A NEW THEORY OF OBESITY
Are ultraprocessed foods to blame? PAGE 38

REVERSING DEATH
Partially revived pig brains raise hard questions PAGE 34

SCIENTIFIC AMERICAN

WINGED TERROR

How pterosaurs evolved to dominate the Mesozoic skies

PLUS

ROOM-TEMPERATURE SUPERCONDUCTORS
Are scientists nearing a breakthrough? PAGE 46

PRESCHOOL PEDAGOGY
Why instilling focus and language skills fosters success PAGE 68

SCIENCE IN CRISIS
The raging debate over statistical significance PAGE 62

OCTOBER 2019
ScientificAmerican.com


SIR EDMUND HILLARY AND TENZING NORGAY 1953


TRIESTE EXPEDITION 1960


VOLCANOLOGIST ANDREW MCGONIGLE


DR. SYLVIA EARLE WITH ASPIRING OCEANOGRAPHER


NATIONAL GEOGRAPHIC PERPETUAL PLANET MOUNTAIN INDEX

JAMES CAMERON
THE DEEPSEA CHALLENGE

GEOLOGIST FRANCESCO SAURO

PERPETUAL PLANET

For Rolex founder Hans Wilsdorf, the world was a living laboratory – the source of exploration, creation and inspiration. He used it as a testing ground for his watches, taking them to the most extreme locations, supporting the explorers who ventured into the unknown. Rolex continues his legacy with the explorers of today on their new mission: to make the planet perpetual. By supporting those who protect the oceans, study the effects of climate change and create a more sustainable world. Rolex stands behind the scientists, explorers and visionaries who will spark the imagination of future generations. Alone we can go far. But only together can we make the planet perpetual.

Discover more on rolex.org.

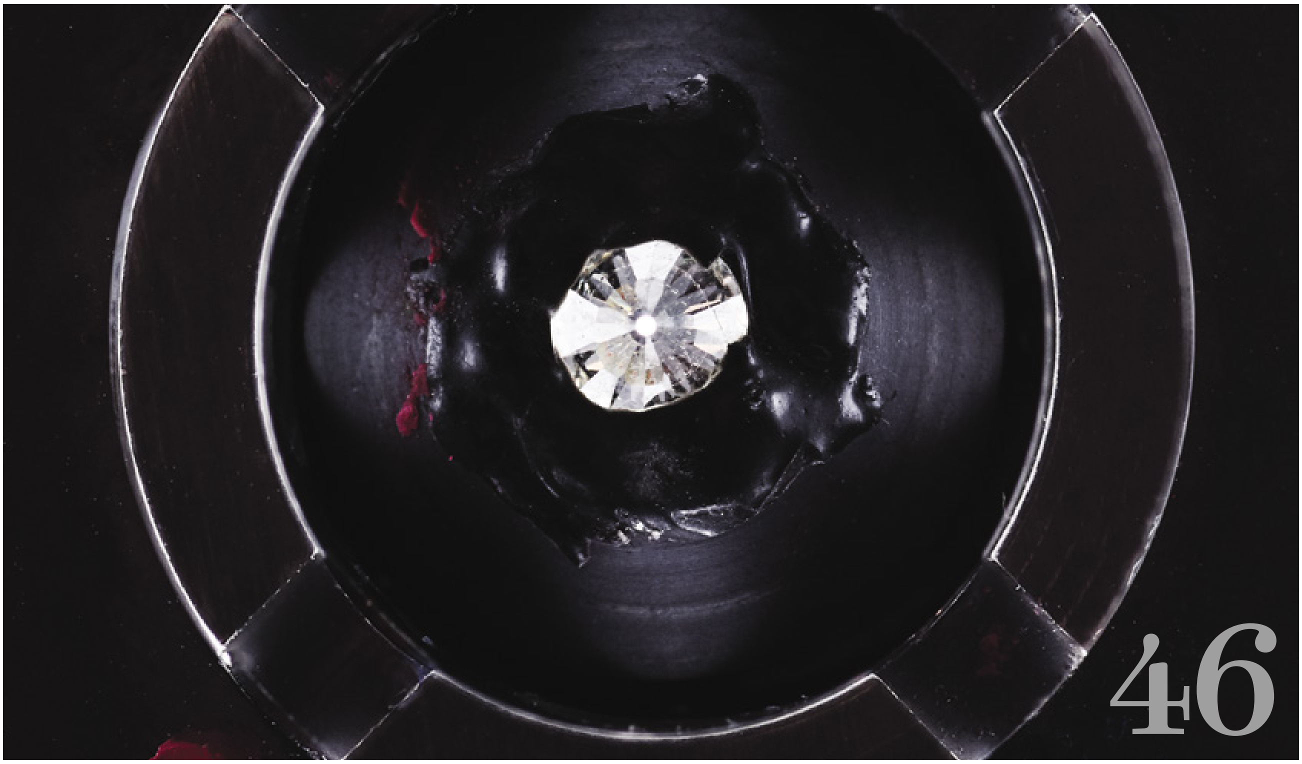
#Perpetual

ROLEX

SCIENTIFIC AMERICAN

OCTOBER 2019

VOLUME 321, NUMBER 4

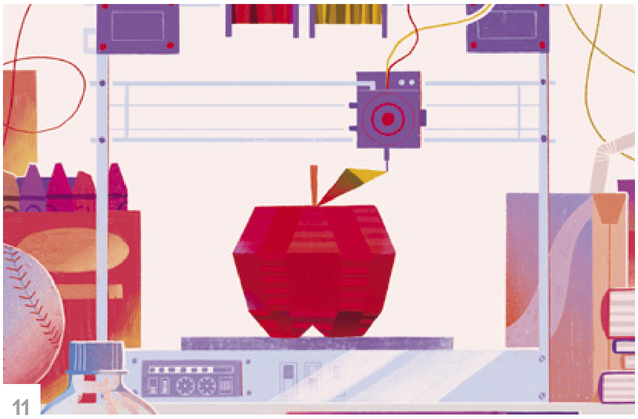


ON THE COVER

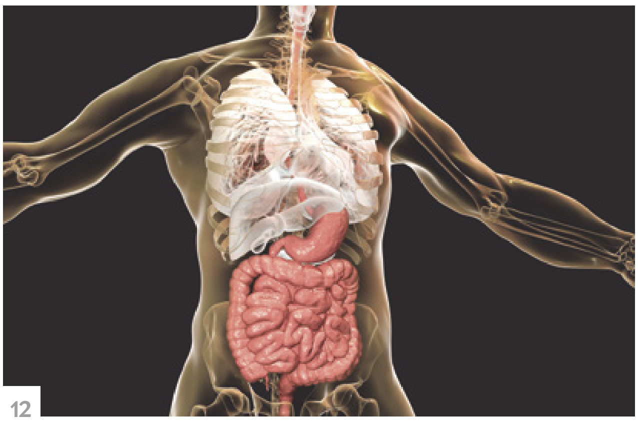
Tupandactylus imperator, a pterosaur, patrolled the skies during the Cretaceous period. Like a number of other pterosaurs from this time, it had extreme anatomical features, including a gigantic head and neck compared with the rest of its body. Researchers have finally begun to understand how these bizarre creatures could fly. **Illustration by Chase Stone.**

Photograph by Spencer Lowell

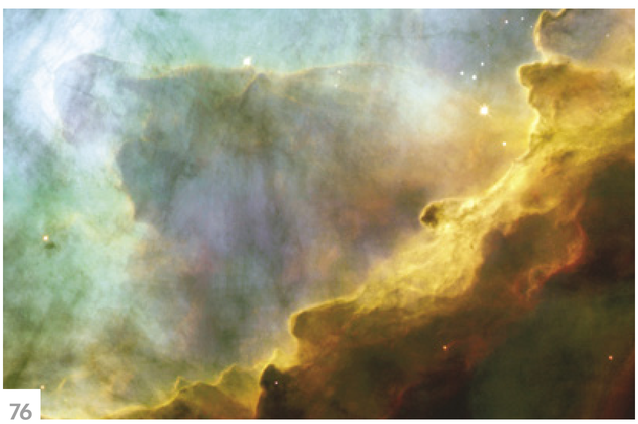
SCIENTIFIC AMERICAN



11



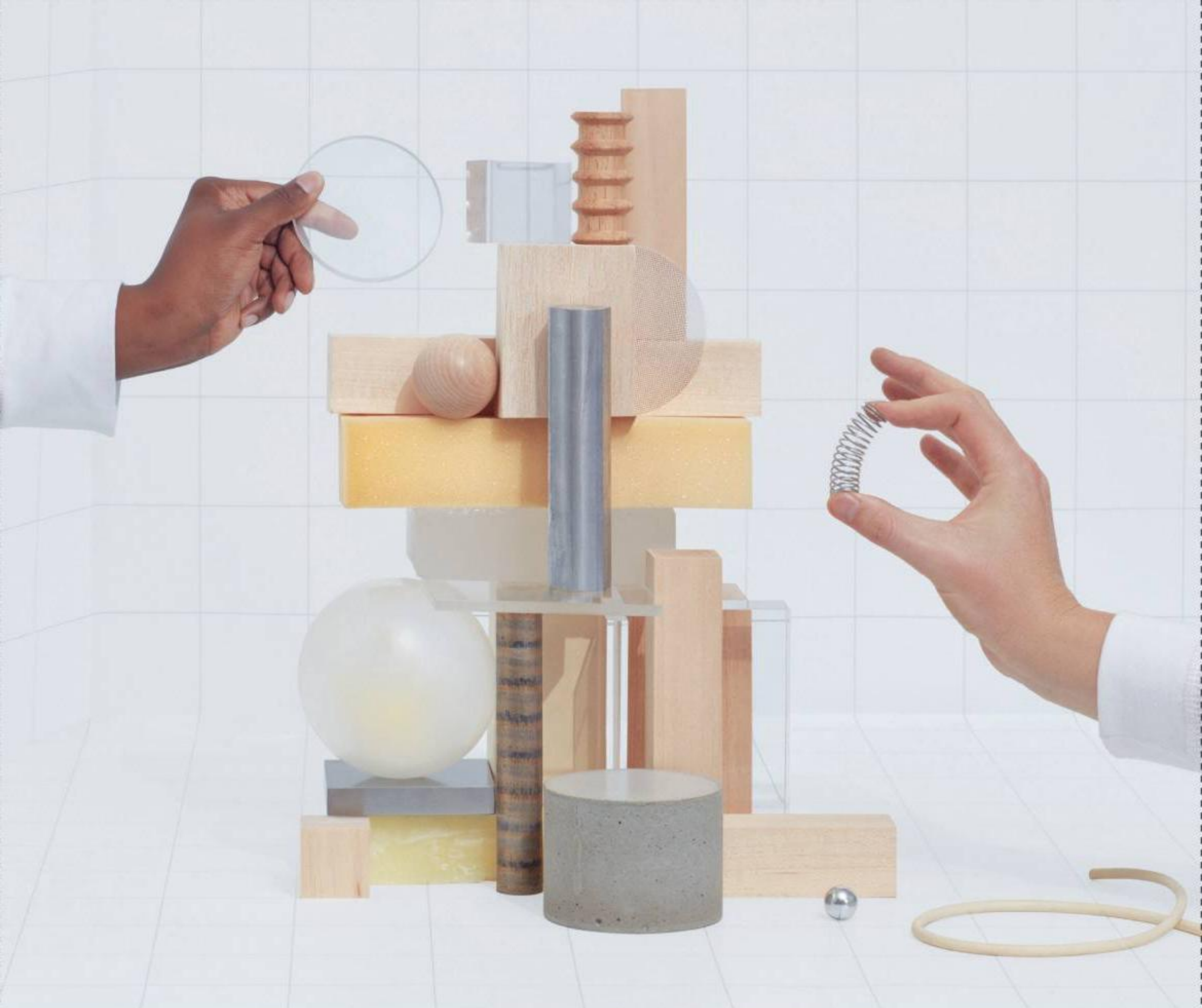
12



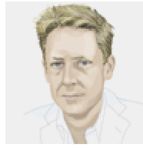
76

Scientific American (ISSN 0036-8733), Volume 321, Number 4, October 2019, published monthly by Scientific American, a division of Nature America, Inc., 1 New York Plaza, Suite 4500, New York, N.Y. 10004-1562. Periodicals postage paid at New York, N.Y., and at additional mailing offices. Canada Post International Publications Mail (Canadian Distribution) Sales Agreement No. 40012504. Canadian BN No. 127387652RT; TVQ1218059275 TQ0001. Publication Mail Agreement #40012504. Return undeliverable mail to Scientific American, P.O. Box 819, Stn Main, Markham, ON L3P 8A2. **Individual Subscription rates:** 1 year $49.99 (USD), Canada $59.99 (USD), International $69.99 (USD). **Institutional Subscription rates:** Schools and Public Libraries: 1 year $84 (USD), Canada $89 (USD), International $96 (USD). Businesses and Colleges/Universities: 1 year $399 (USD), Canada $405 (USD), International $411 (USD). Postmaster: Send address changes to Scientific American, Box 3187, Harlan, Iowa 51537. **Reprints inquiries: (212) 451-8415. To request single copies or back issues, call (800) 333-1199. Subscription inquiries: U.S. and Canada (800) 333-1199; other (515) 248-7684. Send e-mail to scacustserv@cdsfulfillment.com.**

Scientific American is part of Springer Nature, which owns or has commercial relations with thousands of scientific publications (many of them can be found at www.springernature.com/us). Scientific American maintains a strict policy of editorial independence in reporting developments in science to our readers. Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



FROM THE EDITOR



Curtis Brainard is acting editor in chief of *Scientific American.*

Dragon Up

For me, there's nothing particularly special about seeing a small Cessna take to the air. But watching an Airbus A380, the world's largest commercial airliner, ascend is something altogether different. The way it lumbers into the sky just doesn't seem real. Yet mechanical and aerodynamic adaptations make flight possible for such bulky craft.

I imagine I would've had the same impression (and a dose of terror) watching a hulking pterosaur take wing, especially compared with the smaller feathered dinosaurs and birds that evolved later. Pterosaurs were the first vertebrates to fly, and while some were quite small, others were enormous. And like today's jumbo jets, an intricate set of physiological adaptations, which paleontologist Michael B. Habib details in this issue's cover story, "Monsters of the Mesozoic Skies," allowed them to lift off. They were quadrupedal and had massive necks, for instance, much like the fearsome dragons in *Game of Thrones,* which inspired Habib and his colleagues when they were naming one of the pterosaur species. Turn to page 26.

Pterosaurs are now gone, as are, unfortunately, most of the 110,000 or so distinct varieties of rice that were once planted across India. Some could tolerate flood, drought, salt and pestilence; some had unique nutritional value; and some were just uniquely pleasant and used in special rituals. With the Green Revolution in the 1950s and 1960s, the government began to focus on high-yield cultivars, which can produce a lot of grain but are expensive and vulnerable to environmental assaults, and that number has dwindled to about 6,000 varieties across India today. Thankfully, as he writes in "Restoring Rice Biodiversity," starting on page 54, conservationist Debal Deb has made it his life's work to redress this problem.

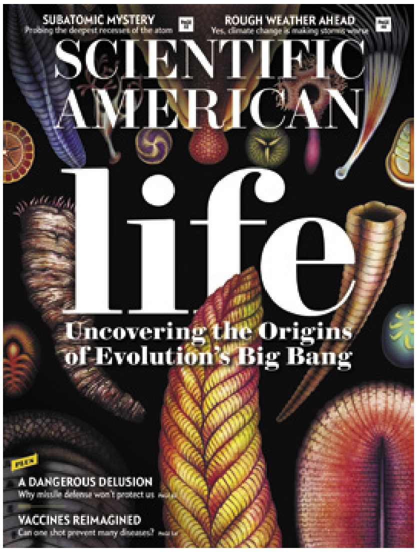
Whether it's rice or wheat, we should all eat more whole grains and more whole foods in general, but markets in the U.S. and elsewhere are littered with "ultraprocessed" foods, including candy bars and potato chips, as well as less obvious things like flavored yogurt and vodka. New research, which journalist Ellen Ruppel Shell describes in "Obesity on the Brain," suggests that these unnatural concoctions disrupt gut-brain signals in a way that encourages overeating. More fruits and vegetables, preferably of heirloom varieties, please! Graze on over to page 38.

Elsewhere, scientists recently used a small device called a diamond anvil cell to apply about half the pressure at the center of the earth to a mix of lanthanum and hydrogen. Then they shot the mash with a laser and synthesized an entirely new material, lanthanum hydride, in hopes of finding a long-coveted room-temperature superconductor. Such a substance, which ferries a current without resistance, could accomplish technological wonders. Beginning on page 46, journalist Bob Henderson explains in "The Stuff of Dreams" how theory and computer modeling are now guiding a decades-old quest that was once based mostly on guesswork and luck.

Of course, whether it's studying ancient creatures, biodiversity or something else, all science involves a bit of conjecture and serendipity. That's part of what makes the process of research and discovery so frustrating and ever so delightful. Fortune may favor the bold, but it rewards inquisitive minds as well. SA

Illustration by Nick Higgins


BECAUSE SOMEDAY
I'll stay overnight for observation.
Plan for your someday without sacrificing the things you want to do today.
Together, we'll help you achieve what matters most.
• Live the life you want today, and into the future.
• Develop a long-term financial game plan.
• Get, and stay, on track toward your goals.
Talk with Fidelity today about your finances. Because you don't have to know all the answers—that's why we're here to help.
Fidelity INVESTMENTS
Fidelity.com/yoursomeday
866.715.2058
Investing involves risk, including the risk of loss.
The trademarks and/or service marks appearing above are the property of FMR LLC and may be registered.
Fidelity Brokerage Services LLC, Member NYSE, SIPC. 900 Salem Street, Smithfield, RI 02917
© 2017 FMR LLC. All rights reserved. 815617.2.0



June 2019

DEFENDING MISSILE DEFENSE

Laura Grego and David Wright damningly criticize the U.S.'s Ground-based Midcourse Defense (GMD) program to intercept incoming nuclear missiles in "Broken Shield." But your readers should not confuse what amounts to a debate over priorities with a claim grounded in established nuclear theory. In fact, ballistic missile defense (BMD) can limit nuclear damage, buttress U.S. deterrence and empower arms control.

The missiles BMD shoots down are not the only ones that it impacts. Rather the *possibility* of directing all BMD to protect, say, Washington, D.C., forces U.S. adversaries to allocate additional warheads to "must kill" targets; accordingly, these bombs are then unavailable for lower-priority cities. A missile shield does not have to be perfect to successfully defend against an attack from a small nuclear power—such as North Korea. And BMD raises the bar for a successful nuclear strike, even for Russia's larger nuclear arsenal.

Mark Massa *Washington, D.C.*

"Ballistic missile defense can limit nuclear damage, buttress U.S. deterrence and empower arms control."

Mark Massa *Washington, D.C.*

BAR-CODING FIX FOR DRUGS

In "All the World's Data Could Fit in an Egg," James E. Dahlman describes how the method of DNA tagging could reduce effort in investigating potential drugs. That sounds like an awesome development, but I wonder if the method could be used for another concern as well.

The fine print for many drugs, particularly psychotropic ones, often says something on the order of "we don't really know how this works," and they can have severe adverse reactions, sometimes even increasing the possibility for violence and suicide. Might DNA bar coding also be used to reduce such reactions?

Moritz Farbstein *St. Louis*

DAHLMAN REPLIES: DNA bar coding could eventually alleviate adverse reactions by helping scientists design drugs that specifically target diseased cells. Many such reactions occur when a drug meant to treat a diseased cell also targets a healthy one. By maximizing the drug delivered to the site of disease, it may be possible to reduce the dose and minimize interaction between that drug and healthy cells. Using DNA bar codes, scientists can track how drugs are delivered to diseased and healthy cells, all in one experiment. The hope is to use these data to rationally design drugs that avoid healthy cells.

AWAKE WHILE ASLEEP

"One Eye Open," by Gian Gastone Mascetti, describes how some animals can sleep with one half of their brain while the other stays awake, sometimes keeping one eye open while they do so. The article particularly caught my interest because I experienced an effect like this often while serving on the front lines in Iraq and Afghanistan.

When I was sleeping, I knew I was asleep, but I was also awake and aware of everything going on around me. I was able to come fully awake in an instant, as if I had never even been asleep, but I felt rested. And I could open one eye slightly to see what was happening around me. This happened many nights in a row, over many months. I've only experienced it when my life was in danger, so it was clearly connected to a sense of life and death hanging on whether I could remain alert.

Mike Scott *via e-mail*

MASCETTI REPLIES: To my knowledge of human sleep behavior, sleeping with one eye open seems to be a metaphor or perhaps a sensation some people experience when sleeping in new, alarming and potentially dangerous conditions. But I cannot exclude the possibility that some individuals might show the capacity to briefly open one eye and awaken during sleep as has been reported in some species of birds. And we do know that humans are able to show a sleep strategy that seems to be reminiscent of the unihemispheric slow-wave sleep in animals I discuss in my article. When sleeping, they show a consistent electroencephalographic slow-wave activity in one hemisphere, indicating a very light sleep level in the other hemisphere.

A hemispheric sleep asymmetry could be present in any unusual, unsafe or dangerous environment, allowing the sleeper to keep a certain level of vigilance. For example, it has been shown that sleeping mothers maintain a high vigilance and a low awakening threshold to smell, noises and the cries of their babies. This hemispheric condition should indeed also be present in soldiers sleeping in a war zone.

BAT BUDDIES

In "Deer Friends" [Advances], Joshua Rapp Learn reports on a study finding that bats follow white tail deer around to prey on insects. That observation is not unique: When my wife is out working on our farm at dusk, several resident little brown bats that nest under the shingles of our house follow her around, preying on mosquitoes. My wife attracts the bugs, and the bats eat them—a perfect symbiosis, as the article notes about the arrangement between bats and deer. We live almost mosquito-free in the summer, and our bat friends keep my wife company at night.

John Davies *Sunshine Coast, B.C.*

ASSISTED MISGIVING

What planet is Wade Roush living on? In "Safe Words for Our AI Friends" [Ven-

tures], he says, "AI assistants should exist to give us more agency over our lives." But by being too lazy to look up a weather report or turn on lights, he apparently allows an ever present listening device—Amazon's Alexa—to hear everything. That seems to be a clear transference of agency.

Further, Roush says he wants such assistants that won't compromise privacy, transparency, security and trustworthiness. Has that ever happened with any online platform? It is naive to think things will ever be different.

Harlan Levinson *Los Angeles*

PLASTICS AT HOME

I could not ignore the irony of tearing the plastic outer packaging from the June issue and throwing it in the trash so that I could read the editorial entitled "What to Do about Plastic Pollution" [Science Agenda]. As a longtime subscriber, I ask you to *please* stop wrapping your magazine in unnecessary plastic packaging. I don't mind reading an issue that arrives slightly wrinkled.

Scott Pierce *Western Carolina University*

THE EDITORS REPLY: Scientific American *wraps issues in plastic for U.S. subscribers only when there is an unbound advertising supplement included in the mailing. The current issue (October), which includes such a supplement, is the seventh mailing of that kind since the beginning of 2017 (newsstand issues are never wrapped). A small number of domestic subscribers and advertisers request wrapped issues, and we wrap issues for all international subscribers (except in Canada). This adds up to only 10 percent of the total print run, but we realize that even that portion contributes to the burden of plastic pollution worldwide, and we are committed to doing better. We are actively investigating options to cease wrapping entirely or to replace our current material with a more sustainable alternative.*

ERRATUM

"The Deepest Recesses of the Atom," by Abhay Deshpande and Rikutaro Yoshida, should have said that quarks, rather than nucleons, are at least 10,000 times smaller than a proton. Protons are one type of nucleon.

