blast from an Earthquake



Seismometers record compression waves and shear waves in the earth. An explosion compresses rock more than shears it, so those signatures are stronger.

How to Tell a Blast from a Cave-in



The signature of a mine collapse or other cave-in looks like a blast, except that the initial rock motion is inward; a blast's is outward.

SOURCES: "THE COUPLED LOCATION/DEPTH/YIELD PROBLEM FOR NORTH KOREA'S DECLARED NUCLEAR TESTS," BY MICHAEL E. PASYANOS AND STEPHEN C. MYERS, IN *SEISMOLOGICAL RESEARCH LETTERS*. PUBLISHED ONLINE AUGUST 8, 2018 (*bomb sizes and blast depths*); "ABSOLUTE LOCATIONS OF THE NORTH KOREAN NUCLEAR TESTS BASED ON DIFFERENTIAL SEISMIC ARRIVAL TIMES AND INSAR," BY STEPHEN C. MYERS ET AL., IN *SEISMOLOGICAL RESEARCH LETTERS*. PUBLISHED ONLINE AUGUST 15, 2018 (*test locations*); WWW.NORSAR.NO (*seismograms*); "THE PUNGGYE-RI NUCLEAR TEST SITE: A TEST TUNNEL TUTORIAL," 38 NORTH, MAY 23, 2018 *www.38north.org/2018/05/punggyetunnel052318* (*tunnel locations*); U.S. GEOLOGICAL SURVEY (*earthquake magnitudes*)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