SCIENTIFIC AMERICAN
ESTABLISHED 1845

ACTING EDITOR IN CHIEF **Curtis Brainard**

COPY DIRECTOR **Maria-Christina Keller** CREATIVE DIRECTOR **Michael Mrak**

EDITORIAL

CHIEF FEATURES EDITOR **Seth Fletcher** CHIEF NEWS EDITOR **Dean Visser** CHIEF OPINION EDITOR **Michael D. Lemonick**

FEATURES

SENIOR EDITOR, SUSTAINABILITY **Mark Fischetti** SENIOR EDITOR, SCIENCE AND SOCIETY **Madhusree Mukerjee**
SENIOR EDITOR, CHEMISTRY / POLICY / BIOLOGY **Josh Fischman** SENIOR EDITOR, TECHNOLOGY / MIND **Jen Schwartz**
SENIOR EDITOR, SPACE / PHYSICS **Clara Moskowitz** SENIOR EDITOR, EVOLUTION / ECOLOGY **Kate Wong**

NEWS

SENIOR EDITOR, MIND / BRAIN **Gary Stix** ASSOCIATE EDITOR, SUSTAINABILITY **Andrea Thompson**
SENIOR EDITOR, SPACE / PHYSICS **Lee Billings** ASSOCIATE EDITOR, HEALTH AND MEDICINE **Tanya Lewis**
ASSOCIATE EDITOR, TECHNOLOGY **Sophie Bushwick** ASSISTANT NEWS EDITOR **Sarah Lewin Frasier**

MULTIMEDIA

SENIOR EDITOR, MULTIMEDIA **Jeffery DelViscio** SENIOR EDITOR, MULTIMEDIA **Steve Mirsky**
ENGAGEMENT EDITOR **Sunya Bhutta** SENIOR EDITOR, COLLECTIONS **Andrea Gawrylewski**

ART

ART DIRECTOR **Jason Mischka** SENIOR GRAPHICS EDITOR **Jen Christiansen**
PHOTOGRAPHY EDITOR **Monica Bradley** ART DIRECTOR, ONLINE **Ryan Reid**
ASSOCIATE GRAPHICS EDITOR **Amanda Montañez** ASSISTANT PHOTO EDITOR **Liz Tormes**

COPY AND PRODUCTION

SENIOR COPY EDITOR **Daniel C. Schlenoff** SENIOR COPY EDITOR **Aaron Shattuck** SENIOR COPY EDITOR **Angelique Rondeau**
MANAGING PRODUCTION EDITOR **Richard Hunt** PREPRESS AND QUALITY MANAGER **Silvia De Santis**

DIGITAL

PRODUCT MANAGER **Ian Kelly** SENIOR WEB PRODUCER **Jessica Ramirez**

CONTRIBUTORS

EDITORS EMERITI **Mariette DiChristina, John Rennie**
EDITORIAL **David Biello, Lydia Denworth, W. Wayt Gibbs, Ferris Jabr, Anna Kuchment, Robin Lloyd, Melinda Wenner Moyer, George Musser, Christie Nicholson, Ricki L. Rusting**
ART **Edward Bell, Bryan Christie, Lawrence R. Gendron, Nick Higgins, Katie Peek**

EDITORIAL ADMINISTRATOR **Ericka Skirpan** EXECUTIVE ASSISTANT SUPERVISOR **Maya Harty**

SCIENTIFIC AMERICAN CUSTOM MEDIA

MANAGING EDITOR **Cliff Ransom** CREATIVE DIRECTOR **Wojtek Urbanek**
MULTIMEDIA EDITOR **Kris Fatsy** MULTIMEDIA EDITOR **Ben Gershman**
ENGAGEMENT EDITOR **Dharmesh Patel**

PRESIDENT **Dean Sanderson**

EXECUTIVE VICE PRESIDENT **Michael Florek**

CLIENT MARKETING SOLUTIONS

VICE PRESIDENT, COMMERCIAL **Andrew Douglas**
PUBLISHER AND VICE PRESIDENT **Jeremy A. Abbate**
MARKETING DIRECTOR, INSTITUTIONAL PARTNERSHIPS AND CUSTOMER DEVELOPMENT **Jessica Cole**
PROGRAMMATIC PRODUCT MANAGER **Zoya Lysak**
DIRECTOR, INTEGRATED MEDIA **Jay Berfas**
DIRECTOR, INTEGRATED MEDIA **Matt Bondlow**
MANAGER, GLOBAL MEDIA ALLIANCES **Brendan Grier**
SENIOR ADMINISTRATOR, EXECUTIVE SERVICES **May Jung**

CONSUMER MARKETING

HEAD, MARKETING AND PRODUCT MANAGEMENT **Richard Zinken**
MARKETING MANAGER **Chris Monello**
SENIOR COMMERCIAL OPERATIONS COORDINATOR **Christine Kaelin**

ANCILLARY PRODUCTS

ASSOCIATE VICE PRESIDENT, BUSINESS DEVELOPMENT **Diane McGarvey**
CUSTOM PUBLISHING EDITOR **Lisa Pallatroni**
RIGHTS AND PERMISSIONS MANAGER **Felicia Ruocco**

CORPORATE

HEAD, COMMUNICATIONS, USA **Rachel Scheer**
COMMUNICATIONS AND PRESS OFFICER **Sarah Hausman**

PRINT PRODUCTION

PRODUCTION CONTROLLER **Madelyn Keyes-Milch** ADVERTISING PRODUCTION CONTROLLER **Dan Chen**

LETTERS TO THE EDITOR

Scientific American, 1 New York Plaza, Suite 4600, New York, NY 10004-1562 or editors@sciam.com
Letters may be edited for length and clarity. We regret that we cannot answer each one.
Join the conversation online—visit *Scientific American* on Facebook and Twitter.

HOW TO CONTACT US

Subscriptions
For new subscriptions, renewals, gifts, payments, and changes of address: U.S. and Canada, 800-333-1199; outside North America, 515-248-7684 or www.ScientificAmerican.com

Submissions
To submit article proposals, follow the guidelines at www.ScientificAmerican.com. Click on "Contact Us." We cannot return and are not responsible for materials delivered to our office.

Reprints
To order bulk reprints of articles (minimum of 1,000 copies): Reprint Department, Scientific American, 1 New York Plaza, Suite 4600, New York, NY 10004-1562; 212-451-8415. For single copies of back issues: 800-333-1199.

Permissions
For permission to copy or reuse material: Permissions Department, Scientific American, 1 New York Plaza, Suite 4600, New York, NY 10004-1562; randp@SciAm.com; www.ScientificAmerican.com/permissions. Please allow three to six weeks for processing.

Advertising
www.ScientificAmerican.com has electronic contact information for sales representatives of Scientific American in all regions of the U.S. and in other countries.

China's Ethical Crossroads

The nation needs better safeguards if it wants to be a medical powerhouse

By the Editors

China's high-tech industrialization policy, known as Made in China 2025, purports to take the country to the front ranks of advanced manufacturing in aerospace, robotics, clean energy, transportation and the life sciences. But the transformation into a global biotech and pharmaceutical dynamo might prove more challenging than making robots or self-driving cars.

That is because China lacks a good regulatory and ethical review process, a serious problem highlighted last November when scientist He Jiankui gave the world an unwelcome surprise. He announced that he had edited the genes of twin girls at the embryo stage with the aim of enhancing their resistance to HIV—an experiment with the potential to produce a host of genetic and health problems that could be passed on to the twins' offspring.

The rogue nature of He's actions brought a wave of condemnation from inside and outside the country, but the experiment was by no means an outlier. China stands out from other technologically advanced countries because of its headlong embrace of new biological and medical developments that raise weighty ethical and human-rights issues.

After He went public, the *Wall Street Journal* reported that other Chinese researchers working with CRISPR-Cas9 gene editing, the same technique used for the twins (but, in these instances, not in embryos), had lost track of the people who had participated in their study. The *Journal* also documented earlier this year accusations that Uighur Muslims, practitioners of Falun Gong, Tibetan Buddhists and "underground" Christians have had organs forcibly removed for transplants. In addition, animal research on the feasibility of head transplants and spinal cord reattachment has been carried out in China—a head transplant on a living human volunteer has even been discussed.

He's gene editing of embryos appears to have pushed Chinese authorities to act. Although China lacks firm regulations on the practice, tinkering with the twins' genes violated its guidelines on human-assisted reproduction, and the scientist was fired from a Chinese university and left a start-up company he founded. China has also begun to open up a process of national self-scrutiny that could put the country on a sturdier foundation of ethical safeguards more in line with international norms. A May commentary in *Nature* by four bioethicists from Chinese universities and institutes laid out both the problem and a series of solutions with extraordinary clarity and forthrightness. The authors assert China is at a crossroads requiring "substantial changes to protect others from the potential effects of reckless human experimentation."

The article criticized Chinese science culture as beset by *jigong jinli:* a motivation to seek "quick successes and short-term gains." Lei Ruipeng of Huazhong University of Science and Technology in Wuhan and three co-authors from other institutions called for better regulation, stringent penalties and clear codes of conduct for research that involves gene editing, stem cells, mitochondrial transfer, neurotechnologies, synthetic biology, nanotechnology and xenotransplantation. They want these codes to supersede the fragmented framework of oversight responsibilities currently apportioned among different government ministries. Policy makers seem to be edging in the same direction: in February the National Health Commission put out draft regulations that propose stricter controls on gene editing.

The bioethicists also suggest a registry that tracks clinical trials and collects ethics evaluations for studies using new medical technologies. They advocate other measures such as dissemination of regulations by a national organization and ethics education for everyone from scientists to the general public. And they call for an end to discrimination of people with disabilities based on the rationale that they are inferior or a societal burden, an attitude biasing any attempt to formulate a set of ethical principles.

China is not the only country that has lagged at some point in developing a regulatory infrastructure to address experiments on humans. In the U.S., the 1978 Belmont Report set out ethics guidelines for human research subjects in the aftermath of the 40-year Tuskegee experiment, which tracked the progress of syphilis in untreated black men who were, unforgivably, not told clearly that they had the disease. As the *Nature* commentary's authors point out, the field of bioethics has only a 30-year history in China. He's regrettable decision to edit the genes of twin sisters could serve as the impetus to spur the nation toward a profound rethinking of its public policy on human research—a necessary prerequisite before China can responsibly become a biotech colossus. SA

JOIN THE CONVERSATION ONLINE
Visit *Scientific American* on Facebook and Twitter
or send a letter to the editor: editors@sciam.com

Illustration by Deshi Deng


Rick Lazio and **Harold Ford, Jr.,** are former members of the U.S. House of Representatives from the Republican and Democratic parties, respectively.

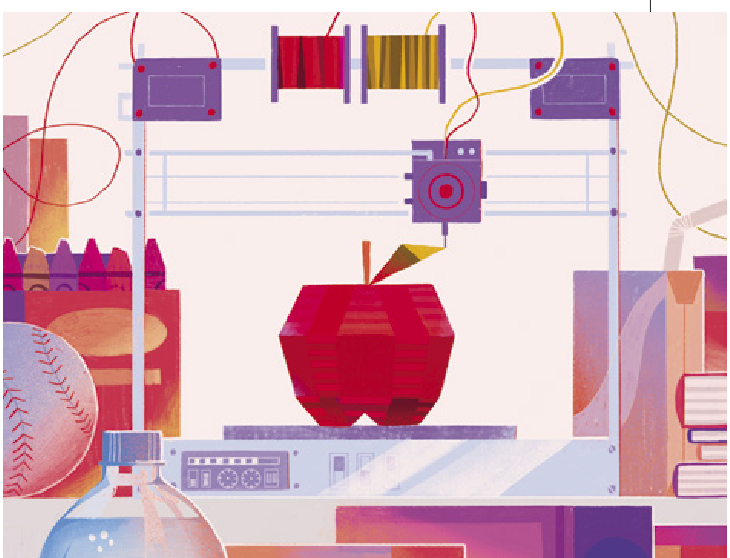
Closing the Skills Gap

Why STEM education reform is the path to a better future

By Rick Lazio and Harold Ford, Jr.

If you're a small business owner with a technology company, this has probably happened to you: One of your best employees is poached by a larger competitor, leaving you scrambling to find a qualified replacement who is able to pick up the load. You post the vacancy on every job board you can find. But after more than a month, the demand from your clients hasn't decreased, and you're struggling to keep up. Your current employees start feeling the strain, increasing your worry that others will soon follow suit and head out the door.

If this sounds familiar, you're not alone—especially if you're looking for someone such as the oh-so-coveted software developer, in high demand in nearly every industry owing to the advancement of the Internet of Things and the boom in robotics and automation. Even engineering, considered by many to be a "staple" in



the American job market, is seeing shortfalls in engineers, which will keep employers from satisfying demand.

Randstad North America reports that as of 2016 there were an estimated three million more STEM jobs than qualified workers available to fill them, and the Education Commission of the States projects a 13 percent increase in that number between 2017 and 2027. Others, including the Bureau of Labor Statistics, say that most shortfalls will occur in IT rather than across all STEM fields. Given these statistics and the rapid adoption of new technology, it is clear that STEM skills will be critical in the new tech economy. If left unaddressed, the shortage of STEM workers will have long-term and extremely consequential ramifications such as stagnated economic growth. This situation leaves our country at considerable risk of losing high-paying jobs to other nations.

What do we do to fix it? The U.S. is falling behind other countries in achievement in STEM areas for a variety of reasons, including a lack of consistent exposure to the relevant subjects for young students—particularly minority students. Although both the Obama and Trump administrations emphasized the importance of STEM education, with the U.S. Department of Education investing $279 million in STEM discretionary grant funds in 2018, more can be done to make the system consistent for all of America's K–12 students.

In 2015, according to the Pew Research Center, the U.S. placed 38th in math and 24th in science out of 71 participating nations in the Program for International Student Assessment (PISA), one of the largest tests to measure reading, math and science literacy. Also, the World Economic Forum reported that in 2013, 40 percent of Chinese graduates completed a degree in STEM—more than double the percentage of Americans. These numbers clearly point to a disturbing trend in our country's ability to funnel technical labor into the workforce and remain competitive on an international scale.

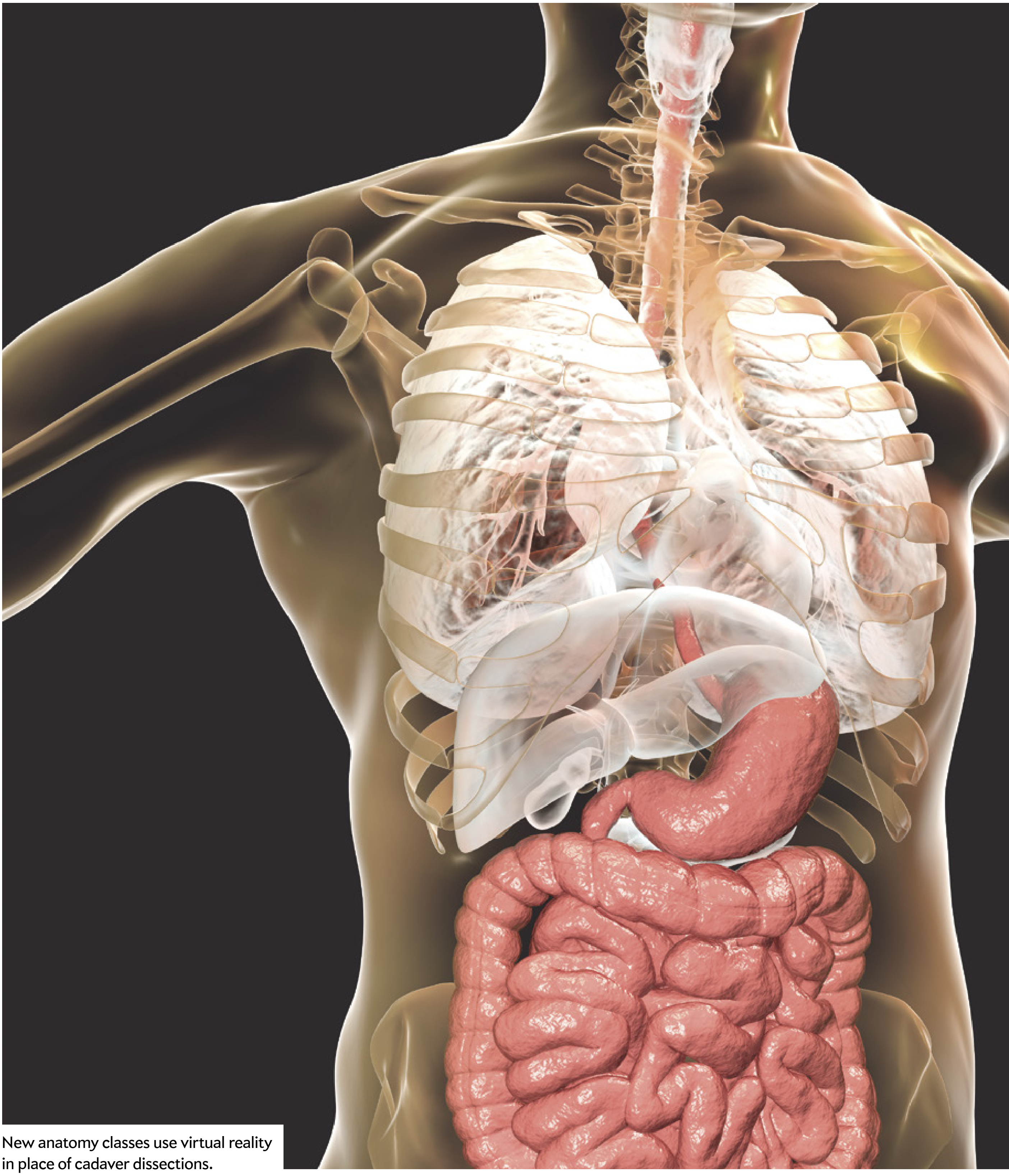
So how do we reverse this alarming trend? First, we must make STEM curricula central to primary and secondary school standards and encourage students to pursue STEM careers. Second, we must rethink our approach to education. Learning should be a lifelong endeavor, not just a K–12 priority. Businesses laying the groundwork for disruptive operational change via automation, AI and other means must also prepare to retrain their workers and give them the technical skills needed for the company's next generation of jobs.

Finally, immigration reform can ensure that those who enter the U.S. for a STEM education receive incentives to stay and contribute to our economy. Immigration reform would allow our labor market to draw on the best minds available, adding much needed dynamism and innovation to our economy. Many issues are driving the policy conversations this election cycle, but the one that could make the most substantial difference to our future has been shockingly ignored for years by presidential candidates, the media and policy makers. Implementing these reforms could be necessary to strengthen our nation's economic standing, but no 2020 presidential candidate has made tackling the STEM skills gap a priority. A greater focus on STEM education could reverse troubling trends that are threatening to take the U.S. out of the race for tomorrow's innovations. SA

JOIN THE CONVERSATION ONLINE
Visit *Scientific American* on Facebook and Twitter or send a letter to the editor: editors@sciam.com

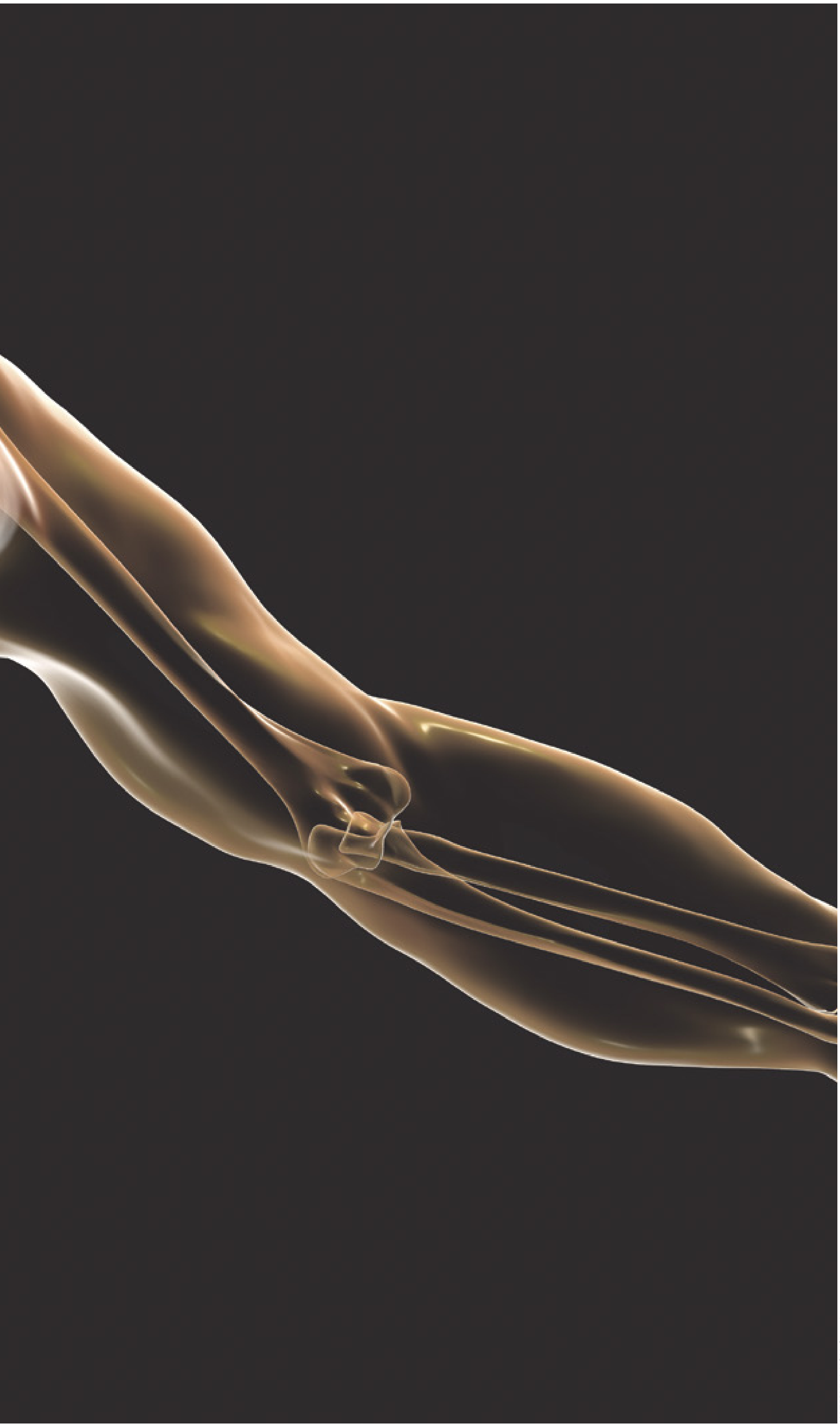
Illustration by Deborah Lee

ADVANCES



New anatomy classes use virtual reality in place of cadaver dissections.

INSIDE



KATERYNA KON *Getty Images*

MEDICAL EDUCATION

Disappearing Bodies

Simulations will replace traditional cadaver dissections in some medical schools

In 1231 Frederick II, the Holy Roman Emperor who ruled over much of Europe, issued a decree requiring schools that trained doctors to hold a human body dissection once every five years. It was a slow debut for what would become a cornerstone of medical education. During the Renaissance, cadaver dissections helped scientists and artists gain a hands-on understanding of human anatomy. Today they are an essential experience for first-year medical students, a time-honored initiation into the secrets of our flesh.

Now, nearly a millennium after its measured introduction, cadaver dissection may have begun an equally slow exit. This year a few U.S. medical schools will offer their anatomy curriculum without any cadavers. Instead their students will probe the human body using three-dimensional renderings in virtual reality, combined with physical replicas of the organs and real patient medical images such as ultrasound and CT scans.

The program developers hope technology can improve on some of the limitations of traditional approaches. It takes a long time to dissect cadavers, and some body parts are so inaccessible that they may be destroyed in the process. Plus, the textures and colors of an embalmed cadaver's organs do not match those of a living body, and donated bodies tend to be old and diseased. "If you want to be truthful about anatomy education, it hasn't changed much since the Renaissance," says James Young, chief aca-

demic officer of the Cleveland Clinic Lerner College of Medicine, a program in collaboration with Case Western Reserve University that opened a new cadaverless campus this summer. "But as technology advanced and as knowledge increased, there came a push to do things better and faster and give students a more appropriate representation of human anatomy."

Young, who studied medicine in the 1970s, experienced a "massive disconnect" between his own anatomy education and what he saw during clinical training in cardiology. When he tried to access organs in living patients, looking at imaging results or footage from tiny inserted cameras, he found the inside of human bodies did not match what he had seen in cadavers. "They're totally different," Young says. "The embalmed cadaver has a very flat, compressed organ presentation. The colors are not the vibrant colors of a living human." The difference can distract from learning, he says.

Virtual anatomy tools, in contrast, provide a more faithful view of living organs, helping students form a foundational understanding of the body's structures, Young and other medical educators say. By donning VR headsets or augmented-reality goggles, which show digital imagery superimposed on the real world, students can examine an organ from all angles. They can connect structure with function by watching a beating heart or moving joints. They can also select views that add other organs or the entire circulatory and nervous systems to better see relations among structures. "I was amazed," says Mark Schuster, dean of Kaiser Permanente School of Medicine in Pasadena, Calif., which will welcome its first class of medical students in 2020. "I wished I had that when I'd been learning anatomy. It really helped make it all come together." His program's first-year students will have a cadaverless curriculum.

Adopting high-tech alternatives makes sense for brand-new medical programs that have neither the tradition nor the facilities for cadaver dissection, but even some existing ones are adopting digital tools to supplement their anatomy courses. "The big advantage I see is that the visuals are very clean," says Darren Hoffman, an assistant professor of anatomy and cell biology, who uses interactive 3-D anatomy software in his courses at the University of Iowa Carver College of Medicine. "That helps building your 3-D mind's eye of the body, so that when you look at a patient's ankle, you know what's underneath the surface and how it's all related."

Besides the educational advantages, going cadaverless is an economic decision for new programs. It costs several million dollars to build a cadaver laboratory, which requires a lot of space, as well as safety measures that meet legal regulations. And although cadavers are donated, medical schools still pay for preparation, maintenance and, eventually, burial. These costs are an even bigger challenge for schools in less wealthy nations, Young says. What is more, many countries still face a shortage of donations and rely on unclaimed bodies for dissection, according to a 2018 study.

Cadaverless anatomy education has its drawbacks. It may be hard to develop a perception of depth in a virtual body, and students will miss out on seeing bodies' natural anatomical variations, according to Hoffman. Students may also lose the emotional, even philosophical impact of working with a cadaver, commonly seen as a doctor's first patient. "There's a sort of awe and

MATH AND ART

Beautiful Truths

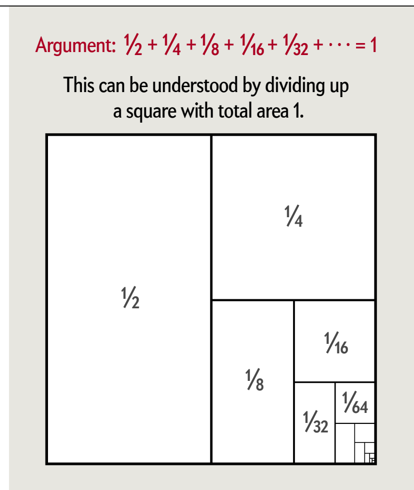
Nonmathematicians agree on what makes proofs pleasing

Scientists and mathematicians often describe facts, theories and proofs as "beautiful," even using aesthetics to help guide their work. Their criteria might seem opaque to nonexperts, but new research finds that novices can consistently assess a proof's beauty or ugliness.

A mathematician and a psychologist analyzed responses from about 200 online participants for each of three experiments in their study, published in August in *Cognition.* Most had attended college but had not studied math beyond university calculus. In each experiment, they read four simple mathematical arguments and were tested for comprehension. (Two included diagrams; see the graphic for an example.)

The subjects rated each argument's "similarity" to each of four landscape paintings, and the results were clearly consistent: people generally agreed on which arguments matched which paintings—and their choices roughly aligned with those made by eight mathematicians. (The argument pictured was most strongly matched to a Yosemite landscape by Albert Bierstadt, seen here.) The second experiment produced a similar result with classical piano music in place of paintings.

For the third experiment, subjects rated the arguments and paintings on 10 adjectives, including "beautiful." Again, results were consistent, and elegance, followed by profundity and clarity, was the biggest factor in judging beauty for both the math and the art. Samuel Johnson, a psychologist at the University of Bath in England, and one of the paper's co-authors, says he was most surprised that those qualities could predict the first group's pairings of ideas and paintings—indicating that the math-



ALAMY (*painting*); SOURCE: "INTUITIONS ABOUT MATHEMATICAL BEAUTY: A CASE STUDY IN THE AESTHETIC EXPERIENCE OF IDEAS," BY SAMUEL G. B. JOHNSON AND STEFAN STEINERBERGER, IN *COGNITION*, VOL. 189; AUGUST 2019 (*mathematical argument*)

Graphic by Jen Christiansen

respect that comes from that," Hoffman says. "You recognize how amazingly cool and intricate the human body is, and you start to realize that everybody on the planet is this amazing—and so am I." Yet the lab is not the only way to forge a student's medical identity, Hoffman and others say. For instance, students could interact with living patients earlier in their studies.

Another open question is whether students learn as well using the digital tools. Educators' studies are probing whether replacing old techniques with new technology will actually improve, and not harm, the quality of their students' education. Their results, if positive, may encourage more schools to convert. "It feels early to call this a trend, but given the sheer number of schools that have shown interest, it feels like something's happening," Schuster says.

Anatomy education has been resistant to change for so long that Young and others see what is happening now as a sign of a possible historic transition. "We're at the beginning of a paradigm shift, no question about that," Young says. "That shift is going to take several years. But if you asked me how is anatomy education going to be done in a decade? It's not going to be done with cadavers. That's my prediction."

—Bahar Gholipour

---

art correspondence was based on something deeper than superficial geometric features.

"It's a very clever study," says Matthew Inglis, a researcher in math education at Loughborough University in England, who was not involved with the work. "I found the results to be quite counterintuitive, albeit very persuasive. Based on my own work"—in which mathematicians disagreed about the quality of proofs—"I would have expected aesthetic judgments in mathematics to be unstable across individuals."

Nathalie Sinclair, a math education researcher at Simon Fraser University in British Columbia, who was also not involved in the study, was surprised as well. "One might have thought that because there is so much fear of mathematics in our culture, people would have thought the questions were absurd," she says.

Stefan Steinerberger, a mathematician at Yale University and a paper co-author, believes educators should highlight the beauty in math. "People have this weird notion of thinking of themselves as incorporeal computing machines," he says. "It's not true."

—Matthew Hutson

NEUROSCIENCE

Depth-Defying Illusion

A common visual correction may distort 3-D motion perception

The lenses in human eyes lose some ability to focus as they age. Monovision—a popular fix for this issue—involves prescription contacts (or glasses) that focus one eye for near-vision tasks such as reading and the other for far-vision tasks such as driving. About 10 million people in the U.S. currently use this form of correction, but a new study finds it may cause a potentially dangerous optical illusion.

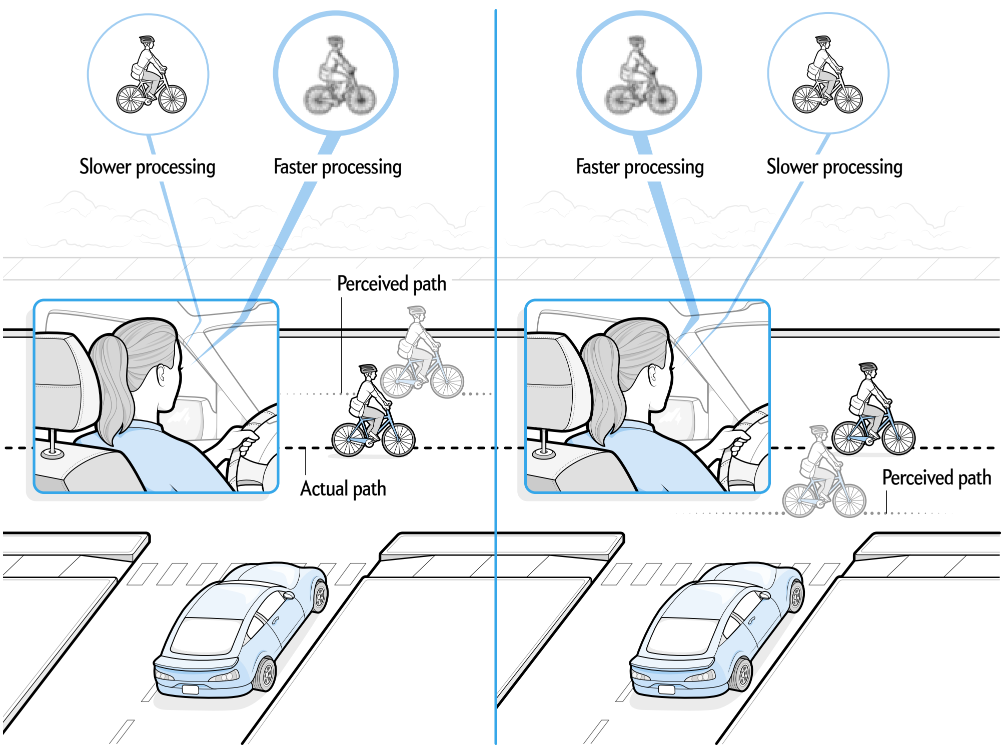
Nearly a century ago German physicist Carl Pulfrich described a visual phenomenon now known as the Pulfrich effect: When one eye sees either a darker or a lower-contrast image than the other, an object moving side to side (such as a pendulum) appears to travel in a three-dimensional arc. This is because the brain processes the darker or lower-contrast image more slowly than the lighter or higher-contrast one, creating a lag the brain perceives as 3-D motion.

Johannes Burge, a psychologist at the University of Pennsylvania, and his colleagues recently found that monovision can cause a reverse Pulfrich effect. They had participants look through a device showing a different image to each eye—one blurry and one in focus—of an object moving side to side. The researchers found that viewers processed the blurrier image a couple of milliseconds faster than the sharper one, making the object seem to arc in front of the display screen. It appeared closer to the viewer as it moved to the right (if the left eye saw the blurry image) or to the left (if the right eye did). "That does not sound like a very big deal," Burge says, but it is enough for a driver at an intersection to misjudge the location of a moving cyclist by about the width of a narrow street lane (*graphic*).

Burge and his colleagues had expected the opposite: that the brain would process the blurry image more slowly because of its lower contrast, similar to the traditional Pulfrich effect. They resolved this paradox by showing that blur reduces the contrast of fine details more than that of coarse ones. Because the brain takes more time to process fine details, the blurry image is processed faster. The researchers published their study in August in *Current Biology.*

Douglas Lanska, a retired University of Wisconsin neurologist who has studied the Pulfrich effect and was not involved in the study, calls the findings "intriguing" but says, "My guess is that the modeling overestimated the real-world impact some." The reverse Pulfrich effect should be tested outside the laboratory, Lanska adds.

Burge and his team found they could correct the effect by tinting the blurrier lens, creating a classic Pulfrich effect that cancels out the reverse one. The brain may also compensate for the limitations of monovision—but further study is needed, Burge says. These misperceptions are rare, he notes, suggesting that "under normal circumstances, our visual systems are exquisitely well calibrated." —*Tanya Lewis*



The Reverse Pulfrich Effect

Monovision, a common visual correction in which a lens in one eye is focused for near vision and the other for far vision, results in one eye forming a blurry image at a given distance. In a phenomenon dubbed the reverse Pulfrich effect, the brain processes the blurry image more quickly than the sharp one, creating an illusion in which a moving object or person (such as a cyclist) appears either farther (*left*) or closer (*right*) than he or she actually is. To err on the side of caution, the far lens could be placed in the right eye in countries where people drive on the right side of the road, and in the left eye where people drive on the left, researchers suggest.

Illustration by Brown Bird Design

IN THE NEWS

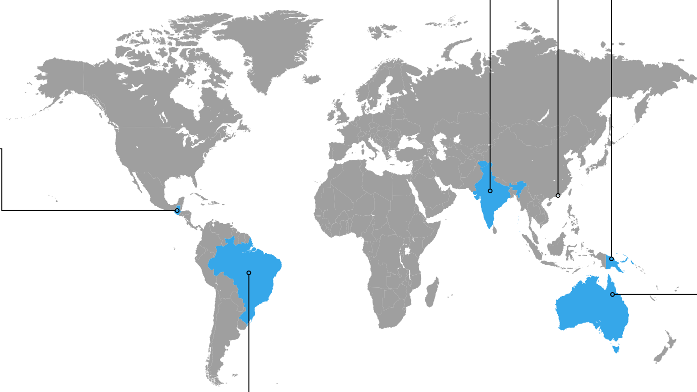
Quick Hits

By Jennifer Leman

INDIA
Wildlife biologists found that adolescent male Asian elephants, usually solitary, are forming large, all-male herds, possibly to help them survive in human-dominated areas.

HONG KONG
Hong Kong's government revealed plans to build an artificial island to alleviate the nation's housing crisis, triggering concerns from activists and residents about nearby marine ecosystems.

PAPUA NEW GUINEA
The government of Papua New Guinea aims to build more than 3,700 miles of road through its rugged landscape by 2022, which a team of scientists cautioned could impact species across the country.



GUATEMALA
Archaeologists studying charred lake sediments found evidence confirming a cryptic historical record saying the ancient Mayan city of Bahlam Jol burned on May 21, A.D. 697. The research suggests it was an act of total warfare, which includes civilian as well as military targets.

AUSTRALIA
Researchers rediscovered two fern species—both thought to be extinct—on the mountaintops of Queensland. *Hymenophyllum whitei* and *Oreogrammitis leonardii* had last been spotted in the wild more than 50 years ago.

BRAZIL
President Jair Bolsonaro fired the head of the Brazilian National Institute of Space Research after the agency reported that deforestation in the Amazon this summer increased significantly from 2018.

For more details, visit www.ScientificAmerican.com/oct2019/advances

ANIMAL BEHAVIOR

Going the Distance

Frog fathers ferry tadpoles past nearby ponds to faraway pools of water

Frog father wearing a radio tracker carries tadpoles.

ANDRIUS PAŠUKONIS *Stanford University*

After poison frog tadpoles hatch from their eggs in the leaf litter, they wriggle onto the backs of their patiently waiting fathers, who piggyback them to water. Scientists studying the candy-colored amphibians, sometimes called poison dart frogs, in the Amazon rain forest recently discovered that frog dads often skip close-by ponds in favor of something more distant—a move that expends precious energy. Sometimes they traveled as far as 400 meters, scientists reported in July in *Evolutionary Ecology*. "It's actually quite the journey," says study author and biologist Andrius Pašukonis of Stanford University.

Pašukonis and his colleagues affixed tiny, diaperlike radio transmitters to the bottoms of seven three-striped poison frogs in Peru and 11 dyeing poison frogs in French Guiana. The researchers used radio signals to chart the frogs' paths on 23 separate journeys, noting each time tadpole-toting fathers passed by water or deposited their young.

Three-striped poison frogs traveled farthest, traversing an average distance of roughly 215 meters—when the nearest available pool was on average only 52 meters away from their home territory. Dyeing dart frogs traveled approximately 39 meters on average, hopping past ponds an average distance of 19 meters away. Two frogs even left the forest's shelter to deposit their tadpoles in flooded pastures.

Despite the energy cost and higher risk of meeting predators, dropping young tadpoles in faraway pools may offer evolutionary benefits such as decreased risk of inbreeding and less competition for resources, Pašukonis says. But it is difficult to say what exactly motivates the frogs themselves to go farther, notes neurobiologist Sabrina Burmeister of the University of North Carolina at Chapel Hill, who studies poison frog cognition but was not involved in the new research.

The findings could help protect amphibians threatened by habitat loss. "Knowing their ranges, and the types of habitats they utilize and why, would be very important for any type of conservation effort," Burmeister says. —*Jennifer Leman*

PHYSICS

Tiniest Sound

Isolating the phonon could boost quantum computing

Researchers have gained control of the elusive "particle" of sound, the phonon. Although phonons—the smallest units of the vibrational energy that makes up sound waves—are not matter, they can be considered particles the way photons are particles of light. Photons commonly store information in prototype quantum computers, which aim to harness quantum effects to achieve unprecedented processing power. Using sound instead may have advantages, although it would require manipulating phonons on very fine scales.

Until recently, scientists lacked this ability; just detecting an individual phonon destroyed it. Early methods involved converting phonons to electricity in quantum circuits called superconducting qubits. These circuits accept energy in specific amounts; if a phonon's energy matches, the circuit can absorb it—destroying the phonon but giving an energy reading of its presence.

In a new study, scientists at JILA (a collaboration between the National Institute of Standards and Technology and the University of Colorado Boulder) tuned the energy units of their superconducting qubit so phonons would not be destroyed. Instead the phonons sped up the current in the circuit, thanks to a special material that created an electric field in response to vibrations. Experimenters could then detect how much change in current each phonon caused.

"There's been a lot of recent and impressive successes using superconducting qubits to control the quantum states of light. And we were curious—what can you do with sound that you can't with light?" says Lucas Sletten of U.C. Boulder, lead author of the study published in June in *Physical Review X*. One difference is speed: sound travels much slower than light. Sletten and his colleagues took advantage of this to coordinate circuit-phonon interactions that sped up the current. They trapped phonons of particular wavelengths (called modes) between two acoustic "mirrors," which reflect sound, and the relatively long time sound takes to make a round trip allowed the precise coordination. The mirrors were a hair's width apart—similar control of light would require mirrors separated by about 12 meters.

Sound's "slowness" also let the experimenters identify phonons of more than one

mode. Typically, Sletten says, quantum computers increase their capacity through additional superconducting qubits. But having just one qubit process information with multiple modes could achieve the same result.

"This is definitely a milestone," says Yiwen Chu, a physicist at ETH Zurich, who was not involved in the study. Analogous experiments with light were a first step toward much of today's work on quantum computers, she notes.

Similar applications for sound are far off, however: among other things, scientists must find a way to keep phonons alive much longer than they currently can—about 600 nanoseconds. Eventually, though, the research could open new paths forward in quantum computing. —*Leila Sloman*

Illustration by Thomas Fuchs

Livestock lessen fires in the Serengeti-Mara ecosystem.

ECOLOGY

Eating Away Fire

Grazing livestock reduce beneficial blazes in a sub-Saharan region

The African continent has a wide variety of habitat types, but savanna ecosystems cover roughly half. And where there is savanna, there is fire. "It's an important part of the ecology of the system," says University of Liverpool ecologist James R. Probert. Burning allows grasses to dominate by keeping taller shrubs and thorn bushes from encroaching on the landscape. Loss of grasses could push out species such as wildebeest, which are famous for their spectacular annual migration.

A decade ago researchers attributed decreasing fires within Tanzania's Serengeti National Park to the recovery of wildebeest herds following an epidemic of rinderpest, a viral disease. When millions of wildebeest gorge on grass, they remove fuel from the landscape, making fires less frequent and less severe.

But Probert and his colleagues found that even after wildebeest populations had stabilized by the mid-1990s, fires continued to decrease in the savanna-dominated Serengeti-Mara ecosystem straddling the Tanzania-Kenya border (of which the protected Serengeti National Park is just one part). Their analysis of satellite data revealed that the region experienced a 40 percent reduction in wildfires between 2001 and 2014—coinciding with dramatic increases in livestock in the area. They reported their findings in July in the journal *Global Change Biology.*

"If you have lots of herbivores eating the grass, then you have less fire. That's well known," Probert says. "But I don't think anybody had realized the magnitude of the decline in fire and linked it to livestock before."

"This is a really interesting pattern," says University of Guelph biologist John Fryxell, who was not involved in the study. He cautions, however, that 15 years' worth of data is still a fairly small amount of information from which to draw definitive conclusions. "What a short-term correlation like that suggests is there's something interesting here that could provide the grounds for a deeper experimental analysis," he adds. That research could include artificially controlling fire frequency or grazing intensity in certain areas and then monitoring the landscape's response over time.

Probert notes that some of these places are suffering from a kind of "tragedy of the commons," with livestock using up more resources than an area can sustain. He says conservationists might consider working with pastoralists to develop a rotational grazing plan, thereby spreading the animals' impact over time and space. Studies such as Probert's continue to reveal the ways wild places like the Serengeti-Mara are inextricably linked to human activity.

—Jason G. Goldman

JASON J. MULIKITA *Getty Images*

MATERIALS SCIENCE

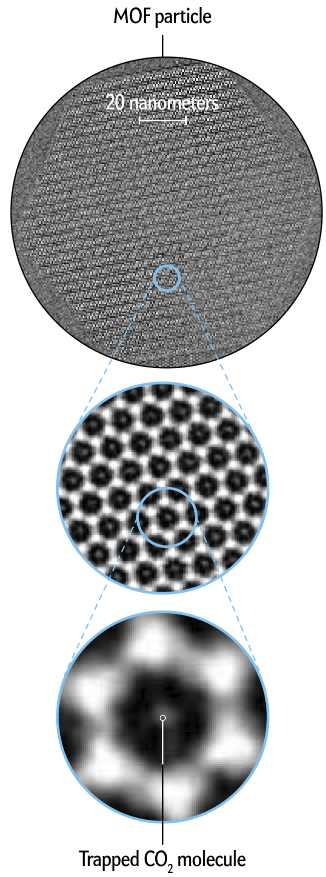
A Molecular Trap

New views reveal single molecules of captured CO_2

For the first time, researchers have obtained images of individual carbon dioxide molecules trapped in a series of molecular "cages"—and they borrowed an imaging technique from biologists to do it. Metal-organic frameworks (MOFs) are exceptionally porous polymers designed to capture particular gas molecules, letting scientists separate or purify various vapors. Even small amounts can slurp up a lot of gas: a single gram can have a gas-grabbing surface area nearly the size of two football fields. MOFs have been proposed for holding hydrogen in automobile tanks or fuel cells (without the need for extra cooling) and for grabbing and storing planet-warming carbon dioxide emissions, among many other uses.

When Yuzhang Li, a materials scientist at Stanford University, and his colleagues examined a sample of a CO_2-trapping MOF with a transmission electron microscope, they found the instrument's powerful electron beam "just melted" the honeycomblike framework, Li says. So the researchers tried an approach that biologists often turn to when imaging delicate proteins, viruses and cell organelles: they used liquid nitrogen to freeze and stabilize the material at a nippy –170 degrees Celsius and also dialed back the strength of their electron beam. This method let them take long-exposure pictures—not only of a slice through the material itself, called ZIF-8 (*top* and *middle*) but of the CO_2 molecules trapped within it (*bottom*). The team reported its results in the August issue of *Matter.*

This flash-freezing process will allow detailed studies of how MOFs trap gas, says Jeffrey Long, a materials chemist at the University of California, Berkeley, who was not involved in the study. For example, Li says, future work might generate 3-D images to investigate how quickly and efficiently the materials pull in gases. *—Sid Perkins*



SOURCE: "CRYO-EM STRUCTURES OF ATOMIC SURFACES AND HOST-GUEST CHEMISTRY IN METAL-ORGANIC FRAMEWORKS," BY YUZHANG LI ET AL., IN *MATTER,* VOL. 1, NO. 2; AUGUST 7, 2019 (*micrographs*)

BIOCHEMISTRY

Venomous Secrets

Synthesized scorpion compounds can help fight dangerous infections

We rarely think of scorpions as beneficial. But researchers have isolated two new compounds in the arachnids' venom that show promise for treating staph infections and drug-resistant tuberculosis.

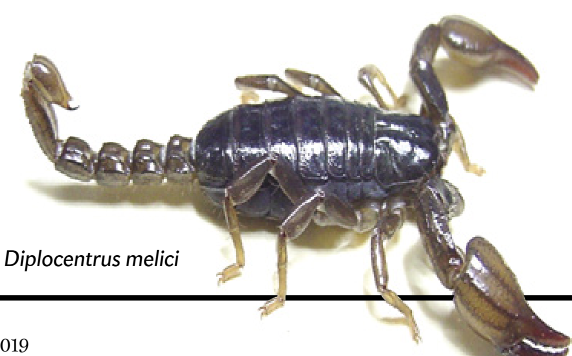
Scorpion venom is beyond expensive: harvesting a milliliter would cost about $10,300, says Richard Zare, a chemist at Stanford University and senior author of a study published in June in the *Proceedings of the National Academy of Sciences USA.* He estimates that "milking" venom from one scorpion can yield only a few thousandths of a milliliter at a time at most, and it takes two or more weeks for an individual's supplies to replenish. The substance can still be worth studying, however. Some of its constituent compounds have intriguing medicinal properties and can be synthesized more cheaply in the laboratory.

Researchers at the National Autonomous University of Mexico milked scorpions of the eastern Mexican species *Diplocentrus melici,* whose venom had never been studied before. They separated its components and tested some on *Staphylococcus aureus, Escherichia coli* and *Mycobacterium tuberculosis* bacteria. Two of these components—one of which happens to be red when isolated and the other blue—killed staph and TB microorganisms, suggesting their potential as antibiotics.

The researchers sent small samples of the isolated compounds to Zare's group at Stanford to determine the substances' compositions and molecular structures. The group then chemically synthesized the compounds and shipped them to the Salvador Zubirán National Institute of Medical Sciences and Nutrition in Mexico City.

There pathologists tested the synthesized substances in mice infected with tuberculosis and on human tissue samples hosting staph bacteria. The red compound proved more effective at killing staph, and the blue one worked better on TB—including a drug-resistant strain—without damaging the lining of the mice's lungs.

Christine Beeton, a molecular physiologist and biophysicist at Baylor College of Medicine, who studies therapeutic uses for venom but was not involved with the new work, says the study's approach seems promising. But she cautions that the compounds still need to be tested in larger animals—and they could also be challenging to synthesize on the scales required for testing in humans. *—Rachel Crowell*



Diplocentrus melici

PABLO BEREA NUNEZ

Graphic by Amanda Montañez

GETTY IMAGES

COSMOLOGY

Tabletop Detector

A mini gravitational-wave detector could probe dark matter

Within one second of the big bang, the first newborn black holes may have announced their formation with gravitational waves that stretched and squeezed the fabric of existence as they rippled outward into the expanding universe. Now researchers at Northwestern University have begun planning a tabletop-size sensor that could detect these primordial howls for the first time.

The gigantic $1-billion Laser Interferometer Gravitational-Wave Observatory (LIGO) first measured the spacetime ripples known as gravitational waves in 2016; these phenomena came from the collision and merging of distant supermassive black holes. Since then, massive detectors have also recorded gravitational waves from merging neutron stars. Northwestern's proposed mini detector, which received an influx of funding in July, could measure higher-frequency waves from objects that have never been measured before—such as black holes in the earliest universe.

Current gravitational-wave detectors such as U.S.-based LIGO and Europe's Virgo use a sprawling system of mirrors and laser "arms" that stretch for kilometers to measure tiny changes in distance caused by passing gravitational waves. Northwestern's Levitated Sensor Detector would use lasers to suspend a glass bead inside a vacuum chamber, creating an extremely force-sensitive sensor with arms just a meter long. It would listen for echoes from the formation of primordial black holes and the activity of theoretical particles called axions, both of which are candidates for mysterious dark matter—hidden materials that may constitute much of the universe's mass and are invisible except for their gravitational presence.

"I think there is more interest in expanding the frequency range in the search for gravitational waves, particularly after the recent exciting LIGO discoveries," says Andrew Geraci, a physicist at Northwestern and principal investigator on the new detector project. "These sources that are dark matter–related are a bit more speculative—the sources that LIGO found were pretty much expected to exist."

To try detecting waves from such sources, the Northwestern project will use $1 million from the W. M. Keck Foundation, a U.S. charitable foundation based in Los Angeles, and additional support from the university. After two years of development, the meter-long prototype would operate for a preliminary year and potentially pave the way for a larger detector that could reach 10 meters in length.

Many researchers question whether anything has the energy to be a strong gravitational-wave source at such high frequencies—above 10 kilohertz—says Rana Adhikari, an experimental physicist at the California Institute of Technology, who is not involved in the levitated sensor project. But he adds that the hypothetical sources linked to dark matter could prove the exception: "We may be surprised by all of the exotica the universe produces in the ultrasonic gravitational-wave regime." —*Jeremy Hsu*

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.*

A Ticking Cancer Time Bomb

Malignancies are on the rise in the most obese generation in history

By Claudia Wallis

Most of us recognize that obesity is not a benign condition. Diabetes, arthritis, plus heart, liver and gallbladder diseases commonly plague folks who carry major excess poundage. Less familiar is the risk of cancer. Being overweight or obese has been linked to at least 13 types of cancer. Obesity more than doubles the risk of the most common forms of uterine and esophageal cancer. It raises the risk of tumors of the colon, gallbladder, kidney, liver, pancreas, upper stomach and brain membranes by 50 to 80 percent compared with adults at a healthy weight, and it ups the odds for multiple myeloma and cancers of the breast, ovary and thyroid.

The danger tends to rise with the number on the scale: extremely obese women, for instance, face seven times the risk of uterine cancer. Obesity also makes it more likely that certain cancers, including breast and prostate, will prove fatal or not respond optimally to treatment. Given that most cancers take decades to develop, one has to wonder what the eventual cancer toll will look like now that nearly 80 percent of American adults and a third of children are overweight or obese—up 60 percent and more than 100 percent, respectively, from 1980.

An analysis released this year by researchers at the American Cancer Society paints an alarming picture. Their study, published in the *Lancet Public Health,* looks at how cancer rates have changed over the past 20 years among younger adults—Americans who came of age during the steepest rise in obesity—compared with older adults. Hyuna Sung and her co-authors examined trends for the 30 most common cancers, 12 of which occur more often in overweight people. Six of those 12—colorectal, gallbladder, kidney, multiple myeloma, pancreatic and uterine—were found to be rising more rapidly in younger Americans (ages 25 to 49). The sharpest jumps—between 2 and 6 percent annually—were in the youngest adults (ages 25 to 35). "This is not negligible," Sung says. "It's a huge and very fast increase."

Trends in young adults can be seen as a "bellwether for future disease burden," Sung notes. She also points to growing evidence that obesity that starts in childhood or adolescence may present a particular risk for some cancers. That said, Sung's study does not address causality and therefore does not prove that the uptick in certain malignancies is a direct consequence of rising obesity.

Other investigators, however, are looking directly at how obesity might promote cancer. Turns out, excess body fat impacts the body in multiple ways that may aid and abet a developing tumor. "The whole hormonal milieu changes dramatically with obesity," says Stephen Hursting, professor of nutrition at the University of North Carolina's Lineberger Comprehensive Cancer Center. The first "big basket" of changes includes a rise in growth factors, including insulin and those that promote blood vessel formation, he explains. A second big basket involves substances that promote inflammation. "The obese state is a kind of smoldering, low but insistent inflammatory state," Hursting says. A third alteration is suppression of the immune responses that fight incipient cancers. And there are other impacts, including obesity-related changes to the microbiome, metabolism and gene expression. Reading Hursting's 2018 review of the many mechanisms linking obesity with cancer was one of the more disturbing things I've done as a health reporter. It made me want to scream at the big food industry, which has done so much to engineer our obesity epidemic.

Screaming is of little use, so the question is: How can we diffuse this time bomb? Clues come from studies of patients who have slimmed down after bariatric surgery and trimmed their cancer rate as well. A study with 88,625 obese women found, for example, that those who underwent such operations had a 50 percent lower rate of postmenopausal breast cancer than those who did not. Newer data suggest the surgery may also lower the risk of virulent "triple-negative" breast cancer in younger obese women.

Whether less drastic measures will do the trick is a hot research topic. At the Dana-Farber Cancer Institute, oncologist Jennifer Ligibel is leading a randomized, controlled trial with 3,136 obese breast cancer patients to see if losing just 7 to 10 percent of their body mass with diet and exercise will lower their risk of cancer recurrence and mortality. That level of weight loss has a big benefit for people with type 2 diabetes, she notes. Results will not be out for a few years, but Ligibel is hopeful: "Wouldn't it be great if we could find a treatment for breast cancer where the side effects are that you have less arthritis and diabetes and you feel better?" SA

Illustration by Celia Krampien

Wade Roush is the host and producer of Soonish, a podcast about technology, culture, curiosity and the future. He is a co-founder of the podcast collective Hub & Spoke and a freelance reporter for print, online and radio outlets, such as *MIT Technology Review,* Xconomy, WBUR and WHYY.

Low-Carbon Air Travel Is Coming

Buy offsets if you want, but for real hope, look to electric planes

By Wade Roush

Back in 2015, I got pretty serious about reducing or offsetting my carbon footprint. I don't have kids, I don't own a car and I don't eat meat, so I already had three of the biggies covered. To make up for my electricity use, I started buying credits from a nonprofit that funds wind turbines and other renewable energy projects in New England. Then it was time to examine my habit of boarding kerosene-fueled jet aircraft.

An online calculator showed that the flights I take every year put a yikes-inducing 15 metric tons of carbon into the atmosphere—equivalent to the overall annual carbon emissions of *three* average earthlings. So I signed up with a company called Terrapass to buy offsets for 12 tons of carbon a year, at about $10 per month. Terrapass uses that money to do commendable things such as capturing methane from landfills, building wind farms and preserving carbon-sequestering forests.

I'm not under the illusion that these projects cleanse my sins as an air traveler. At best, they simply prevent the release of an equal quantity of greenhouse gases down the road. The offsets do help me and other consumers feel less guilty about flying—which is probably why airlines such as United and Delta now offer them as part of the booking process. And on a larger scale, there's evidence that offsets function as a kind of self-imposed carbon tax, encouraging people who buy them to keep their own energy use in check. But the reality is that voluntary offsets will never come close to matching aviation emissions, which account for 2 percent of overall human-induced carbon emissions.

For one thing, any benefit from offsets is likely to be overwhelmed by growing demand for air travel. According to a recent report from Airbus, about 40 percent of the world population is now middle class, and by 2037 this group will have mushroomed to more than 50 percent, or some five billion people—"all in the pool of regular or potential new" passengers.

And buying an offset isn't a guarantee that your flight emissions will actually be, you know, offset, since it's difficult to prove that carbon-avoidance projects wouldn't have happened anyway or that the neutralized carbon will never be released in the future. And critics say offsets can be an excuse for inaction. Australian engineer and author Sharon Beder has called them "a greenwashing mechanism that enables individuals to buy themselves green credentials without actually changing their consumption habits."

Regardless of their relation to consumer trends, offsets aren't a solution to the underlying physics problem in aviation, which is that today's long-haul passenger jets can't take off without burning a high-energy-content fuel such as kerosene. That's why OPEC is confident that worldwide demand for jet fuel will reach nine million barrels a day by 2040, up from 6.3 million in 2017.

Short of drastic rationing of air travel, the only long-term solution for aviation's carbon woes is electrification. Biofuels from feedstocks such as sugarcane, algae and household garbage, which burn more cleanly than fossil fuels, could help in the short run—United has been mixing them into traditional jet fuel since 2016. But the real hope lies in projects such as E-Fan X, a test plane from Airbus, Rolls-Royce and Siemens in which one of the four gas-powered turbofans is replaced by an electric motor. The partners see the project as a step toward meeting the European Union's ambitious "Flightpath 2050" goal of reducing aviation's carbon dioxide emissions by 75 percent by 2050.

Start-ups are getting into the game, too: Seattle's Zunum Aero, backed by Boeing and JetBlue, is designing a regional jet with batteries in the wings and fans powered with a "hybrid to electric" power train. To be light enough for flight, aviation batteries will need a specific energy—a measure of how much power a battery contains for its weight—far beyond that of today's lithium-ion battery packs. So, for the time being, Zunum's power train will run partly on jet fuel.

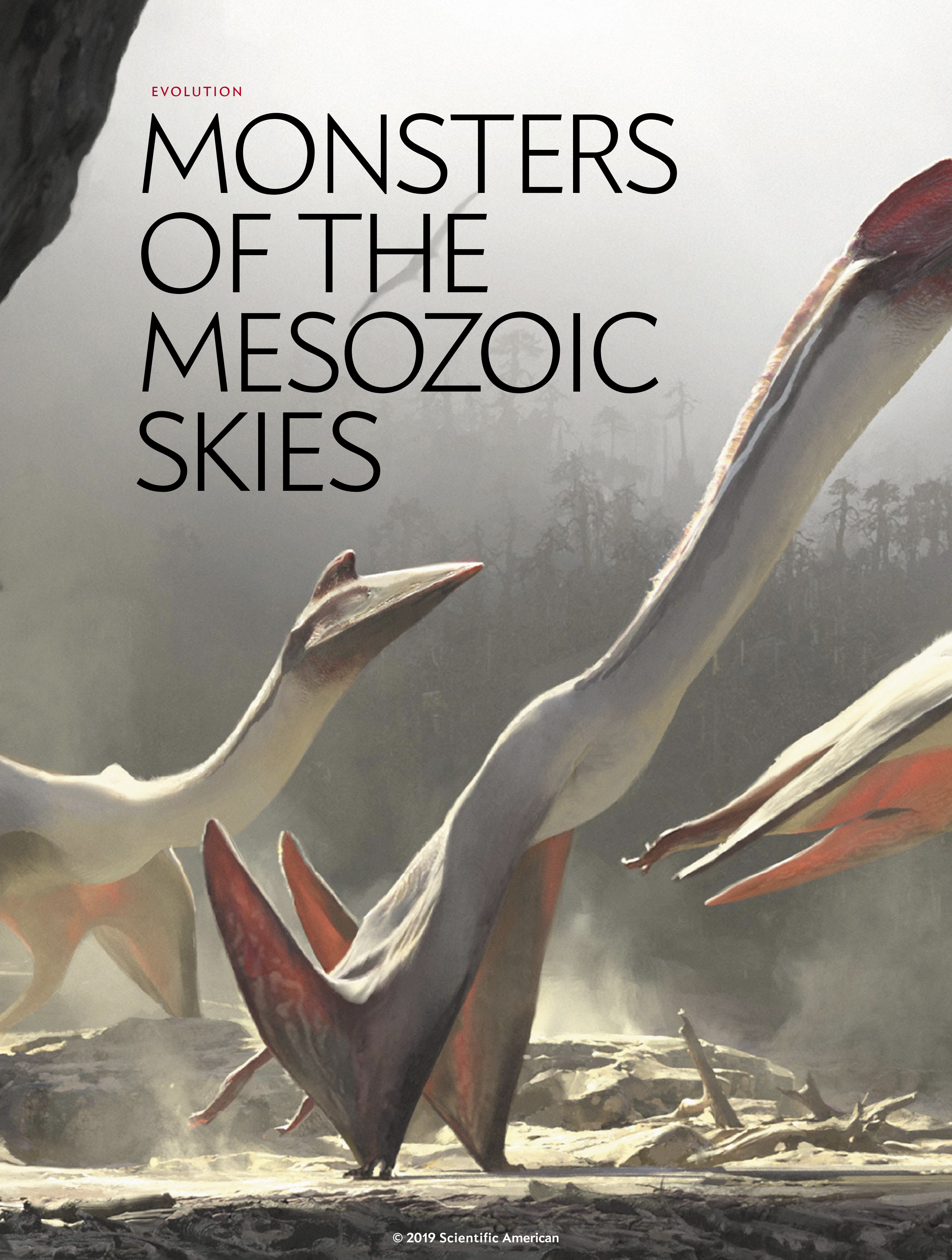
The improvements in batteries and motors needed to fully electrify the skies could take "the next few decades," Zunum cofounder B. Matthew Knapp acknowledged in a recent *Nature Sustainability* op-ed. Meanwhile buying offsets is a substitute that both feels good and does good. Just don't assume that it will keep our climate-spoiling travel habits aloft forever. SA

JOIN THE CONVERSATION ONLINE
Visit *Scientific American* on Facebook and Twitter
or send a letter to the editor: editors@sciam.com

Illustration by Jay Bendt

EVOLUTION

MONSTERS OF THE MESOZOIC SKIES



Fossils and mathematical modeling are helping to answer long-standing questions about pterosaurs

By Michael B. Habib

Illustration by Chase Stone

Michael B. Habib is a paleontologist and biomechanist at the University of Southern California. He studies the anatomy and motion of pterosaurs, birds and feathered dinosaurs.

THE MESOZOIC ERA, WHICH SPANNED THE TIME FROM 251 MILLION TO 66 MILLION YEARS AGO, is often referred to as the age of dinosaurs. But although dinosaurs reigned supreme on land back then, they did not rule the air. Instead the skies were the dominion of an entirely different group of beasts: the pterosaurs.

IN BRIEF

Pterosaurs were the first vertebrate animals to evolve powered flight—nearly 80 million years before birds.

Over their long reign they evolved some of the most extreme adaptations of any animal.

New fossils and mathematical modeling are finally producing answers to long-standing questions about how they lived—and why they eventually went extinct, allowing birds to take over the aerial realm.

Pterosaurs were the first vertebrate creatures to evolve powered flight and conquer the air—long before birds took wing. They prevailed for more than 160 million years before vanishing along with the nonbird dinosaurs at the end of the Cretaceous period, around 66 million years ago. In that time, they evolved some of the most extreme anatomical adaptations of any animal, living or extinct. The smallest of these aerial predators was the size of a sparrow. The largest had a wingspan that rivaled that of an F-16 fighter jet. Many possessed heads larger than their bodies, making them, in essence, flying jaws of death. Pterosaurs patrolled every ocean and continent on Earth. No animal in the Mesozoic would have been safe from their gaze.

Unlike dinosaurs, which are survived today by birds, pterosaurs left behind no living descendants. As a result, all that paleontologists know about pterosaurs comes from the fossil record. And that record has been frustratingly fragmentary, leaving us with just a glimmer of their former glory and a host of questions about their bizarre anatomy and ill fate. Paleontologists have scratched their heads over these mysteries for decades. Now new fossil discoveries, combined with mathematical modeling methods in which anatomical structures are simplified just enough that equations of physical properties can be applied to get best estimates of strength, weight, speed, and so forth, are finally generating insights. And what scientists are finding is that pterosaurs were even more extraordinary than we ever imagined.

WINGED LEVIATHANS

ONE OF THE ENDURING MYSTERIES of pterosaurs is how the largest members of this group became airborne. Giants such as *Quetzalcoatlus,* first discovered in Texas, and *Hatzegopteryx,* from modern-day Romania, stood as tall as a giraffe and had wingspans of more than 30 feet. These animals possessed jaws twice the length of those belonging to *Tyrannosaurus rex.* Their upper arms would have been nearly as large around as the torso of an average-sized adult human. They were true behemoths, attaining weights exceeding 650 pounds. For comparison, the largest bird to ever take to the air—*Argentavis,* living six million years ago in Argentina—most likely weighed less than 165 pounds.

The discrepancy between the biggest members of each of these groups is so vast, in fact, that multiple researchers have suggested that the largest pterosaurs could not fly at all (although this would be puzzling given their many anatomical adaptations for flight). Others have suggested that they could fly but only under very special air and surface conditions—if the atmosphere in their day were denser than it is today, for instance. After all, it seems unfathomable that birds of such sizes could fly. In fact, recent power-scaling studies from several researchers, including me, have demonstrated that supersized birds would have insufficient power to launch themselves into the air in the first place.

But pterosaurs were not birds. Indeed, over the past decade my colleagues and I have carried out numerous calculations of pterosaur launch and flight power, showing not only that giant pterosaurs could launch and fly but also that they probably did not need any special circumstances to do so. In line with these conclusions, we now know from geochemical analyses of sedimentary rocks and microanatomical analyses of plant fossils that air and surface conditions in the Late Cretaceous—the heyday of enormous pterosaurs—were not remarkably different from what we experience today. What was different, and unique, was the anatomy of pterosaurs.

There are three things that an animal needs to be able to fly at gigantic sizes. The first is a skeleton with a very high ratio of strength to weight, which translates to a skeleton with large volume but low density. Pterosaurs and birds both have such skeletons: many of their bones are quite hollow. The walls of the upper arm bone of *Quetzalcoatlus,* for example, were about 0.12 inch thick—comparable to an ostrich eggshell—yet the bone had a diameter of more than 10.5 inches at the elbow.

The second thing that a giant flier needs is a high maximum lift coefficient. This number describes how much lift the wings produce for a given speed and wing area. At a high lift coefficient, an animal can be heavier because its wings will support more weight at a lower speed. This relation, in turn, means the creature needs less speed on takeoff, which makes a huge difference in the muscle power required for launch. Membrane wings, such as those of pterosaurs and bats, produce more lift per unit speed and area than the feathered wings of birds. This additional lift improves slow-speed maneuvering capability, which for small animals helps with making tighter turns and for big animals facilitates takeoff and landing.

The third and most important prerequisite is launch power. Even with very efficient, large wings, a big flier still needs to produce lots of leaping power to become airborne. Flying animals do not flap their way into the air or use gravity to take off from an elevated location such as a cliff. Wings do not produce much lift at low speeds, and gravity launching would mean trying to take off by accelerating in the wrong direction—a dangerous prospect. Instead, a powerful jump provides critical speed and height to begin flight. Increased leaping power yields better launching power. Large fliers therefore need to be good jumpers.

Many birds can manage impressive leaps. They are constrained by their heritage as theropod dinosaurs, however: like their theropod ancestors, all birds are bipedal, meaning they have only their hind limbs to use for jumping. Pterosaurs, in contrast, were quadrupedal on the ground. Their wings folded up and served as walking, and therefore jumping, limbs. Numerous exquisitely preserved fossil trackways confirm this odd aspect of pterosaur anatomy. Being quadrupedal drastically changes the maximum size of a flying animal. Pterosaurs could use not only their hind limbs for launch but also their much larger forelimbs, thereby more than doubling the available power for takeoff. They had the perfect combination of adaptations to become aerial behemoths.

Previous studies have modeled bipedal launches for giant pterosaurs. For example, in 2004 Sankar Chatterjee of Texas Tech University and his colleague worked out how *Quetzalcoatlus* could propel itself into the air using only its hind limbs. But the researchers determined that for that approach to work, the animal could not weigh more than 165 pounds and had to run downhill into a headwind. The quadrupedal launch allows for more realistic body weight and less restrictive environmental conditions.

HEAVY-HEADED

ALTHOUGH THE GREAT MYSTERY of overall pterosaur size may finally be largely resolved, the relative sizes of their body parts continue to vex researchers. The proportions of pterosaurs are downright bizarre. All pterosaurs had oddly proportioned limb elements. Their hands, for example, are probably the most specialized in all of the vertebrate world, with an immense fourth finger that supported the wing. Yet this is not especially surprising in and of itself because that unusual hand was intrinsic to the pterosaur wing and the animal's ability to fly. What really confuses scientists and enthusiasts alike is not the wings of pterosaurs but the heads.

Even early pterosaurs had decidedly large noggins. The head on *Rhamphorhynchus,* a representative species from 150 million years ago, in the Late Jurassic period, was nearly as long as its body. Then in the Cretaceous head size got even more extreme. Fossils of species such as *Quetzalcoatlus,* as well as *Anhanguera* from Brazil, show that pterosaurs got bigger on average, but their heads became proportionately gigantic. The skull on a rather typical Cretaceous pterosaur might be two or even three times the body length (usually taken as the distance between the shoulder and hip). Some had skulls surpassing four times the length of their bodies. The braincases on these animals were not terribly large, though. It is mainly the faces and jaws that expanded to an outrageous degree. Bony flanges under the jaw, towering crests atop the cranium and other elaborations further exaggerated pterosaur skull anatomy. In all, the head could almost seem like it was from a different animal than the body.

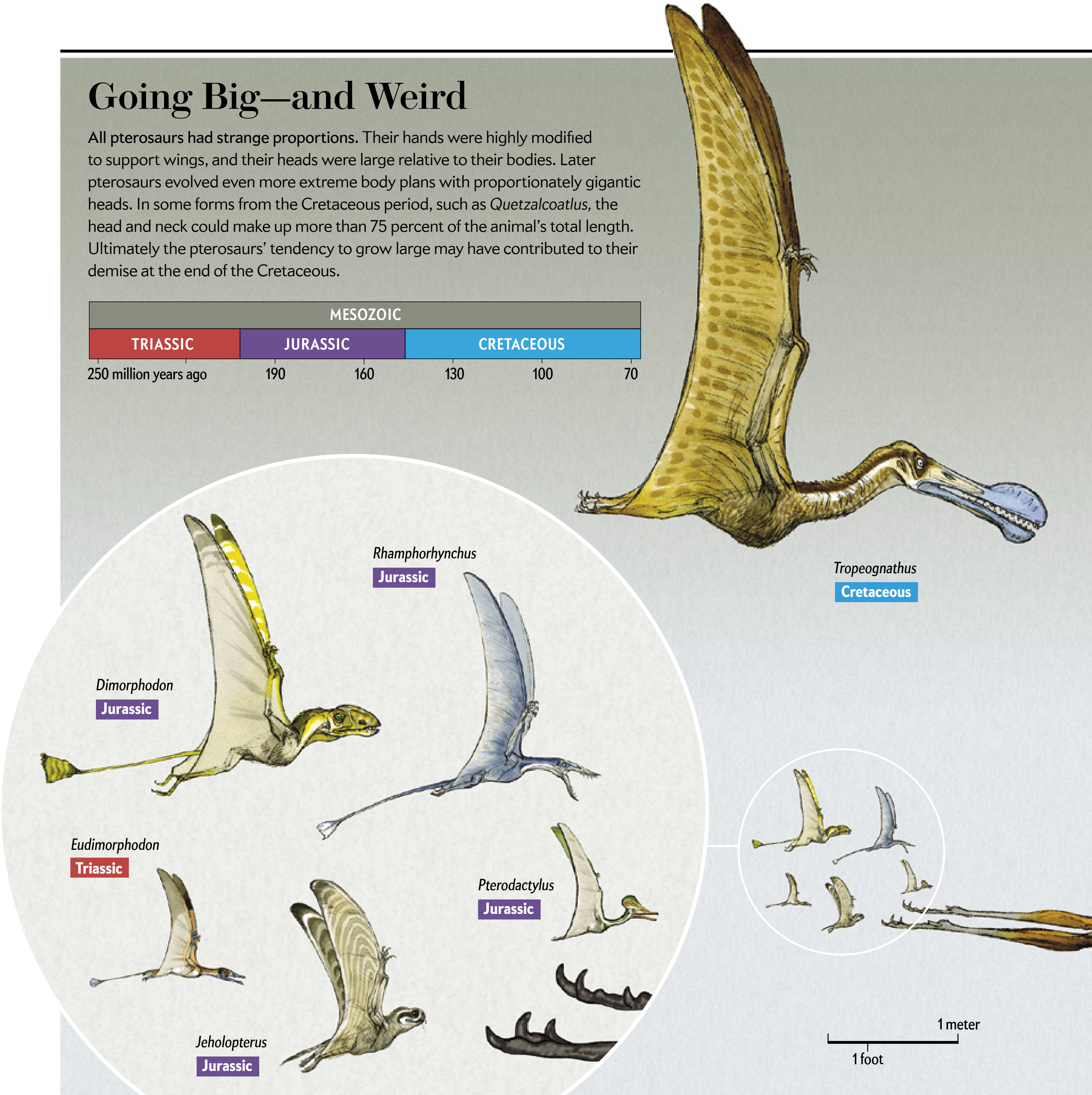
Why would any animal be so ridiculously proportioned?

The oddities do not end there. Whereas in most animals, including humans, the bones of the neck are among the smallest in the spine, the neck vertebrae in pterosaur specimens are often the largest. In fact, the neck vertebrae are often twice the volume of the vertebrae in the torso. One of the newest additions to the pterosaur family tree offers a great example of this trend. David Hone of Queen Mary University of London, François Therrien of the Royal Tyrrell Museum in Alberta, Canada, and I will soon unveil fossils from this species, found in Alberta, in a paper in press at the *Journal of Vertebrate Paleontology.* We have given it a name that means "frozen dragon of the north," which is officially a reference to where it was found but reflects personal inspiration by the *Game of Thrones* dragon Viserion. It has neck vertebrae that are nearly as long and twice as strong as its humerus, the wing bone to which most of the flight muscles attach and that does most of the work to keep the animal up in the air. In some species the neck is triple the length of the torso, with the head size triple again, such that the head and neck could make up more than 75 percent of the total length of the pterosaur. Why would any animal be so ridiculously proportioned? And how could such a body plan possibly work for a flying creature?

Specialists are still working out why pterosaurs ended up with such crazy anatomy, but one probable explanation is what I call

Going Big—and Weird

All pterosaurs had strange proportions. Their hands were highly modified to support wings, and their heads were large relative to their bodies. Later pterosaurs evolved even more extreme body plans with proportionately gigantic heads. In some forms from the Cretaceous period, such as *Quetzalcoatlus*, the head and neck could make up more than 75 percent of the animal's total length. Ultimately the pterosaurs' tendency to grow large may have contributed to their demise at the end of the Cretaceous.

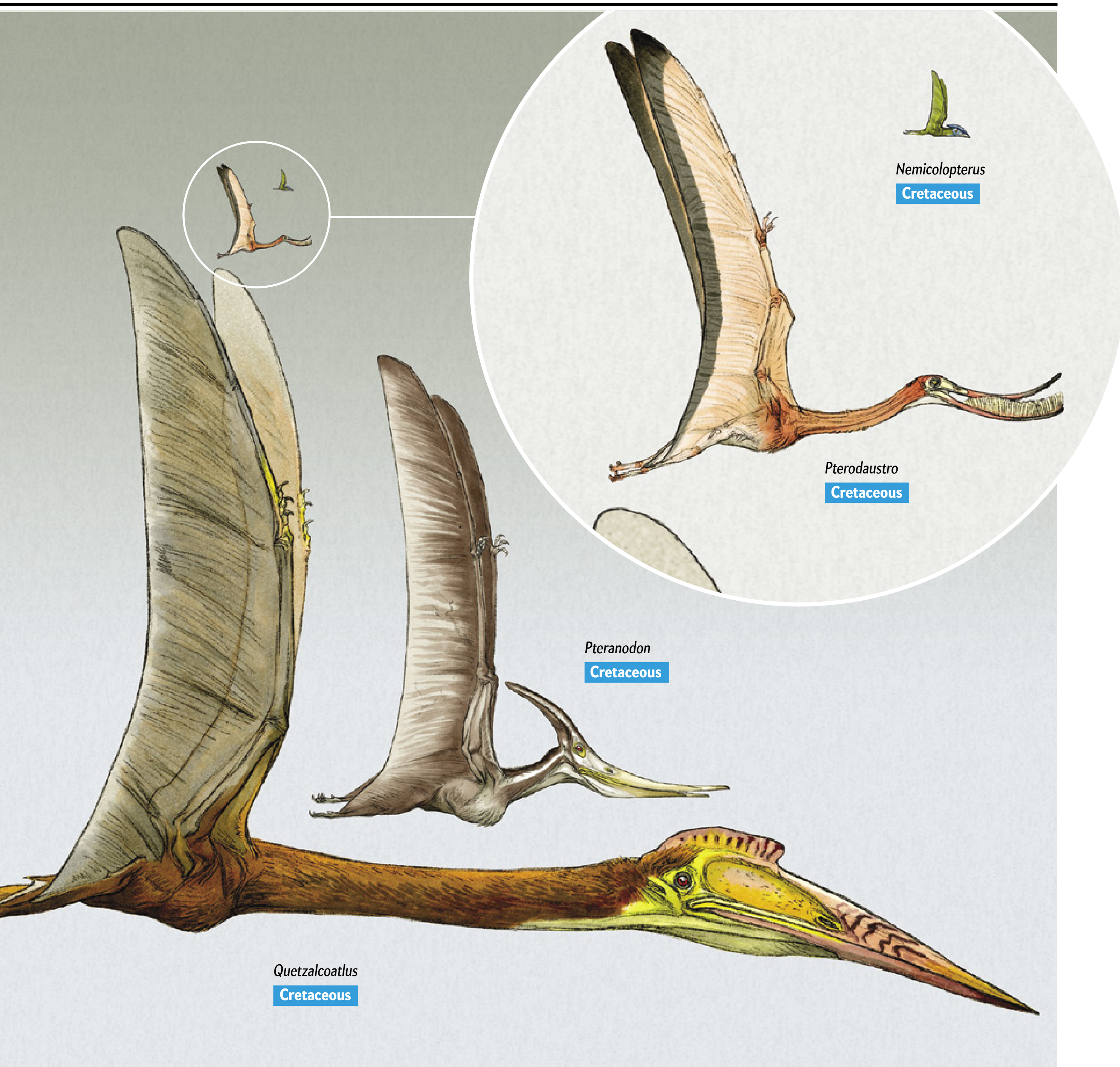


SOURCE: *FLYING MONSTERS*, DESIGN STUDIO PRESS

the "if it were easy, everyone would do it" hypothesis. In short, having a big set of jaws to eat with and a big face with which to signal to mates and rivals might be a great option for a lot of animals if the costs associated with these traits were not normally so prohibitive. For example, mammals have big braincases, so mammal heads become very heavy as they grow larger in overall dimensions. Pterosaurs might have stumbled into a developmental zone where the proportions of the face were less coupled to those of the back of the skull. This would have allowed them to evolve a giant set of jaws without having a huge braincase.

Pterosaurs also had extra openings in their skulls, the largest of which was an opening in front of the eyes known as an antorbital fenestra. Dinosaurs had this opening, too, but pterosaurs took it further, in some cases evolving an opening so large that the torso skeleton could have fit inside it. This opening would have been covered with skin and other tissues in life and probably would not have been visually obvious, but it made the skull quite light relative to its volume. The bones of the skull might

Illustration by Terryl Whitlatch



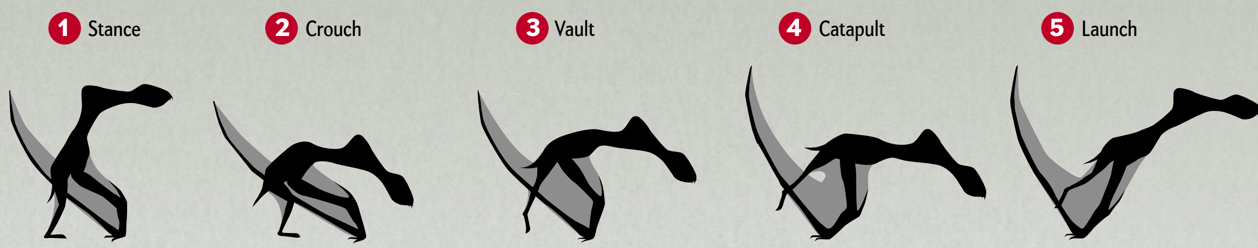
also have had large air spaces within them, similar to the air-filled skull bones of some living birds.

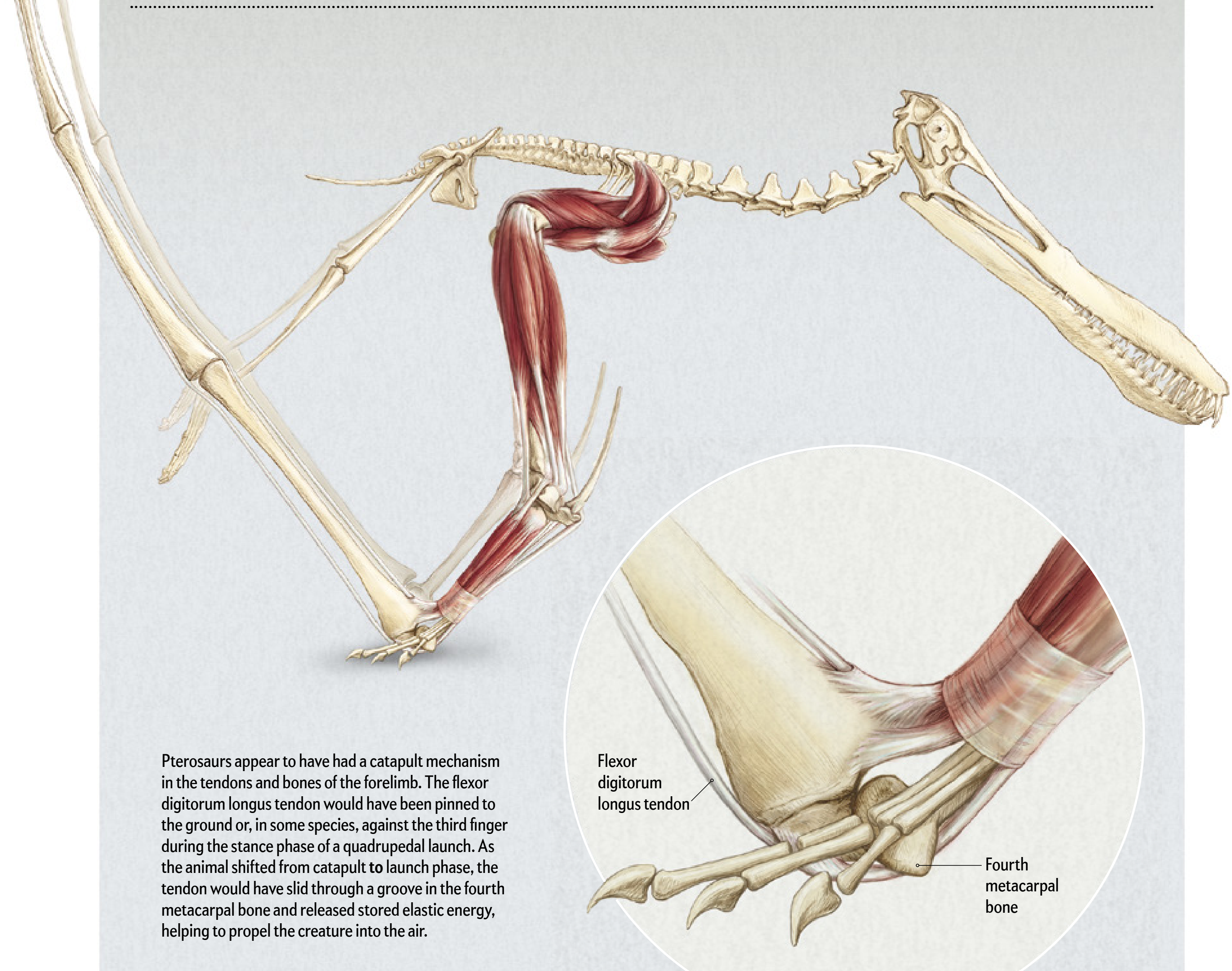
Even with these weight-saving features, however, pterosaurs' heads were often so colossal that they still would have been quite heavy. Perhaps counterintuitively, the fact that they were flying animals may have worked in their favor in this regard. The main problem with a heavy head is not the overall increase in body weight. Rather it is the disproportionate effect that the skull weight has on the animal's center of gravity. A huge head, especially if mounted on a huge neck, moves the center of gravity quite far forward. For a typical walking animal, this creates a serious problem with gait: the forelimbs have to move into an awkward forward position for the animal to be balanced. But pterosaurs had enormous forelimbs purpose-built for flight.

Gait reconstructions by Kevin Padian of the University of California, Berkeley, have shown that when a pterosaur was walking, those forelimbs were positioned just about right to take up the weight of the head, neck and chest. Most of the propulsion dur-

Up and Away

The largest pterosaurs had clear adaptations to flight but probably weighed upward of 600 pounds—far more than the largest known flying birds. How did such behemoths become airborne? Unlike birds, which walk and jump into the air using only their hind limbs, pterosaurs walked on all fours, as evidenced from fossil trackways. Mathematical modeling indicates that launching from a quadrupedal stance—pushing off first with the hind limbs and then with the forelimbs—would have provided the leaping power that giant pterosaurs required for takeoff. Unlike a bipedal launch, a quadrupedal launch would have leveraged the powerful flight muscles and a catapult mechanism in the forelimb.





Pterosaurs appear to have had a catapult mechanism in the tendons and bones of the forelimb. The flexor digitorum longus tendon would have been pinned to the ground or, in some species, against the third finger during the stance phase of a quadrupedal launch. As the animal shifted from catapult **to** launch phase, the tendon would have slid through a groove in the fourth metacarpal bone and released stored elastic energy, helping to propel the creature into the air.

Illustration by Julia Molnar

ing walking came from the legs, so pterosaurs could hold the weight of their hefty heads on their extrabulky arms and push themselves along with their much more normal-sized hind limbs. Imagine using crutches to walk while minimizing the weight on both legs—you would advance both crutches simultaneously and let them bear all your weight, then swing your legs forward between them, touch down and repeat. This is what the gait would have looked like for the longest-armed pterosaurs. (During takeoff, incidentally, the legs would have pushed first, followed by the arms, for a perfect one-two push-off.)

This arrangement would not have made for the most efficient walking gait, but it was doable. And anyway, pterosaurs traveled primarily by flying. Pterosaur species with especially long, narrow wings, like those of some modern seabirds, might have flown continuously for months or even years, touching down only to mate or lay their eggs. The pterosaur *Nyctosaurus* may have had the most efficient wings—and thus the longest continuous soaring flight—of any vertebrate animal ever.

In the air, the center-of-gravity problem becomes much easier to deal with. For an animal to be stable in the air, its center of lift and center of gravity must be in alignment. This might seem like a difficult prospect for a creature with a supersized head and a correspondingly forward center of gravity. But a pterosaur's center of lift was close to the front of a wing, which means that the animal needed only to angle its wings moderately forward from the root to align the center of lift with the center of gravity, as Colin Palmer of the University of Bristol in England and his colleagues were first to point out. Forward-swept wings can themselves be sources of instability, but the flexibility of pterosaur wings and the rapid cerebellar reflexes that all vertebrate creatures possess could have compensated for it.

Stability challenges aside, forward-swept wings can offer some serious benefits. One is that their tips tend to be the last part of the wing to stall. During a stall, which typically occurs at low speed, the wing suddenly loses much of its lift. Tip stall is especially catastrophic because it quickly disrupts the wake of the wing, severely compromising thrust and control, and sharply increasing drag. The ability to delay that loss of lift makes landing and takeoff much gentler, which is important for big animals. In this sense, a giant head could actually be advantageous for a large flying animal with flexible wings: it moves the center of gravity forward, which moves the wing sweep forward, which makes it harder to stall the wing, which means the animal can fly more slowly and grow larger.

DEATH OF A DYNASTY

PTEROSAURS were the only vertebrates with powered flight for about 80 million years. Then around 150 million years ago, in the Jurassic period, a second group of backboned animals started to take wing: feathered dinosaurs. This group included four-winged creatures such as *Microraptor* and *Anchiornis,* as well as the most accomplished fliers of the bunch: birds. By the Early Cretaceous, a wide variety of birds shared the skies with pterosaurs. Despite this shakeup in the aerial niche, pterosaurs continued to dominate among the medium to large fliers, particularly in open habitats. Birds were mainly restricted to vegetated areas where their small body size and agility were advantageous. Pterosaurs were thus able to maintain supremacy as the rulers of the open sky.

But when an asteroid crashed into Earth 66 million years ago, killing all the nonavian dinosaurs, the pterosaurs' reign also came to a close. Paleontological discoveries so far indicate that not a single pterosaur species made it across the End Cretaceous boundary; they all perished, as did the majority of birds. Only one lineage—the neornithines, or "new birds"—made it through. (Nevertheless, that single lineage was enough. It went on to produce thousands on thousands of new species, and today neornithine birds represent the second-largest group of vertebrates, behind only the bony fish, with more than 12,000 recognized species.)

Why did pterosaurs suffer a fate worse than that of the birds at the end of the Cretaceous? One reason might be their tendency to grow large. Hardly any land animals with an adult body mass of more than 44 pounds survived that apocalyptic time. And being not only large but also volant might have been particularly costly, because big fliers tend to rely on soaring flight for much of their travel. Soaring is dependent on the right weather conditions. When the asteroid struck, it vaporized part of Earth's crust, along with much of itself, and the reentry of this superenergized rock-metal cloud essentially set the sky on fire around the world. Soaring experts such as Jim Cunningham, an independent industry engineer with decades of experience with aircraft design, have pointed out that global soaring conditions might well have been ruined for a month after the impact—enough time to starve every pterosaur that needed to soar to eat.

Clearly, just being a small flier did not cut it either, given that most birds perished as well. The ones that survived might have been able to eat foods that could withstand a nuclear-style winter, such as seeds. They might also have been able to burrow out of harm's way, just as many modern-day birds do. Pterosaurs do not seem to have been seed specialists, nor do they appear to have been capable of burrowing. And why should they have been? A dinosaur-munching, 14-foot-tall, flying monstrosity does not need to dig its way out of danger—it *is* the danger.

Although it ends with extinction, the story of pterosaurs is one of success: they were the ultimate aerial giants, having evolved a dazzling array of extraordinary anatomical features not seen in any other group before or since. From them we have learned much about the limits of animal form and function. Those lessons help us understand the history of Earth and the complexity of ecology. They are even inspiring new technologies, including novel aircraft designs. Their fossil record is a thrilling window into a bygone world filled with real flying monsters. Pterosaurs were not just extreme—they were exceptional. SA

MORE TO EXPLORE

On the Size and Flight Diversity of Giant Pterosaurs, the Use of Birds as Pterosaur Analogues and Comments on Pterosaur Flightlessness. Mark P. Witton and Michael B. Habib in *PLOS ONE,* Vol. 5, No. 11, Article No. e13982; November 2010.

The Wingtips of the Pterosaurs: Anatomy, Aeronautical Function and Ecological Implications. David W. E. Hone, Matt K. Van Rooijen and Michael B. Habib in *Palaeogeography, Palaeoclimatology, Palaeoecology,* Vol. 440, pages 431–439; December 2015.

***Cryodrakon boreas* Gen. et Sp. Nov. a Late Cretaceous Canadian Azhdarchid Pterosaur.** David W. E. Hone, Michael B. Habib and François Therrien in *Journal of Vertebrate Paleontology* (in press).

FROM OUR ARCHIVES

Giants of the Sky. Daniel T. Ksepka and Michael Habib; April 2016.

scientificamerican.com/magazine/sa

NEUROSCIENCE

IS DEATH REVERSIBLE?

An experiment that partially revived slaughterhouse pig brains raises questions about the precise end point of life

By Christof Koch

"And death shall have no dominion" —***Dylan Thomas, 1933***

You will die, sooner or later. We all will. For everything that has a beginning has an end, an ineluctable consequence of the second law of thermodynamics.

Few of us like to think about this troubling fact. But once birthed, the thought of oblivion can't be completely erased. It lurks in the unconscious shadows, ready to burst forth. In my case, it was only as a mature man that I became fully mortal. I had wasted an entire evening playing an addictive, first-person shooter video game—running through subterranean halls, flooded corridors, nightmarishly turning tunnels, and empty plazas under a foreign sun, firing my weapons at hordes of aliens relentlessly pursuing me. I went to bed, easily falling asleep but awoke abruptly a few hours later. Abstract knowledge had turned to felt reality—I was going to die! Not right there and then but eventually.

Evolution equipped our species with powerful defense mechanisms to deal with this foreknowledge—in particular, psychological suppression and religion. The former prevents us from consciously acknowledging or dwelling on such uncomfortable truths while the latter reassures us

IN BRIEF

Death has had a changing definition over the millennia. Originally, it meant cessation of breathing and a heart that had stopped.

The advent of mechanical ventilators shifted the locus of death to the brain—dying became loss of brain function, an irreversible coma.

Partial revival of pig brains hours after decapitation, which was demonstrated in a recent experiment, could again upend definitions of mortality.

Illustration by Bill Mayer

Christof Koch is chief scientist and president of the Allen Institute for Brain Science in Seattle. He serves on *Scientific American*'s board of advisers and is author of *The Feeling of Life Itself: Why Consciousness Is Widespread but Can't Be Computed* (MIT Press, 2019).

by promising never-ending life in a Christian heaven, an eternal cycle of Buddhist reincarnations or an uploading of our mind to the Cloud, the 21st-century equivalent of rapture for nerds.

Death has no such dominion over nonhuman animals. Although they can grieve for dead offspring and companions, there is no credible evidence that apes, dogs, crows and bees have minds sufficiently self-aware to be troubled by the insight that one day they will be no more. Thus, these defense mechanisms must have arisen in recent hominin evolution, in less than 10 million years.

Teachings from religious and philosophical traditions have long emphasized the opposite: look squarely into the hollow eyes of death to remove its sting. Daily meditation on nonbeing lessens its terror. As a scientist with intimations of my own mortality, my reflections turn toward understanding what death is.

Anyone who undertakes this quest will soon come to realize that death, this looming presence just over the horizon, is quite ill defined from both a scientific as well as a medical point of view.

FROM THE CHEST TO THE HEAD

THROUGHOUT HISTORY, everyone knew what death was. When somebody stopped breathing and his or her heart ceased beating for more than a few minutes, the person was, quite simply, dead. Death was a well-demarcated moment in time. All of this changed with the advent of mechanical ventilators and cardiac pacemakers in the middle of the 20th century. Modern high-tech intensive care decoupled the heart and the lungs from the brain that is responsible for mind, thought and action.

In response to these technological developments, in 1968, the famous *Report of the Ad Hoc Committee of the Harvard Medical School* introduced the concept of death as irreversible coma—that is, loss of brain function. This adjustment was given the force of law by the Uniform Determination of Death Act in 1981. This document defines death as either irreversible cessation of circulatory and respiratory functions or irreversible halting of brain function. Quite simply, when your brain is dead, you are dead.

This definition is, by and large, in use throughout most of the advanced world. The locus of death shifted from the chest to the brain (and from public view into the private sphere of the hospital room), with the exact time of actual brain death uncertain. This rapid and widespread acceptance of brain death, reaffirmed by a presidential commission in 2008, is remarkable when compared with the ongoing controversy around abortion and the beginning of life. It may perhaps be reflective of another little noticed asymmetry—people agonize about what happens in the hereafter but rarely about where they were before being born!

The vast majority of deaths still occur following cardiopulmonary cessation, which then terminates brain functioning as well. Neurological death—specified by irreversible coma, absence of responses, brain stem reflexes or respiration—is uncommon beyond the intensive care unit, where patients with traumatic or anoxic brain injury or toxic-metabolic coma (say, following an opioid overdose) are typically admitted.

Brain death may be the defining factor, but that does not simplify clinical diagnosis—biological processes can persist after the brain shuts down. Indeed, a brain-dead body can be kept "alive" or on "life support" for hours, days or longer. For the grieving relatives and friends, it is challenging to understand what is happening. When visiting the ICU, they see the chest moving in and out, they feel a pulse, the skin pallor looks normal, and the body is warm. Looking healthier than some of the other denizens of the ICU, their beloved is now legally a corpse, a beating-heart cadaver. The body is ventilated and kept suspended in this quasi-living state because it is now a potential organ donor. If permission has been obtained, the organs can be harvested from the cadaver to help the living who need a heart, kidney, liver or lung, which are always in short supply.

Brain-dead bodies can continue to grow fingernails, to menstruate, with at least some working immune function that allows them to fight off infections. There are more than 30 known cases of pregnant brain-dead mothers placed on a ventilator to support gestation of a surviving fetus, born weeks or months (in one case 107 days) after the mother became brain-dead. In a widely discussed 2018 story in the *New Yorker,* a young woman, Jahi McMath, was maintained on ventilation in a home care setting in New Jersey by her family following her brain death in a hospital in California. To the law and established medical consensus, she was dead. To her loving family, she was alive for close to five years until she died from bleeding associated with liver failure.

Despite technological advances, biology and medicine still lack a coherent and principled understanding of what precisely defines birth and death—the two bookends that delimit life. Aristotle wrote in *De anima* more than two millennia ago that any living body is more than the sum of its parts. He taught that the vegetative soul of any organism, whether a plant, animal or person, is the form or the essence of this living thing.

The essence of a vegetative soul encompasses its powers of nutrition, growth and reproduction that depend on the body. When these vital capacities are gone, the organism ceases to be animate (a term whose roots lead back to *anima,* Latin for "soul"). The sensitive soul mediates the capacities of both animals and humans to sense the world and their bodies. It is the closest to what we moderns call "conscious experience." Finally, the rational soul is the sole province of people, mediating reason, language and speech. Of course, this is now increasingly mimicked by artificial-intelligence algorithms.

The modern emphasis on machine learning, genomics, proteomics and big data provides the illusion of understanding what this sensitive soul is. Yet it obscures the depth of our ignorance about what explains the breakdown of the vegetative soul. A conceptual challenge remains to define what constitutes anyone's living body—which is clearly more than the sum of its individual organs. How can one precisely delimit this body in space (are clothing, dental implants and contact lenses part of the body?) and in time (its beginning and its end)?

Note the word "irreversible" in the contemporary definition of neurological death. In the absence of a precise conceptual formulation of when an organism is alive or dead, the concept of irreversibility depends on the technology du jour, which is constantly evolving. What at the beginning of the 20th century was irreversible—cessation of breathing—became reversible by the end of the century. Is it too difficult to contemplate that the same may

be true for brain death? A recent experiment suggests this idea is not just a wild imagining.

PARTIAL REVIVAL OF DEAD BRAINS

THIS YEAR a large team of physicians and scientists at the Yale School of Medicine under Nenad Sestan took advantage of hundreds of pigs killed at a Department of Agriculture–approved slaughterhouse for a remarkable experiment, published in the journal *Nature*. The researchers removed the brains from their skulls and connected the carotid arteries and veins to a perfusion device that mimics a beating heart. It circulates a kind of artificial blood, a synthetic mixture of compounds that carry oxygen and drugs that protect cells from damage. The magic resides in the exact molecular constitution of the circulating solution. Think of closed-circuit dialysis machines that thousands of patients use daily to flush out toxins from their body because their own kidneys have stopped working.

These machines are needed because when blood stops flowing through the large, energy-demanding brain, oxygen stores are depleted within seconds, and consciousness is lost. Depriving a brain of oxygen and blood flow for more than a few minutes begins to trigger irreversible damage. Cells start degenerating in all sorts of ways (tissue damage and decomposition, edema, and so on) that are readily visible under a microscope.

The Sestan team studied the brains' viability four hours after the pigs were electrically stunned, bled out and decapitated. (If this sounds gruesome, it is what happens to livestock in an abattoir, one reason I'm a vegetarian.) The researchers compared a variety of biological indicators with those of postmortem control brains from pigs that did not undergo this perfusion procedure four hours after death, an eternity for the sensitive nervous system.

At first glance, the restored brains with the circulating solution appeared relatively normal. As the compound circulated, the fine net of arteries, capillaries and veins that suffuse brain tissue responded appropriately; the tissue integrity was preserved with a reduction in swelling that leads to cell death; synapses, neurons and their output wires (axons) looked normal. Glial cells, the underappreciated entities supporting neurons proper, showed some functionality, and the brain consumed oxygen and glucose, the universal energy currency of the body, an indication of some metabolic functioning. The title of the researchers' paper announcing their technology boldly states "Restoration of Brain Circulation and Cellular Functions Hours Post-mortem."

What was not present in these results were brain waves of the kind familiar from electroencephalographic (EEG) recordings. Electrodes placed onto the surface of the pig brains measured no spontaneous global electrical activity: none of the deep-slow waves that march in lockstep across the cerebral cortex during deep sleep, no abrupt paroxysm of electrical activity followed by silence—what is known as burst suppression. Only a flat line everywhere—a global isoelectric line—implying a complete absence of any sort of consciousness. A silent brain, electrically speaking, is not harboring an experiencing mind. But this was not a surprise. This state was exactly what was intended by Sestan and his co-workers, which is why the circulating solution contained a cocktail of drugs that suppresses neuronal function and corresponding synaptic communication among cells.

Even with the absence of brain waves it came as a surprise to me, a working neuroscientist, that individual pig cortical neurons still retained their capacity to generate electrical and synaptic activity. The Yale team demonstrated this by snipping a tiny sliver of neural tissue from these brains, washing off the perfused solution and then exciting individual neurons via an electric current delivered by a tiny electrode. Some of these cells responded appropriately by generating one or a series of the stereotypical electrical pulses, so-called action potentials or spikes, that are the universal idiom of rapid communication in any advanced nervous system.

This finding raises a profound question: What would happen if the team were to remove the neural-activity blockers from the solution suffusing the brain? Most likely nothing. Just because some individual neurons retain some potential for excitability does not imply that millions and millions of neurons can spontaneously self-organize and break out into an electrical chorus. And yet! It cannot be ruled out that with some kind of external help, a sort of cortical defibrillator, these "dead" brains could be booted up, reviving the brain rhythms characteristic of the living brain.

To state the obvious, decapitating any sentient creature and letting its brain bleed out is not conducive to its well-being. Reanimating it after such a major trauma could well lead to profound pathology, such as massive epileptic seizures, delirium, deep-seated pain, distress, psychosis, and so on. No creature should ever suffer in this manner. It is precisely to avoid this situation that the Yale team obstructed neuronal function.

This brings me to the elephant in the room. Can this procedure be applied to the human brain? Before you recoil, think of the following. What would you want done if your child or partner were found drowned or overdosed, without a pulse or breath for hours? Today it is likely that they would be declared dead. Could this change tomorrow with the kind of technology pioneered by the Yale group? Isn't that a worthwhile goal to pursue?

The pig brain is a large brain, unlike the one of the much smaller mouse, by far the most popular laboratory animal. Pig cortex is highly folded, like the human cortex. Neurosurgical procedures are routinely tested on pigs before moving to human trials. So, the technical answer is yes; in principle, this could be done.

But should it be done?

Certainly not until we understand much better whether a reconstituted animal brain shows global electrical activity typical of a healthy brain, without stress responses indicative of pain, distress or agony. The field as a whole should pause and discuss the medical, scientific, legal, ethical, philosophical and political questions of such research with all stakeholders.

Yet the fear of the grim reaper will not be denied. Sooner or later, somewhere on the planet's face, someone will try to temporarily cheat death. SA

MORE TO EXPLORE

The Undead: Organ Harvesting, the Ice-Water Test, Beating-Heart Cadavers—How Medicine Is Blurring the Line between Life and Death. Dick Teresi. Pantheon, 2012.

Modern Death—How Medicine Changed the End of Life. Haider Warraich. St. Martin's Press, 2017.

Restoration of Brain Circulation and Cellular Functions Hours Post-mortem. Zvonimir Vrselja et al. in *Nature,* Vol. 568, pages 336–343; April 18, 2019.

FROM OUR ARCHIVES

Brain Restoration System Explores Hazy Territory between Being Dead or Alive. Simon Makin; ScientificAmerican.com, April 19, 2019.

scientificamerican.com/magazine/sa

NUTRITION

Obesity on the Brain

“Ultraprocessed” foods seem to trigger neural signals that make us want more and more calories, unlike other foods in the Western diet

By Ellen Ruppel Shell

Photography by Jamie Chung

Ellen Ruppel Shell is a professor of science journalism at Boston University and author of *The Job: Work and Its Future in a Time of Radical Change* (Crown Publishing, 2018). She writes frequently on medical issues and is author of *The Hungry Gene: The Inside Story of the Obesity Industry* (Grove Press, 2002). She wrote about the controversy over lead poisoning in Flint, Mich., in the July 2016 issue of *Scientific American.*

NUTRITION RESEARCHER KEVIN HALL STRIVES TO PROJECT A ZEN-LIKE STATE OF equanimity. In his often contentious field, he says he is more bemused than frustrated by the tendency of other scientists to "cling to pet theories despite overwhelming evidence that they are mistaken." Some of these experts, he tells me with a sly smile, "have a fascinating ability to rationalize away studies that don't support their views."

IN BRIEF

Many nutrition scientists blame overeating fats or carbohydrates for the world's obesity pandemic.

But new research points to "ultra-processed" foods such as chicken nuggets and instant soup mixes that dominate modern diets.

These foods seem to distort signals between the gut and brain that normally tell us we are full, so instead people overeat.

Among those views is the idea that particular nutrients such as fats, carbs or sugars are to blame for our alarming obesity pandemic. (Globally the prevalence of obesity nearly tripled between 1975 and 2016, according to the World Health Organization. The rise accompanies related health threats that include heart disease and diabetes.) But Hall, who works at the National Institute of Diabetes and Digestive and Kidney Diseases, where he runs the Integrative Physiology section, has run experiments that point fingers at a different culprit. His studies suggest that a dramatic shift in how we make the food we eat—pulling ingredients apart and then reconstituting them into things like frosted snack cakes and ready-to-eat meals from the supermarket freezer—bears the brunt of the blame. This "ultraprocessed" food, he and a growing number of other scientists think, disrupts gut-brain signals that normally tell us that we have had enough, and this failed signaling leads to overeating.

Hall has done two small but rigorous studies that contradict common wisdom that faults carbohydrates or fats by themselves. In both experiments, he kept participants in a hospital for several weeks, scrupulously controlling what they ate. His idea was to avoid the biases of typical diet studies that rely on people's self-reports, which rarely match what they truly eat. The investigator, who has a physics doctorate, has that discipline's penchant for precise measurements. His first study found that, contrary to many predictions, a diet that reduced carb consumption actually seemed to slow the rate of body fat loss. The second study, published this year, identified a new reason for weight gain. It found that people ate hundreds more calories of ultraprocessed than unprocessed foods when they were encouraged to eat as much or as little of each type as they desired. Participants chowing down on the ultraprocessed foods gained two pounds in just two weeks.

"Hall's study is seminal—really as good a clinical trial as you can get," says Barry M. Popkin, a professor of nutrition at the University of North Carolina at Chapel Hill, who focuses on diet and obesity. "His was the first to prove that ultraprocessed foods are not only highly seductive but that people tend to eat more of them." The work has been well received, although it is possible that the carefully controlled experiment does not apply to the messy way people mix food types in the real world.

The man who designed the research says he is not on a messianic mission to improve America's eating habits. Hall admits that his four-year-old son's penchant for chicken nuggets and pizza remains unshakable and that his own diet could and probably should be improved. Still, he believes his study offers potent evidence that it is not any particular nutrient type but the way in which food is manipulated by manufacturers that plays the largest role in the world's growing girth. He insists he has no dog in any diet wars fight but is simply following the evidence. "Once you've stepped into one camp and surrounded yourself by the selective biases of that camp, it becomes difficult to step out," he says. Because his laboratory and research are paid for by the national institute whatever he finds, Hall notes that "I have the freedom to change my mind. Basically, I have the privilege to be persuaded by data."

THE CARB TEST

HALL ONCE HAD GREAT SYMPATHY for the theory that specific nutrients—in particular carbs—were at fault for our collective losing battle with body weight. "I knew that consumption of carbohydrates increases insulin levels in the blood and that insulin levels affect fat storage and fat cells," he says. "So it was certainly plausible that consumption of carbohydrates versus other macronutrients could have a deleterious effect on body weight. But while plausible, it wasn't certain, so I decided to test it."

In Hall's carb study, 10 men and nine women, all obese, were sequestered in a hospital ward at the National Institutes of Health and fed a high-carbohydrate/low-

PROP STYLING BY AMY HENRY

ULTRAPROCESSED foods and drinks are designed to be ready-to-consume, with numerous additives that can include oils, fats, color enhancers, flavor enhancers, nonsugar sweeteners, and bulking and firming agents. (No specific brand has been linked to obesity.)

SOURCE FOR PHOTOGRAPHS ON PAGES 41, 43 AND 44: "NOVA. THE STAR SHINES BRIGHT," BY CARLOS A. MONTEIRO ET AL., IN *WORLD NUTRITION*, VOL. 7, NO. 1: JANUARY–MARCH 2016

fat diet for two weeks. Then they left for a short time and returned to repeat another two-week stint. For the first five days of each stay, the balance was kept at 50 percent carbohydrate, 35 percent fat and 15 percent protein, with calorie intakes matched to their energy expenditure—measured in a specially constructed metabolic chamber—to ensure they neither gained nor lost weight. Over the next six days of each stay, they ate a diet with 30 percent fewer calories from the carb category.

"We were not surprised to find that when you manipulate the level of carbohydrates versus fats, you do see very different insulin levels," Hall says. He had expected the low-carb diet would reduce insulin activity. "But what did surprise us was that we did not see a significant effect of the sharply lower insulin levels on the rate of calories burned over time or on body fat." Typically lowered insulin affects the way fat cells burn calories. Yet, Halls says, "we found that the reduced-carbohydrate diet slightly slowed body fat loss." It also slightly increased the loss of lean body mass. A year later Hall and his colleagues did a similar experiment over a longer, eight-week period. This time they cut carbohydrates to very low levels. In the end, they found no meaningful difference in body fat loss or calorie expenditure between the very low-carb diet and a baseline high-carb/high-sugar diet. The scientists published the first results in 2015 in the journal *Cell Metabolism* and the second set in 2016 in the *American Journal of Clinical Nutrition*.

If it's not carbohydrates, what is to blame for our global obesity problem? Sure, meal portions today are

larger, food more abundant, and many of us are eating more calories than people did decades ago. But with temptations so plentiful, almost all Americans could be overeating—yet a good number do not. That, Hall thinks, is the real nutrition mystery: What factors, for some people, might be acting to override the body's inborn satiety mechanisms that otherwise keep our eating in check?

PROCESSED CALORIES

HALL LIKES TO COMPARE humans to automobiles, pointing out that both can operate on any number of energy sources. In the case of cars, it might be diesel, high-octane gasoline or electricity, depending on the make and model. Similarly, humans can and do thrive on any number of diets, depending on cultural norms and what is readily available. For example, a traditional high-fat/low-carb diet works well for the Inuit people of the Arctic, whereas a traditional low-fat/high-carb diet works well for the Japanese. But while humans have evolved to adapt to a wide variety of natural food environments, in recent decades the food supply has changed in ways to which our genes—and our brains—have had very little time to adapt. And it should come as no surprise that each of us reacts differently to that challenge.

At the end of the 19th century, most Americans lived in rural areas, and nearly half made their living on farms, where fresh or only lightly processed food was the norm. Today most Americans live in cities and buy rather than grow their food, increasingly in ready-to-eat form. An estimated 58 percent of the calories we consume and nearly 90 percent of all added sugars come from industrial food formulations made up mostly or entirely of ingredients—whether nutrients, fiber or chemical additives—that are not found in a similar form and combination in nature. These are the ultraprocessed foods, and they range from junk food such as chips, sugary breakfast cereals, candy, soda and mass-manufactured pastries to what might seem like benign or even healthful products such as commercial breads, processed meats, flavored yogurts and energy bars.

Ultraprocessed foods, which tend to be quite high in sugar, fat and salt, have contributed to an increase of more than 600 available calories per day for every American since 1970. Still, although the rise of these foods correlates with rising body weights, this correlation does not necessarily imply causation. There are plenty of delicious less processed foods—cheese, fatty meats, vegetable oil, cream—that could play an equal or even larger role. So Hall wanted to know whether it was something about ultraprocessing that led to weight gain. "Basically, we wondered whether people eat more calories when those calories come from ultraprocessed sources," he says.

Tackling that question is not simple. The typical nutritional study, as noted earlier, relies on self-reports of individuals who keep food diaries or fill out questionnaires from memory. But Hall knew that in the case of ultraprocessed foods, that approach would fail to provide convincing evidence either way. For one thing, nutrition study participants are notorious for cheating on dietary surveys—claiming more broccoli and fewer Double Stuf Oreos than they actually eat or "forgetting" drinking that third beer with friends. For another, with such a large percentage of the American diet coming from ultraprocessed foods, it would be hard to find a group of people with a markedly different diet for comparison.

To avoid these and related problems, in 2018 Hall turned once again to the metabolic ward, where he randomly assigned 20 adult volunteers to receive either ultraprocessed or unprocessed diets for two weeks. Then people switched: if they had been on one diet, they went on the alternative one for two more weeks. (Clearly, 20 is not a large enough sample size from which to draw conclusions that apply to the public as a whole, but this pilot study was meant as a "proof of concept" on which to build future, larger studies. Subjecting more people to the strict study regimen at this preliminary stage, Hall says, "would be unethical.") Dietitians scrupulously matched the ultraprocessed and processed meals for calories, energy density, fat, carbohydrate, protein, sugars, sodium and fiber. They also made sure that the research subjects had no taste preference for one category of food over the other. On both diets, participants were instructed to eat as much or as little of the meals and snacks as they liked.

This past spring, in his office, Hall showed me color photographs of each of the meals and snacks. The ultraprocessed meals included food such as canned ravioli, hot dogs, burgers topped with processed cheese, white bread, margarine and packaged cookies. Breakfast in this category had foods such as turkey bacon, sugared cereals, egg substitutes, Tater Tots, fruit-flavored drinks (most sweetened with artificial sweetener) and Spam. The unprocessed meals had dinners with roast beef, rice pilaf, couscous and pasta and breakfasts with nuts, vegetable omelets fried in oil, hash browns cooked with butter, and full-fat yogurt.

Roast beef, pasta and fried eggs are very appealing to many of us, and it would not have been shocking if people ate more of these than they ate, say, ultraprocessed Spam. But that's not what happened. Hall's results, published earlier this year in *Cell Metabolism,* showed that on the ultraprocessed diet people ate about 500 extra calories every day than they did when eating the unprocessed diet, an increase that caused them to gain about two pounds in two weeks. "What was amazing about Hall's findings was how many extra calories people eat when they are faced with ultraprocessed foods," says Carlos Augusto Monteiro, a physician and professor of nutrition and public health at the School of Public Health at the University of São Paulo in Brazil.

A GUT-BRAIN DISCONNECT

WHY ARE MORE of us tempted to overindulge in egg substitutes and turkey bacon than in real eggs and hash brown potatoes fried in real butter? Dana Small, a

PROCESSED FOODS add a few substances such as sugar, fat, and salt to natural food products, with the goal of improving preservation or sharpening taste. The category includes canned vegetables and fish, cured and salted meats, cheeses, and fermented drinks such as wine and beer.

neuroscientist and professor of psychiatry at Yale University, believes she has found some clues. Small studies the impact of the modern food environment on brain circuitry. Nerve cells in the gut send signals to our brains via a large conduit called the vagus nerve, she says. Those signals include information about the amount of energy (calories) coming into the stomach and intestines. If information is scrambled, the mixed signal can result in overeating. If “the brain does not get the proper metabolic signal from the gut,” Small says, “the brain doesn’t really know that the food is even there.”

Neuroimaging studies of the human brain, done by Small and others, indicate that sensory cues—smells and colors and texture—that accompany foods with high-calorie density activate the striatum, a part of the brain involved in decision-making. Those decisions include choices about food consumption.

And that is where ultraprocessed foods become a problem, Small says. The energy used by the body after consuming these foods does not match the perceived energy ingested. As a result, the brain gets confused in a manner that encourages overeating. For example, natural sweeteners—such as honey, maple syrup and table sugar—provide a certain number of calories, and the anticipation of sweet taste prompted by these foods signals the body to expect and prepare for that calorie load. But artificial sweeteners such as saccharin offer the anticipation and experience of sweet taste without the energy boost. The brain, which had antici-

UNPROCESSED FOODS are the edible parts of plants (such as seeds or roots or leaves) and animals (such as meat and eggs). The main processing of this food type is freezing, drying or pasteurizing to extend storage life. Salts, sugars, oils and fats are not added.

pated the calories and now senses something is missing, encourages us to keep eating.

To further complicate matters, ultraprocessed foods often contain a combination of nutritive and nonnutritive sweeteners that, Small says, produces surprising metabolic effects that result in a particularly potent reinforcement effect. That is, eating them causes us to want more of these foods. "What is clear is that the energetic value of food and beverages that contain both nutritive and nonnutritive sweeteners is not being accurately communicated to the brain," Small notes. "What is also clear is that Hall has found evidence that people eat more when they are given highly processed foods. My take on this is that when we eat ultraprocessed foods we are not getting the metabolic signal we would get from less processed foods and that the brain simply doesn't register the total calorie load and therefore keeps demanding more."

Small says that animal studies bear out the theory that ultraprocessed foods disrupt the gut-brain signals that influence food reinforcement and intake overall. "We've gone in with this cavalier attitude, that a calorie is a calorie, but a lot of foods have unintended consequences," she says. "For example, in the natural world, carbohydrates almost always come packaged with fiber, whereas in ultraprocessed foods, fiber is either not there at all or included in a form not found in nature. And it is rare to find carbohydrates and fat in the same food in nature, but ultraprocessed foods tend to have both in one package. We've created all these

hyperpalatable foods filled with fat, sugar, salt and additives, and we clearly prefer these foods. But these foods don't necessarily provoke satiety. What they seem to provoke is cravings."

Small and other scientists speculate that ultraprocessed foods in some sense resemble addictive drugs, in that consuming them leads not to satisfaction but to a yearning for more. Neuroscientist Ann Graybiel of the Massachusetts Institute of Technology, a recognized expert on habit formation, says that external cues—like the mere sight of a candy bar—can provoke a reflexive response that causes the brain to encourage a behavior almost automatically. "Part of what's happening when habits form is 'chunking,'" she says. "You learn the behavior pattern, and your brain packages the whole sequence, including the beginning and the end markers, so you don't have to think about it further." (Certain neurons in the striatum are responsible for grouping behaviors into a single, habitual routine.)

Eating large amounts of ultraprocessed foods may actually change brain circuitry in ways that increase sensitivity to food cues, adds Kent Berridge, a professor of psychology and neuroscience at the University of Michigan. He has shown this effect in rodents. "When you give rats junk-food diets, some gain weight, but others do not. In those that became obese, their dopamine systems changed, and they became hypersensitive to food cues—they became superfocused on that one reward. They showed no more pleasure, but they did show more wanting, and that wanting led to more actions—that is, more food-seeking behavior."

But this is not a uniform reaction, Berridge emphasizes, and he does not think it will turn out to be the only cause of overeating. "It's very plausible that altering foods (through ultraprocessing) could trigger this response in some of us, but my guess is that we aren't going to find that it affects all of us in the same way. My guess is that in the case of obesity, we are going to find subgroups—that is, that there are different avenues to becoming obese depending on one's genes."

FOOD FIGHT

NOT ALL RESEARCHERS agree that Hall's avenue—the ultraprocessed one—is the major road leading to obesity. Rick Mattes, a professor of nutrition science at Purdue University and the incoming head of the American Society of Nutrition, says that he is concerned that Hall is damning a whole food category without sufficient cause. "He's saying that ultraprocessed foods result in overeating, but there is no [large] body of evidence to support that claim. My view is that how items are manipulated may not be the primary driver of our response to them but that it is the nutrient composition that is the more relevant factor."

Hall points out that he did match the nutritional composition of the diets, but Mattes has several other objections. Perhaps the most serious is that the participants were offered only ultraprocessed or unprocessed foods in each leg of the study. "In the real world, people would mix" different food types, he wrote in an e-mail. "This is not a fault with the study, but it is a serious issue when attempting to extrapolate the findings to free-living people."

Another possible factor driving overconsumption of ultraprocessed foods is that they are eaten quickly, so people could devour a lot before any satiation mechanisms kick in to slow them down. Ultraprocessed foods tend to be energy-dense and pack a relatively large number of calories into a relatively small package. This, too, might encourage rapid consumption that bypasses satiety mechanisms. Still, fast eating does not explain why people continued to eat more ultraprocessed food at their next meal, when, at least in theory, they should have been less hungry.

If ultraprocessed foods are indeed a big problem, the question is what, if anything, we can and should do about them. When I asked Hall, he was reluctant to call for stringent measures such as a tax on these foods. "I worry that because almost 60 percent of our calories come from ultraprocessed foods, taxing those foods might add to some people's food insecurity," he says. "We've found an association of ultraprocessed foods and overeating, and there are many hypotheses about the causal mechanism. But until you fully understand the mechanism, it's too early to intervene. It could be that the additives and artificial flavoring are having an impact or that ultraprocessed foods have micronutrient deficiencies that the body senses and responds to by overeating. There are likely other factors as well. We just don't know—yet."

At the same time, he does think the available evidence on ultraprocessed foods is a reason to worry about them: "We can change our diet to minimize the damage. And for now I think that's where we need to set our sights." The food industry can help, perhaps by designing more foods with less processing, but people have to show they want such food by buying more of it. "I'm no evangelist," Hall asserts, "but I do think that the public demand on the food system is more powerful than any government regulation." His job in all this, he says, is to get the science right. SA

MORE TO EXPLORE

Calorie for Calorie, Dietary Fat Restriction Results in More Body Fat Loss Than Carbohydrate Restriction in People with Obesity. Kevin D. Hall et al. in *Cell Metabolism,* Vol. 22, No. 3, pages 427–436; September 1, 2015.

Energy Expenditure and Body Composition Changes after an Isocaloric Ketogenic Diet in Overweight and Obese Men. Kevin D. Hall et al. in *American Journal of Clinical Nutrition,* Vol. 104, No. 2, pages 324–333; August 2016.

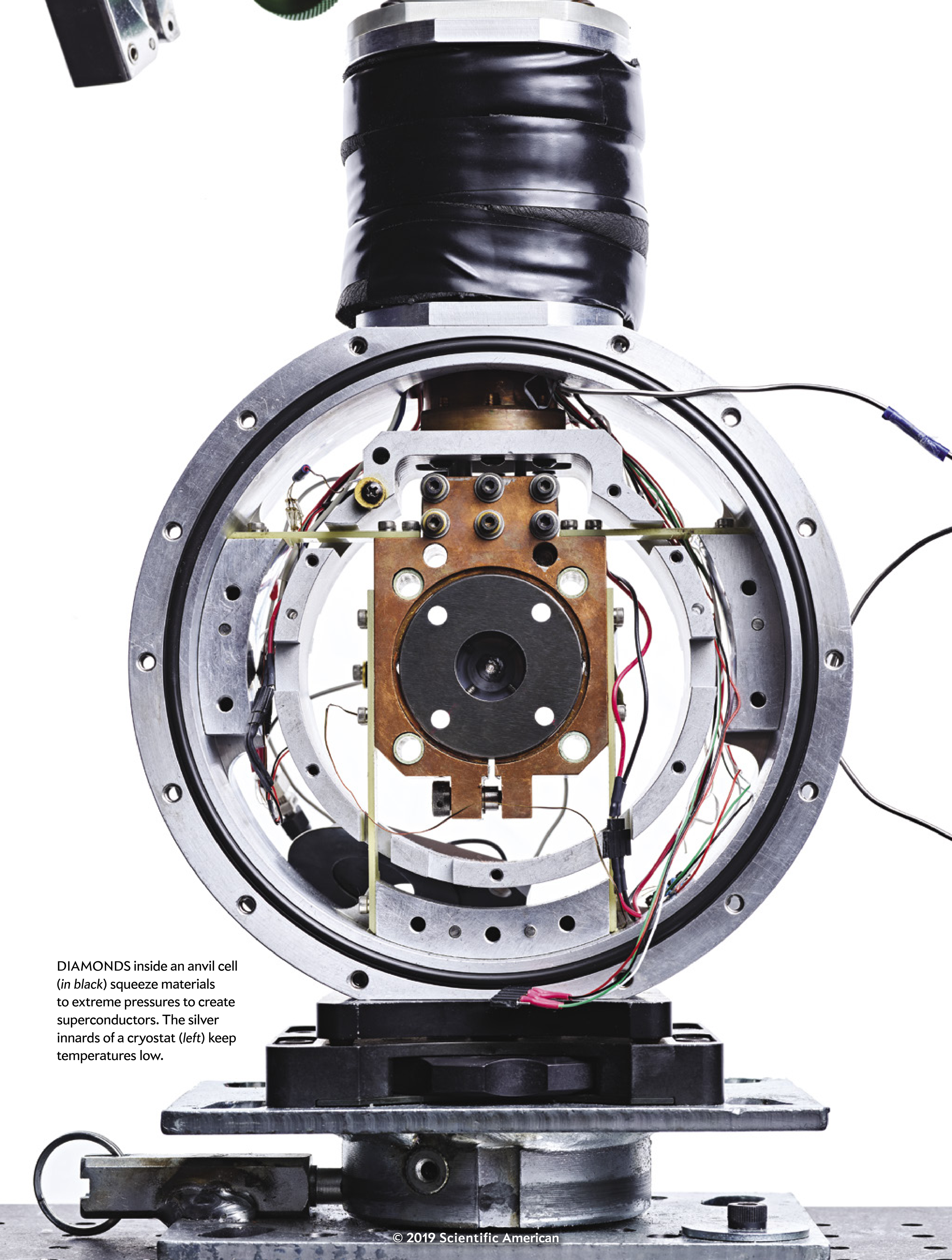
Processed Foods and Food Reward. Dana M. Small and Alexandra G. DiFeliceantonio in *Science,* Vol. 363, pages 346–347; January 25, 2019.

Ultra-Processed Diets Cause Excess Calorie Intake and Weight Gain: An Inpatient Randomized Controlled Trial of Ad Libitum Food Intake. Kevin D. Hall et al. in *Cell Metabolism,* Vol. 30, No. 1, pages 67–77 and e1–e3; July 2, 2019.

FROM OUR ARCHIVES

The Food Addiction. Paul J. Kenny; September 2013.

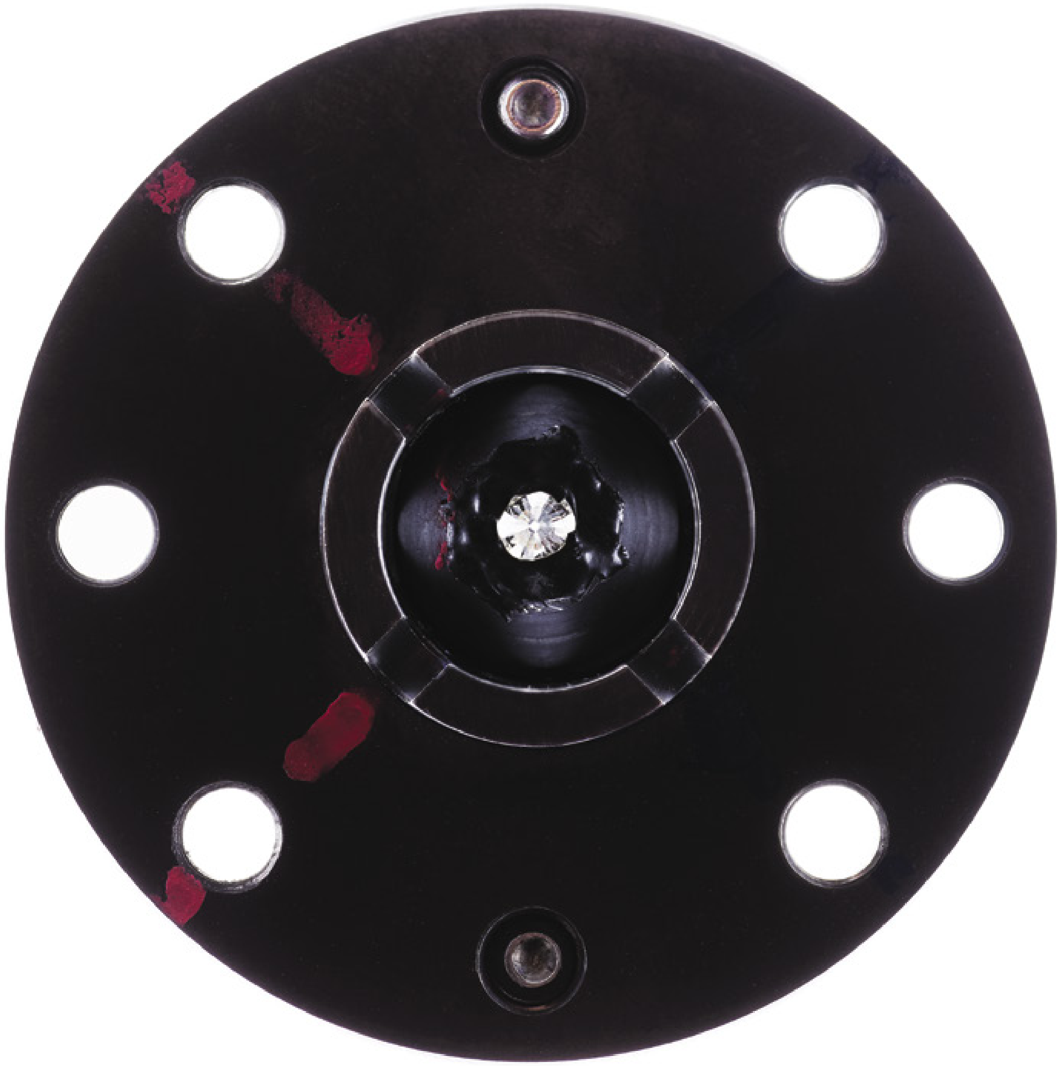
scientificamerican.com/magazine/sa



DIAMONDS inside an anvil cell (*in black*) squeeze materials to extreme pressures to create superconductors. The silver innards of a cryostat (*left*) keep temperatures low.

PHYSICS

THE STUFF OF DREAMS



Could new theoretical and computational advances finally deliver the elusive room-temperature superconductor?

By Bob Henderson

Photographs by Spencer Lowell

Bob Henderson is an independent writer based in upstate New York. He has a doctorate in high-energy theoretical physics from the University of Rochester and has made his living at various times as a photojournalist, an electrical engineer, and a financial derivatives quant and trader.

MADDURY SOMAYAZULU, AN EXPERIMENTAL PHYSICIST WHO GOES BY Zulu, could only hope that being close would be good enough. In an equipment-crammed room at Argonne National Laboratory in Illinois, he was huddled with postdoctoral researcher Zachary Geballe over a plum-sized cylindrical gadget called a diamond anvil cell. Inside was a dust speck's worth of the rare-earth metal lanthanum and a bit of hydrogen gas, which theorists had predicted could morph into a novel compound under the enormous pressure of 2.1 million atmospheres. That is more than half the pressure at the center of Earth and, more relevant on that June 2017 day, near the limits of the cell's capacity to compress its contents between its two pebble-sized diamonds—among the hardest materials in nature. As the scientists turned the cell's screws up to 1.7 million atmospheres, they felt them tighten. The diamonds, already warped by the pressure, could break. "Okay, that's it. We can't go any higher," Somayazulu said. "Let's try to synthesize here and see what happens."

The scientists had surrounded the anvil cell with a kind of high-tech firing squad: two long tubes for bombarding it with x-rays, a constellation of lenses and mirrors for blasting it with a laser, and a video camera to record the assault. They hoped that once activated, the laser would catalyze the lanthanum-hydrogen reaction. Outside the room, behind a sliding metal door that shielded them from the x-rays, the scientists watched a computer screen showing a graph of the x-rays' assessment of their mixture's microscopic structure. The plot quickly assumed the desired shape. They had successfully crushed and blasted lanthanum hydride, or LaH_{10}, into existence. "We were shocked," Somayazulu says. "We didn't even have to heat it much and it formed the compound"—and not just any compound.

Theory and computer modeling had suggested that LaH_{10} could be a superconductor, a material with the uncanny ability to conduct electricity without the energy losses that bedevil conventional wires. This efficiency allows a prodigious amount of current to be packed into a small space and circulate, perpetual-motion style, forever. Better yet, LaH_{10} was supposed to work this magic at about 44 degrees Fahrenheit (280 kelvins), a far higher temperature than achieved by any known superconductor and tantalizingly close to room temperature, a longstanding goal. The frigid conditions required by existing superconductors have tended to limit their use to niche applications such as MRI machines and particle accelerators. But a room-temperature superconductor might be put to many more uses, including transporting solar and wind energy to greater distances than currently practical, increasing the capacity of creaking power grids, making batteries that never lose their charge, and countless others in computers and medicine.

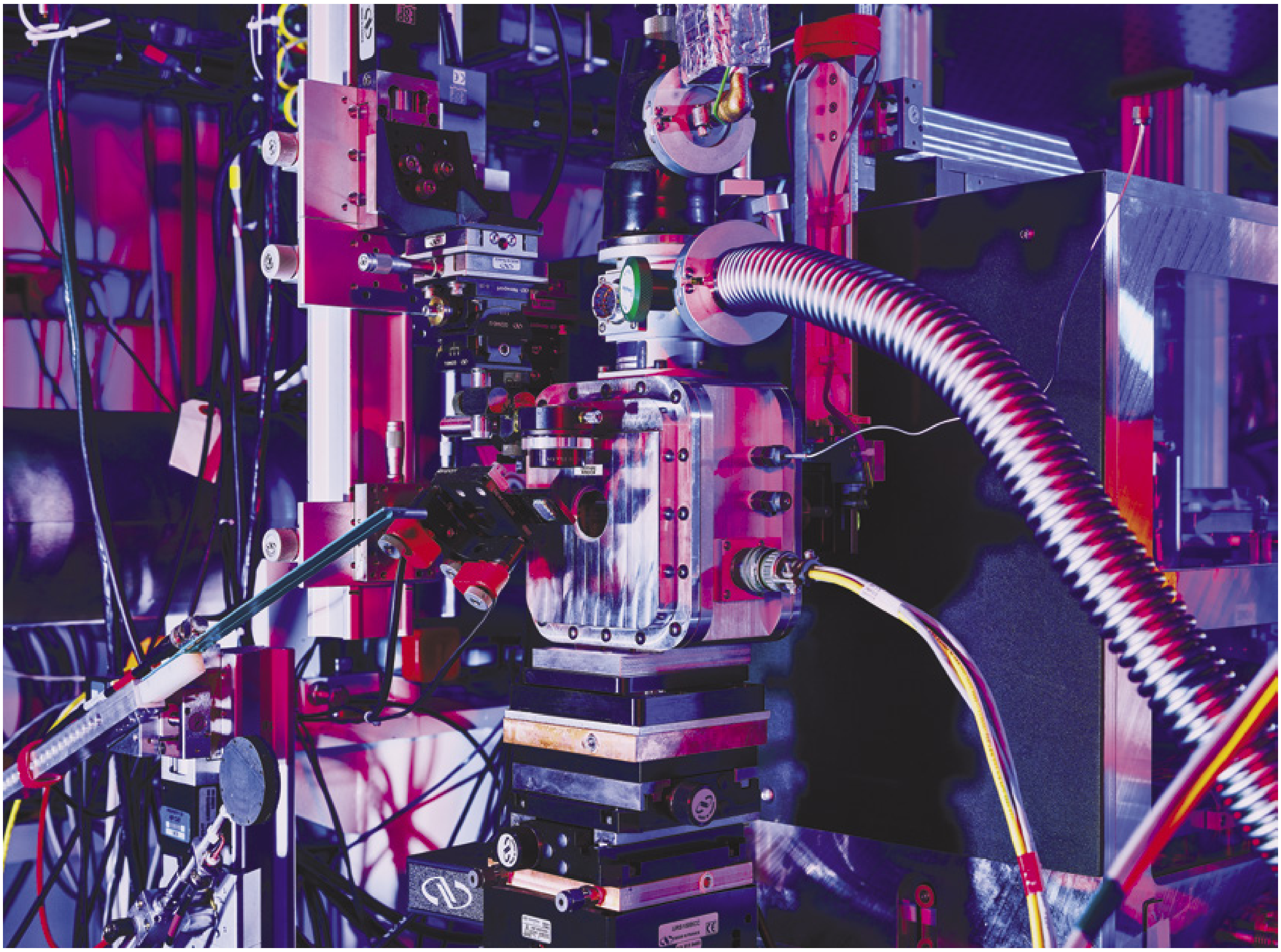
The x-ray analysis that Somayazulu and Geballe received indicated that the LaH_{10} they had created showed the *exact* microscopic structure theorists had predicted. "That hit us," Somayazulu told me during a recent visit to Argonne, where he joined the staff in May. When he and his colleagues synthesized LaH_{10}, he was still working for the Geophysical Laboratory of the Carnegie Institution for Science in Washington, D.C. His boss at the time, Russell Hemley, calls LaH_{10} "a beautiful example of materials by design." Hemley led the team that created the compound, as well as the theoretical group that predicted

IN BRIEF

Scientists dream of creating a superconductor—a material that can conduct electricity without resistance—that can function at room temperature. To date, all require cold temperatures and sometimes high pressures.

Historically, researchers have discovered new superconductors through trial and error, but recent breakthroughs have come from theoretical algorithms that use new tools, such as machine learning, to predict novel superconducting materials.

Physicists hope that theory improvements and experimental expertise may help them discover more useful superconductors, which could expand the reach of renewable energy technologies, improve power grids and allow for batteries that never lose charge.



NOVEL SUPERCONDUCTORS form inside a diamond anvil cell, kept in the central circular window in this cooling cryostat at Argonne National Laboratory.

its existence and its properties. "We built this material on a computer first, and a calculation told us where to look for it."

That was the real novelty of LaH_{10}. Scientists have searched for high-temperature superconductors for more than a century, but nearly every breakthrough has come from some combination of guesswork—essentially, trying out different ingredients and processes one by one, in hopes of success—and good luck. Only once before had a computer program prophesied a high-temperature superconductor—H_3S, another high-pressure compound found in 2014 that also falls into the hydrogen-bearing class of "hydrides"—but even in that case its creators were actually trying to make something else. The diamond-breaking pressures required to keep hydrides intact make it highly unlikely that they will ever be useful, but the algorithms that anticipated them, along with other recent computational advances, have the potential to make the search for more practical superconductors more systematic, and possibly more fruitful, than ever before.

A THEORY OF SUPERCONDUCTIVITY

"LAH_{10} WAS REALLY A GODSEND," Somayazulu says, recounting the years of labor that led to the material's discovery. Clearly excited as he recalls the tale, he sounds like he is still trying to believe he made it. He would still be out there, he says, "lost" and navigating the wilds with "rough ideas" and "high school chemistry," were it not for the new algorithms and their predictions.

Even so, once LaH_{10} had been conjured, he still had to figure out how to test it for superconductivity. Ever since the phenomenon's discovery in 1911, when Dutch physicist Heike Kamerlingh Onnes observed the electrical resistance of a mercury wire immersed in liquid helium inexplicably vanish at 4.2 kelvins, findings of new superconducting materials have tended to precede theories that explain them. Although superconductivity turns out to be surprisingly common, and many other elements have since been shown to superconduct (all below 10 kelvins), no one could begin to make sense of it until quantum mechanics was developed in the 1920s. The explanation depends on the electrons responsible for electricity behaving as both localized particles and spread-out waves, the way quantum mechanics says all subatomic particles do. On this basis, scientists John Bardeen, Leon N. Cooper and John Robert Schrieffer devised a theory now known as BCS (after their initials) to describe the physics of superconductors and published it in 1957.

It built on scientists' basic understanding of current: Inside a metal, the atoms (actually, atomic nuclei plus some bound elec-

trons, which create positively charged ions) form a crystal lattice—a structure with regular spacing—plus a sea of free electrons that, when a voltage is applied, flow through the lattice to form an electric current. Typically lattice imperfections and vibrations resulting from heat impede this flow and create resistance. According to BCS theory, however, electrons can foil this friction with a feat of quantum aikido that turns lattice motions to their advantage. First, as an electron moves through the lattice it bends the lattice's atoms in its direction of travel (because of the attraction between its negative charge and the lattice's positive charge). This bending bunches positive charges together, and the resulting concentration of positive charge pulls a second electron into the first's wake, bonding the two into a so-called Cooper pair. Second, those pairs, acting more like waves than particles now, overlap, synchronize and coalesce into one big wave called a Bose-Einstein condensate that is too large to be impeded by the lattice and so flows through it without any resistance at all.

BCS theory has led to many successful predictions, including the so-called critical temperatures above which superconductors lose their superpowers. Nevertheless, it has generally been of little help in the search for new superconductors with higher critical temperatures. In fact, the most successful superconductor hunter in history was an experimentalist named Bernd Matthias who deemed BCS irrelevant to his pursuit. Matthias discovered hundreds of superconductors (many of which were metal alloys) between the 1950s and the 1970s by testing countless materials in his lab, guided largely by five empirical rules relating to material properties (for example, "high symmetry is good") and one overarching principle: "Stay away from theorists."

But despite Matthias's many conquests, the highest critical temperature seen in a superconductor rose only slightly, from 17 to 23 kelvins, between 1955 and 1973. And there it stayed until 1986, when Georg Bednorz and Alex Müller, two IBM scientists in Zurich, discovered superconductivity in a class of complex layered ceramics called cuprates. These materials still hold the record for high temperature at ambient pressure that they set in 1993: 135 kelvins. Unlike Matthias, Bednorz and Müller "had a very robust theoretical view about what they were looking for," says physicist Peter Littlewood of the University of Chicago. "Now those ideas are probably wrong."

Wrong because they were based on BCS theory and the way it invokes atomic lattice vibrations, or phonons, to create Cooper pairs. Although such pairs, and the Bose-Einstein condensate they form, are believed to underlie the cuprates' superconductivity, many experts today believe the Cooper bonds in cuprates depend on some form of direct electromagnetic interaction between the electrons instead of, or at least in addition to, phonons. Alas, those direct interactions are so difficult to model mathematically that more than three decades of intensive research have failed to yield an equivalent to BCS theory for the cuprates or even to create a consensus on the details of the electrons' pairing mechanism. Scientists lump cuprates into a catchall category with several other classes of superconductors whose success seems to depend on various types of direct electron-to-electron interactions. These materials are called unconventional superconductors to distinguish them from the conventional, phonon-driven kind described by BCS.

So Bednorz and Müller found what they were looking for, but it did not work the way they thought it would. Yet that is

MADDURY SOMAYAZULU has spent decades trying to create superconductors that can operate at warm temperatures.

superconductivity's serendipitous way. For example, in 2006 scientists stumbled on iron-based superconductors—another unconventional class that lacks a theory to describe or predict it—while doing research to improve flat-panel displays. "Almost invariably, some new weird material is discovered," Littlewood says, "and that then teaches us about a new mechanism [for electron pairing] that we hadn't thought about."

THE TEMPERATURE BARRIER

SUPERCONDUCTIVITY FAVORS a chill, says Michael Norman, a materials scientist at Argonne, because "temperature is just bad" for sustaining wavelike quantum behavior at useful, macroscopic scales. The energy of heat tends to break up the bonds in Cooper pairs and disrupt the coordinated quantum state of a wavelike condensate.

The number of pairs in a condensate and the strength of the bonds holding them together provide a barrier to thermal disruption. A superconductor's critical temperature represents the height of this barrier—above this point it cannot withstand the heat. (The high barriers of the cuprates, for example, are thought to result from the way their direct electron-to-electron interactions create stronger Cooper pair bonds than those that come from the indirect mechanism of phonons.)

And yet "I don't think anybody now doubts that there is a possibility for a room-temperature superconductor at ambient pressure," says Norman, partly because of the way new superconductors and pairing mechanisms keep cropping up. Even for conventional superconductors, there is "no fundamental limit" to critical temperature, says Igor Mazin, a physicist at the Naval Research Laboratory in Washington, D.C. Instead, he says, there

is "a sort of statistical limit," meaning that such materials are simply less likely to exist. Phonon-mediated pairing tends to be stronger in wobblier atomic lattices (a perfectly rigid lattice could not support conventional superconductivity, which requires the lattice to pull toward an electron). Therefore, the exceptionally robust pairing needed for high-temperature conventional superconductivity seems to demand a special type of crystal structure, analogous to the elaborate designs engineers employ in modern bridges to keep them sturdy despite their flexing with the wind.

So room-temperature superconductors, if they exist, are undoubtedly rare. Yet hope springs from the immensity of the searchable landscape: the approximately 100 stable elements in the periodic table could yield 4,950 combinations of two, 161,700 of three, and so on. Factor in choices of stoichiometry (the ratios of elements in a compound) and lattice structure, and the possibilities are endless. So how do scientists find the exceptional materials in that chemical haystack?

THE SUPERCONDUCTOR DREAM

ONE MORNING in November 2017, Somayazulu was driving to work and racking his brain. The test to confirm LaH_{10}'s superconductivity was not going well. It required replacement of a metal gasket in the diamond anvil cell with an insulating material to prevent a short circuit during measurement of the resistance. But for months the hydrogen gas had been leaking out of every design the team tried. "Every day we'd come in and discuss, and we'd try once more," Somayazulu says. "It was very frustrating."

Then, sitting in traffic on the D.C. Capital Beltway, he had an idea: "Why don't we use a source of hydrogen that is solid?" Somayazulu thought that ammonia borane, a hydrogen-rich substance he knew of from earlier research, just might release hydrogen in the right way. After several months of refinement, the design worked. He saw LaH_{10}'s resistance plummet at 265 kelvins. He quickly snapped a picture with his phone, and then the team's computer program crashed and the cell's diamonds disintegrated. The photograph was all that was left of their feat, and it would be another six months before they could repeat it.

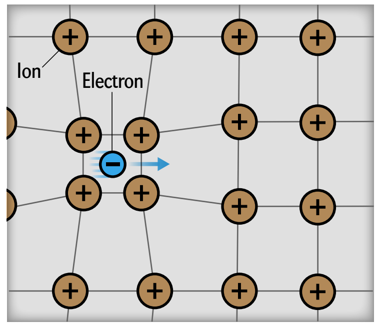
Somayazulu had spent nearly a quarter of a century trying to compress hydrogen into a superconductor. This was a dream Hemley had been chasing for decades, based on a prediction first made by physicist Neil Ashcroft of Cornell University in 1968. It could take as much as 10 million atmospheres of pressure to achieve such a material, Ashcroft acknowledged in 1983, but he theorized that a second element added to hydrogen might reduce that requirement by acting like a wedge to break up the H_2 molecules that hydrogen is prone to form. Thus freed, the hydrogen atoms could vibrate in ways conducive to high-temperature superconductivity: the pliable bonds between them would promote strong phonon coupling between electrons, and their low atomic mass would foster phonons that vibrated at an unusually high frequency (and therefore high energy), which would attract electrons in large numbers to the condensate.

For years after arriving from India in 1994 to work with Hemley as a postdoctoral fellow at the Carnegie Institution, Somayazulu dutifully crushed and heated myriad hydrogen mixtures in various ways, finding plenty of interesting physics but no superconductivity. "Here I am trying to dope hydrogen systematically with all kinds of things," he says. "I'm squeezing

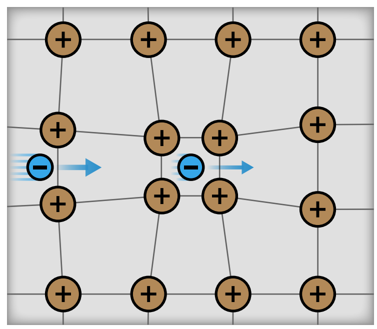
Superconductor Primer

Within a superconductor, complex quantum-mechanical effects allow electricity to flow without resistance. A theory known as BCS (after its three inventors' initials) describes a basic picture of how it works, although physicists think the details for many superconducting materials are more complicated. The BCS process goes like this:

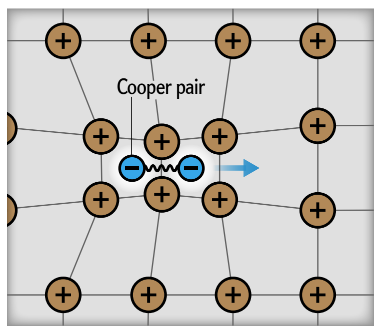
1 As a negatively charged electron travels through a lattice of positively charged ions, the ions pull toward it, scrunching up the lattice.



2 The resulting bunching of positive charge pulls another electron toward the first.



3 The two electrons form a connection that links them into a united entity, called a Cooper pair.



4 A large number of Cooper pairs synchronize and combine to create a giant wave, known as a Bose-Einstein condensate, that is so large it can pass through the lattice unimpeded.

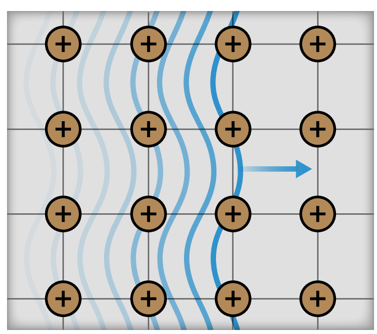
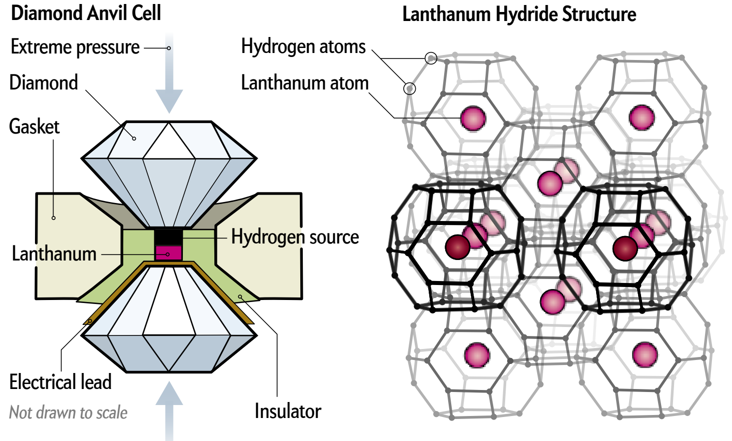


Illustration by Jen Christiansen

Lanthanum Hydride

Lanthanum hydride, or LaH_{10}, the highest-temperature superconductor known, can function at a surprisingly warm 17 degrees Fahrenheit and possibly warmer, albeit at excruciatingly high pressure. Scientists created LaH_{10} in 2017, using a so-called diamond anvil cell to compress hydrogen and lanthanum. The resulting material contains a lattice of hydrogen atoms enclosing a single lanthanum atom (*pink*) in a cagelike structure, which seems to be particularly conducive to superconductivity.



it to higher and higher pressures, and nothing is happening, and I'm kind of thinking, 'Was Ashcroft wrong?'"

Ashcroft, in fact, was right, but it took the help of a new class of "structure search" computer programs to prove it. The programs seek viable compounds by virtually moving atoms around in search of a stable crystal structure, which, by the second law of thermodynamics, is that with the lowest capacity to lose energy as heat. Some programs use an evolutionary search approach that starts with a group of crystal structures, mashes them up, selects the fittest of the offspring to breed, then repeats the process until the best of the bunch is found. Scientists then apply BCS to evaluate that structure's potential for superconductivity and to estimate its critical temperature.

In 2012 a group in China led by Yanming Ma used one such program to predict, in line with Ashcroft's ideas, that calcium hydride (CaH_6) could be made at pressures created by diamond anvil cells and would superconduct at a high temperature. Hemley and his team were soon crushing calcium into hydrogen, and they were not alone.

In 2014 a group led by Mikhail Eremets in Germany, following up on another of Ma's predictions—that hydrogen sulfide (H_2S), the noxious gas that rotten eggs emit, would superconduct at 80 kelvins under sufficient pressure—squeezed the smelly gas in a diamond anvil cell and saw, to the team members' surprise, that it superconducted at 203 kelvins instead. Eremets had chanced on another superconducting compound, H_3S, which held the high-temperature record before the synthesis of LaH_{10}.

Hemley's quest had become a race. In 2017, with help from a postdoc named Hanyu Liu from Ma's group, he used a structure-search algorithm to predict LaH_{10} and gave his group the marching orders that led to that compound's synthesis. Eremets soon made it, too; he confirmed the telltale resistivity drop, and, most recently, put it through a more comprehensive battery of tests to confirm its compatibility with BCS theory. It passed.

These discoveries combine elements of design with surprise. LaH_{10}, for example, grew out of Hemley's suggestion that Liu focus on compounds with the most hydrogen possible, to best approximate Ashcroft's original idea. On the other hand, LaH_{10} is believed to derive its high-temperature performance in part from the vibrational modes of its special clathrate structure, in which hydrogen atoms enclose a lanthanum atom in a "cage"—a configuration that theorists "would have never guessed," says Eva Zurek, a chemist who carries out structure searches at the University of Buffalo. But whether by design or surprise, the new programs have made theorists such as Ma and Zurek suddenly more relevant to the superconductor search. "I think experimentalists are taking us a lot more seriously than in the past," Zurek says.

DESIGN PRINCIPLES

THAT THEORISTS EXPEDITED the discovery of H_3S and LaH_{10}, conventional superconductors to which BCS theory applies, is one thing. What is more surprising is that they might do the same for unconventional superconductors, for which physicists have no working theory at all.

LaH_{10}, in fact, was not the only big superconductivity story of 2018. The other was the discovery of the phenomenon in twisted bilayer graphene. Graphene is a single-atom-thick sheet of carbon atoms arranged in a hexagonal lattice. Twisted bilayer graphene consists of two such sheets, one on top of the other, with their lattices rotated by an angle. Despite its low critical temperature of 1.7 kelvins, this material has uncommonly strong Cooper pair bonds. Its simple structure involving a single element has inspired hope that it can be understood theoretically and that it might elucidate unconventional superconductivity in general. The discovery straddles the line between serendipity and computer foresight—"It's half and half," says Pablo Jarillo-Herrero, head of the group at the Massachusetts Institute of Technology behind the finding. The material superconducts only at a specific "magic" twist angle of 1.1 degrees, a value that first popped out of a computer model. Yet although theorists correctly predicted that this angle would produce a spike in electron-electron interactions, they did not guess that it would lead to superconductivity. That surprise was uncovered in the lab.

Still, the find highlights the potential of what Norman calls design principles: calculable qualities that can help predict superconductivity even in the absence of a comprehensive theory. Matthias's first five rules were such principles, but exceptions to each ultimately arose in work with unconventional superconductors. Norman, however, pointed out in a 2016 paper that even unconventional superconductors of different classes display suggestive similarities, including many features of their phase diagrams, which are plots that show how their properties change with vari-

SOURCE: "SYNTHESIS AND STABILITY OF LANTHANUM SUPERHYDRIDES," BY ZACHARY M. GEBALLE ET AL., IN *ANGEWANDTE CHEMIE INTERNATIONAL EDITION*, VOL. 57, NO. 3; JANUARY 15, 2018 (*lanthanum hydride structure*)

Illustration by Jen Christiansen

ables such as pressure and temperature. He also noted that layered, quasi-two-dimensional structures such as the cuprates seem to support high critical temperatures and that certain crystal structures appear to be advantageous. As more classes of superconductors turn up, he reasoned, more design principles should become apparent. And even now, with more than 12,000 known superconducting materials catalogued and characterized, it is reasonable to wonder whether there are useful yet undiscovered design principles lurking in the existing data.

Machine-learning algorithms are computer programs that modify themselves as they receive more data. Last year one such algorithm, trained on a database of thousands of materials, developed the ability to identify superconductors (conventional and unconventional) in another data set with 92 percent accuracy and to estimate their critical temperatures. Furthermore, it did so using only simple elemental properties such as atomic weight and melting temperature. But "it's not the fact that the machine-learning algorithm can do it," says the study's lead author, Valentin Stanev of the University of Maryland. "The interesting part is *how* it is doing it. The insight is really which predictors the machine is using."

Stanev pointed out that the most important design principle the algorithm found for the cuprates' critical temperatures is a parameter (related to the numbers of electrons in the outermost orbits of the compound's atoms) that, to his knowledge, no one had noticed before. The hope is that as more such predictors are identified they can be applied in aggregate to accelerate the search for new and better superconductors.

Instead of relying on luck in the lab, says Stefano Curtarolo, Stanev's co-author and a materials scientist at Duke University, "machine learning will suggest a subset of compounds to try. Experimentalists, instead of testing 10 compounds and taking one year in the lab, are going to test 10,000 compounds on the computer and take only a few weeks."

A BLACK ART

ALTHOUGH THEORISTS have begun to predict new and interesting compounds, they are a long way from giving step-by-step instructions for making them in the lab. "There is something you do which works," Somayazulu says, describing the process of material synthesis. "And you just keep doing exactly the same thing to make it work, and *why* you do it you have no idea." It took him six months to repeat the LaH_{10} superconductivity test, for example, because the researchers were still debugging their protocol for making the compound. But at least they could create LaH_{10}, which is not the case for CaH_6, a compound that Ma's search predicted in 2012 but that still evades all attempts to synthesize it. And yttrium? Don't even get Somayazulu started on yttrium. Yttrium hydride (YH_{10}) is supposed to superconduct at even higher temperatures than LaH_{10}, but its behavior in Somayazulu's experiments was just "horrible." His ammonia borane trick, for example, does not work with it. Nor did it work with selenium at high pressure, although it did at low pressures. And recall how Eremets chanced on H_3S when shooting for H_2S. Clearly, materials synthesis is still very much a black art.

Structure search, meanwhile, entails its own difficulties. "The algorithms themselves you can just click a button," Zurek says. "But the analyses can be tricky, and I wouldn't want to have a nonexpert doing it," she adds with a chuckle. It takes a supercomputer about a week, on average, to complete a search for a given stoichiometry and pressure, and many such combinations may be of interest for a given pair of elements. The heavy computation load, as well as the trickiness of analysis, restricts most searches to compounds of just two elements and not too many atoms in a unit cell, the fundamental building block of a crystal. "We still cannot reliably predict a system that has three elements and 50 atoms in a unit cell," Zurek says.

Machine-learning programs, for their part, need not be so computationally intensive. Stanev ran his on a laptop. Their big limitation, and that of design principles generally, is that they can only leverage lessons learnable from known superconductors, which makes them unlikely to uncover a completely new class.

As for LaH_{10} and the other hydrides, their likely legacy depends on whom you ask. Hemley, who recently moved to the University of Illinois at Chicago, hopes that they hold lessons for creating an "analog" material able to maintain its high-temperature superconducting mojo at ambient pressure. Littlewood sees no reason for that to be impossible. Others are skeptical, though, because of pressure's pivotal role in the hydrides' performance so far. "You can afford to have strong electron–phonon coupling without destroying your crystal," Mazin says, "because it's being held together by external pressure."

If such an analog is possible, it probably consists of at least three elements, Zurek says, and has a complex crystal structure, according to Mazin. More generally, the arc of higher-temperature superconductors seems to bend toward more complex materials. Single-element superconductors with single-digit critical temperatures were surpassed by Matthias's metal alloys, which were outdone by materials with more elements and more complicated crystal structures. If, as many experts believe, the best hope for the room-temperature dream is an as yet unknown class of superconductors, then it seems likely to lie deep in the periodic table's endless frontier.

Somayazulu, for one, is happy to have dispensed with Matthias's rule against theorists. At Argonne, he spoke passionately about the failed attempts to make CaH_6: the struggles in trying to produce it and the debates with theorists he had along the way. Sometimes the theorists taught the experimentalists something. Other times it was the reverse. For Somayazulu, that was the most important legacy of the hydrides: this new "feedback loop" between experiment and theory. "Every time the theory guys make a prediction, there's a 50–50 chance it will work," he says. "But at least now there's that 50 percent chance." SA

MORE TO EXPLORE

Superconductivity at 250 K in Lanthanum Hydride under High Pressures. A. P. Drozdov et al. in *Nature*, Vol. 569, pages 528–531; May 23, 2019.

Evidence for Superconductivity above 260 K in Lanthanum Superhydride at Megabar Pressures. Maddury Somayazulu et al. in *Physical Review Letters*, Vol. 122, No. 2, Article No. 027001; January 14, 2019.

Viewpoint: Pushing towards Room-Temperature Superconductivity. Eva Zurek in *Physics*, Vol. 12, No. 1; January 2019.

FROM OUR ARCHIVES

Low-Temperature Superconductivity Is Warming Up. Paul C. Canfield and Sergey L. Bud'ko; April 2005.

Room-Temperature Superconductors. Michael Moyer; June 2010.

scientificamerican.com/magazine/sa

AGRICULTURE

Restoring Rice Biodiversity

Long-forgotten varieties of the staple crop can survive flood, drought and other calamities. The challenge is bringing them back

By Debal Deb

IN BRIEF

India originally possessed some 110,000 landraces of rice with diverse and valuable properties. These include enrichment in vital nutrients and the ability to withstand flood, drought, salinity or pest infestations. **The Green Revolution** covered fields with a few high-yielding varieties, so that roughly 90 percent of the landraces vanished from farmers' collections.

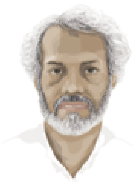
High-yielding varieties require expensive inputs. They perform abysmally on marginal farms or in adverse environmental conditions, forcing poor farmers into debt.

Collecting, regenerating, documenting the traits of and sharing with farmers the remaining landraces, to restore some of the lost biodiversity of rice, is the author's life mission.

Photographs by Zoë Savitz

PANICLES, or seed clusters, of diverse rice varieties are tagged after the harvest at the Basudha conservation farm.

Debal Deb is founder of the Basudha rice conservation farm and Vrihi seed distribution center in Kerandiguda and founder and chair of the Center for Interdisciplinary Studies in Barrackpore, all in India.



One scorching summer day in 1991, having spent hours surveying the biodiversity of sacred groves in southern West Bengal, India, I approached Raghu Murmu's hut to rest. Raghu, a young man of the Santal tribe, sat me under the shade of a huge mango tree while his daughter fetched me cold water and sweets made from rice. As I was relishing these, I noticed that Raghu's pregnant wife was drinking a reddish liquid. Raghu explained that it was the starch drained from cooked Bhutmuri rice—meaning "ghost's head" rice, perhaps because of its dark hull. It "restores blood in women who become deficient in blood during pregnancy and after childbirth," he said. I gathered that this starch is believed to cure peripartum anemia in women. Another rice variety, Paramai-sal, meaning "longevity rice," promotes healthy growth in children, Raghu added.

As I would subsequently establish, Bhutmuri is one of several varieties of indigenous rice in South Asia that are rich in iron, and it also contains certain B vitamins. And Paramaisal rice has high levels of antioxidants, micronutrients and labile starch, which can be converted rapidly to energy. At the time, however, such uncommon rice varieties, with their evocative names and folk medicinal uses, were new to me. When I returned home to Kolkata, I conducted a literature survey on the genetic diversity of Indian rice and realized that I had been lucky to encounter Raghu. Farmers like him, who grow indigenous rice and appreciate its value, are as endangered as the varieties themselves.

In the years since, I have become familiar with a cornucopia of native rice varieties (also called landraces) that possess astonishingly useful and diverse properties. Some can withstand flood, drought, salinity or pest attacks; others are enriched in valuable vitamins or minerals; and yet others are endowed with an enticing color, taste or aroma that has given them special roles in religious ceremonies. Collecting, regenerating and sharing with farmers these exceedingly rare but valuable varieties has become my life's mission.

1

LOST TREASURE

ASIAN CULTIVATED RICE (*Oryza sativa*) resulted from centuries of selection and breeding of wild ancestral species—a process that Charles Darwin called "artificial selection"—by early Neolithic humans. Archaeological and genetic evidence suggests that the *indica* subspecies of Asian rice (almost all cultivated rice from the Indian subcontinent belongs to this group) was grown about 7,000 to 9,000 years ago in the foothills of the eastern Himalayas. Over the ensuing millennia of domestication and cultivation, traditional farmers created a treasure trove of landraces that were perfectly adapted to diverse soils, topographies and microclimates and suited to specific cultural, nutritional or medicinal needs.

According to pioneering rice scientist R. H. Richharia, more than 140,000 landraces were grown in India's fields until the 1970s. If we exclude synonyms (that is, the same variety referred to by different names in different locales), this figure boils down to around 110,000 distinct varieties. As I learned from my literature survey, however, the genetic diversity of Indian rice has declined steeply since the advent of the Green Revolution.

In the late 1960s the International Rice Research Institute (IRRI) provided the Indian government with a few high-yielding varieties (HYVs) of rice, which provide substantial quantities of grain when supplied with ample water, fertilizer and pesticides. In concert with international development agencies, the IRRI urged the replacement of indigenous varieties across all types of fields with these imported strains. Heavily promoted and sometimes forced onto farmers' fields, the new rice types rapidly displaced the landraces.

In the late 1970s and early 1980s IRRI researchers listed 5,556

BRINGING BACK forgotten rice landraces requires the sowing, tending and harvesting of more than 1,000 varieties every year. Scenes from Basudha depict an indigenous farmer transplanting baby plants into a flooded field (*1*) and another working (*2*) on the farm.

landraces in West Bengal and collected 3,500 of these for its gene bank. In 1994, finding no documentation of surviving varieties in the state, I began my own, lone survey. Finally completed in 2006, it revealed that 90 percent of the documented varieties had vanished from farmers' fields. In fact, it is likely that no more than 6,000 rice landraces exist in fields across India. Similarly, the Bangladesh Rice Research Institute documented the names of 12,479 varieties between 1979 and 1981, but my analysis of a recent study indicates that no more than 720 landraces are still cultivated in the entire country.

When I got an inkling of this staggering loss of biodiversity in the subcontinent, it shocked me as a biologist and as a concerned citizen. I wondered why agricultural institutions were unconcerned about the genetic erosion of the most important cereal of the region. After all, the dire consequences of the loss of genetic diversity of a key crop should have been evident from Ireland's Great Famine of 1845–1849.

Most potatoes grown in Ireland were of a single variety, the Irish Lumper, which had no inherent resistance to *Phytophthora infestans,* the microorganism that causes potato blight. In 1846 three quarters of the harvest was lost to infection, resulting in a scarcity of seed potatoes in subsequent years and major demographic effects: up to 1.5 million people died from starvation and disease over the course of the famine, and in more than a decade of hunger and deprivation about 1.3 million people emigrated from Ireland to North America and Australia. The unforgettable lesson for agriculturists is that the absence of multiple varieties of a crop can make that plant vulnerable to pest or disease infestations: monocultures are disastrous for long-term food security. In the wake of the Green Revolution, insects such as the rice hispa and the brown planthopper, which had never before posed a significant problem, devastated rice crops in several Asian countries.

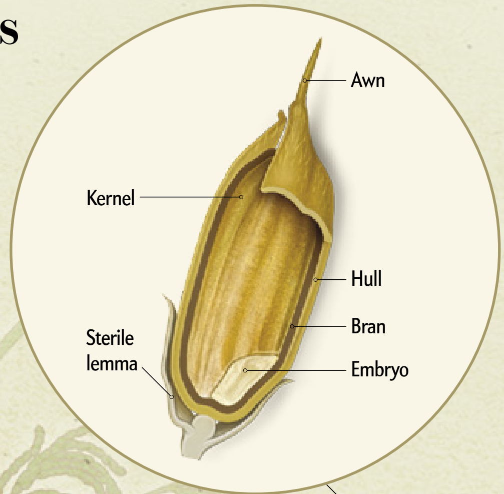
Vast expanses of monocultures provide banquets for certain pests. Farmers may try to eliminate them with generous applications of pesticides—which end up killing the natural enemies of those pests. The net effect is to enhance the diversity and abundance of pests, thus driving the pesticide mill wheel. The genetic uniformity of crop species—in particular the Green Revolution varieties, selected for the single trait of high yields—also means the plants lack endowments that would enable them to withstand vagaries of the weather such as insufficient or too late rain, seasonal floods or storm surges that inundate coastal farms with seawater. Their fragility makes a poor farmer who might not have the money to, say, buy a pump to irrigate his or her fields more vulnerable to environmental fluctuations.

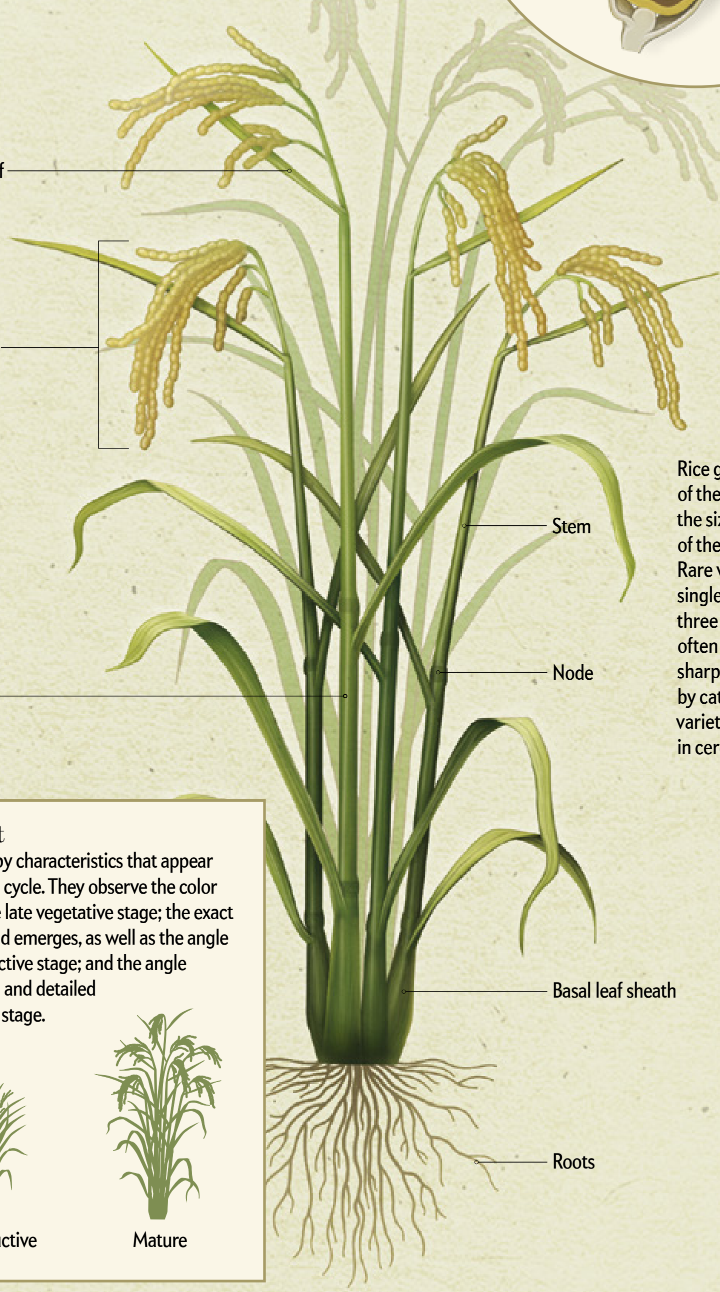
The loss of landraces further entails the withering of a knowledge system associated with their cultivation. For example, traditional farmers can distinguish varieties by observing the flowering time; the color of the basal leaf sheath; the angle of the flag leaf; the length of the panicle; and the size, color and shape of the grain [*see box on next page*]. Using these and other characteristics, they eliminate all atypical or "off-type" plants to maintain the genetic purity of the landrace. Nowadays, however, the vast majority of South Asian farmers rely on an external seed supply, which obviates the need to conserve the purity of homegrown seeds. When a local variety is no longer available, the knowledge related to its agronomic and cultural uses fades from the community's memory. Millennia-old strategies for using biodiversity to control pests and diseases have been supplanted by advice from pesticide dealers—to the detriment of soil and water quality, biodiversity and human health.

The Green Revolution and, more broadly, the modernization of agriculture have also had severe social and economic effects. Rising costs of inputs such as seeds, fertilizer, pesticides and fuel for irrigation pumps require farmers to borrow money, often

A Treasure Trove of Rice Varieties

Traditional farmers in South Asia can distinguish among thousands of varieties of rice by carefully examining more than 50 characteristics. These include temporal ones, such as the flowering time or the period required for maturation. Just as important, however, are physical ones such as the length, size and color of the panicle or seed cluster; the angle of the flag leaf; the length, thickness and color of the stem; the size, shape and color of the grain; the node color; and others. This expertise, which is seriously endangered—as are the varieties themselves—enables traditional farmers to carefully select varieties for use in different ecological niches, such as dryland slopes or lowlands prone to flooding, or for specific nutritional, cultural or medicinal uses.





A flood-resistant variety can either tolerate prolonged submergence underwater, for up to two weeks, or elongate its stem in tandem with rising water levels, so that the panicle stays dry. These properties are governed by specific genes, such as *SUB1* (for submergence) and *SNORKEL 1* and *SNORKEL 2* (for stem elongation).

Rice grains may vary in the length of the awn; the color of the hull; the size, color, shape and aroma of the kernel; and other features. Rare varieties exist in which a single grain contains two or even three kernels. Indigenous farmers often prefer varieties with long, sharp awns, which deter grazing by cattle, and some aromatic varieties are used for delicacies in ceremonies.

Stages of Development

Farmers also distinguish varieties by characteristics that appear only at particular phases of the life cycle. They observe the color and hairiness of the leaf during the late vegetative stage; the exact time at which the panicle forms and emerges, as well as the angle of the flag leaf, during the reproductive stage; and the angle of the panicle, the color of the awn and detailed features of the grain at the mature stage.

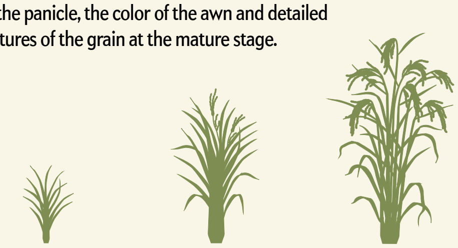


Illustration by Rebecca Konte

from private money lenders. Debt, coupled with falling prices for the harvested crops, has contributed to distress sales of small farms and an epidemic of farmer suicides in India. In contrast, over decades of working with tribal farmers who are still growing local rice and millet varieties on their marginal farms, I have encountered not a single case of farm-related suicide.

In 1996, with 152 landraces in my collection, I approached the West Bengal State Directorate of Agriculture's Rice Research Station, where all heirloom rice germplasm is supposed to be conserved. Not only did it refuse to accept and maintain the seeds I had collected, but the director chastised me for pursuing the "unscientific and retrogressive" goal of reviving the forgotten landraces. To insist on growing them would mean "going back to the caveman's age" and condemning farmers to low productivity and lifelong poverty, he said. When I argued that none of the HYVs can survive on dryland farms without irrigation, on deep-water farms or on coastal saline farms, he assured me that modern transgenics would soon come up with the best varieties for those marginal farms, so I should leave the matter with the experts in agricultural science.

LIVING SEEDS

TRAINED AS AN ECOLOGIST specializing in ecosystem structures and functions, I was working with the eastern regional office of World Wide Fund for Nature-India. At that time, it and other conservation organizations typically sought to safeguard large, charismatic animals such as the tiger, but because cultivated crops are not "wildlife," there was no focus on their protection. Research institutions were also uninterested because the conservation of folk crop varieties would receive no funding support.

The only option left to me was to go it alone. I resigned from my job in 1996 and settled in a village in West Bengal to set up a folk rice seed bank and exchange center for farmers. In 1997 I named it Vrihi, Sanskrit for "broadcast rice." In the early years I used my savings and considerable support from Navdanya, a New Delhi–based nongovernmental organization, to collect rare seeds from different corners of the country and distribute them for free to farmers in need. Since 2000, however, donations from friends and supporters have constituted the bulk of our funding.

In 1999, while in northern Bengal to survey biodiversity for the state's forest department, I took the opportunity to explore the region's fields. One day, after six hours of travel by bus and on foot to a remote village named Lataguri, I collected a critically endangered rice variety named Agni-sal. (I define a critically endangered variety as one that is being grown on only one farm.) The grain was fiery red in color—hence the name *Agni,* meaning "fire"—and its stem was strong enough to withstand storms. The next season I gave the seeds to a farmer who was looking for a rice that would flourish on his highland farm, which was swept by strong winds. He returned the following year with a broad smile of gratitude because of the great harvest from this rice, despite a cyclone that had devastated all the neighboring farms. The year after that, however, an officer from the district's agriculture department persuaded him to replace Agni-sal with an HYV. As a result, Agni-sal was lost from our accession. I rushed to Lataguri to procure another sample from the original donor farmer, only to learn that he had passed away the year before and that his son had abandoned that rice. Agni-sal thus, to my knowledge, went extinct from the world.

Another incident at about this time persuaded me that I needed to do more than collect and distribute seeds. Traditional lowland farmers in India used to grow two types of flood-tolerant rice. One can grow taller and taller in tandem with rising water levels. This underwater "stem elongation" property, governed by the genes *SNORKEL 1* and *SNORKEL 2,* located on chromosome 12, is seen in traditional varieties such as Lakshmi dighal, Jabrah, Pantara and Rani kajal. A second type of flood-tolerant landrace can withstand prolonged submergence in floodwater. One of the genes governing submergence tolerance is *SUB1,* found in several Bengal landraces.

In June 1999 a southern district of West Bengal experienced a flash flood. All rice crops perished. At the time, my accession had no varieties that could tolerate submergence, but I knew that the IRRI and the National Bureau of Plant Genetic Resources in New Delhi possessed several dozen. I wrote to both institutions, requesting that they send me 10 to 20 grams of these seeds to save the distressed farmers. I received no acknowledgment from either of the gene banks. If an educated person, writing in a European language on letterhead showing his academic degrees and affiliations, does not merit any response from the national and international gene banks, one can imagine how likely it is that a poor farmer from Kenya or Bangladesh might receive seed samples from them. To my knowledge, no farmer in any country has ever received any seeds from these lofty ex situ, or off-site, gene banks—even though their accessions were built on contributions from traditional farmers.

In contrast, the gene banks do make their accessions available to seed companies for hybridization programs and patenting. An estimate by the International Food Policy Research Institute indicates that by 1996 about three quarters of U.S. rice fields had been sown with material descendant from the IRRI collection. And in 1997 the U.S. Patent and Trademark Office granted the broadest ever patent on an indigenous rice, for a hybrid strain of basmati whose parents originated in South Asia and were accessed from the IRRI collection, to Texas-based company RiceTec. The IRRI, which supposedly holds its accession in trust for the world's farmers, itself applied in 2014 for an international patent on a yield-boosting rice gene called *SPIKE* discovered in the Indonesian landrace Daringan. (The governing body of the International Treaty on Plant Genetic Resources for Food and Agriculture has reviewed the legality of this controversial application but has yet to announce its decision.)

Not only are ex situ seed banks physically and socially distant from farmers, but also their seeds are handicapped by long isolation. Rice seeds are dried and preserved at –20 degrees Celsius, which keeps them viable for up to 35 years. Frozen in time, they are separated from the constantly evolving life-forms in the outer world. When grown out after 35 years, they will have lost any inherent resistance to specific pathogens, which will meanwhile have evolved into newer strains. In contrast, farmers' in situ seed banks are necessarily low budget, so they must sow all the seeds every year—otherwise most of the rice would fail to germinate. Thanks to this imperative, the seeds conserved on farms continue to coevolve with diverse pathogens and pests.

After a series of such experiences and observations, I decided to set up a conservation farm of my own to maintain a small population of each landrace so that it would survive even if abandoned by most farmers. I used my savings from a postdoctoral fellowship at the University of California, Berkeley, to found Basudha farm in 2001. Vrihi is now South Asia's largest open-access rice gene bank,

and its 1,420 varieties are grown every year on Basudha farm in a tribal village in southern Odisha. Of the varieties in our accession, 182 are now extinct from India's fields.

With less than 0.7 hectare at our disposal, we have to grow 64 individual plants of each variety on only four square meters of land. (The minimum number of plants required to maintain all the genetic endowments of a given landrace is about 50.) Because we cannot adhere to the internationally recommended isolation distance of at least 110 meters on every side of each landrace, preventing cross-pollination between neighboring varieties is a challenge. I managed to overcome this constraint by planting the different varieties so that each is surrounded by others with different flowering dates. Furthermore, we eliminate the off-type plants in each population at different life stages by observing 56 different characteristics, as per Bioversity International guidelines. After this step, all the seeds harvested are assumed to be 100 percent genetically pure, barring some undetected mutations.

1

DEBAL DEB and his long-term associate Debdulal Bhattacharya examine, record (*1*) and discuss (*2*) the detailed characteristics of rice grains from the harvest.

On Basudha farm, all the rice landraces are grown in accordance with the agroecological principle of "zero external input"—no agrochemicals, no groundwater extraction, no fossil fuels. Nutrient supply comes from leaf and straw mulch, legume cover crops (whose roots are rich in nitrogen-fixing microbes), composted greens and animal manure, biochar and soil microbes. We control pests by growing "weed" grasses and shrubs that provide habitats for predators such as spiders, ants and reptiles, as well as parasites. Another strategy is to maintain puddles of water as breeding habitats for aquatic insects and frogs, which also prey on crop pests. And we occasionally use herbal pest repellents such as tobacco, garlic and tulsi (*Ocimum sanctum;* also known as holy basil). Crop diseases are never a problem on Basudha: varietal and species diversity has repeatedly been documented as the best strategy for protection against crop pathogens.

We store some of the harvested seeds in earthen pots, which protect them from insects and rodents while allowing them to "breathe," for the next year's sowing. The rest we distribute among farmers, in exchange for a handful of seeds of other folk varieties, which we cultivate and donate to farmers. This system is a conscious attempt to revive the ancient practice of seed exchange in all farming communities, which had once helped all crop varieties to spread across continents.

My co-workers and I have helped establish more than 20 other seed banks in different parts of India, so that local farmers can access the varieties they need without having to travel to Vrihi. We also promote seed-exchange networks among farmers. These banks and networks have benefited more than 7,800 farmers in five Indian states. Further, we document the characters and properties of each variety and register the landraces in the name of farmers to preclude any biopiracy patents on them. By such means, we seek to restore to farmers sovereignty over seeds—essential to their long-term financial and nutritional security.

CORNUCOPIA

ON PRECARIOUS FARMS experiencing drought or seasonal floods, traditional landraces are the only reliable means of providing food security to poor farmers. After 22 years of growing folk rice varieties, I am confident that landraces such as Kelas, Rangi, Gadaba, Kaya and Velchi will provide greater yields than any of the modern HYVs in drought conditions. Lakshmi dighal, Rani kajal and Jabra can elongate their stems as floodwaters rise, keeping their seed-bearing panicles above water up to four meters deep. Matla, Getu, Talmugur and Kallurundai can grow on saline soil and survive seawater incursion. These landraces are stable germ lines with a suite of genes conferring broad adaptive plasticity.

Moreover, given optimal soil conditions in rain-fed farms, a considerable number of folk rice varieties such as Bahurupi, Bourani, Kerala sundari and Nagra can outyield modern HYVs. A set of exceedingly rare varieties with relatively high yields includes double- and triple-kernel rice; these may have resulted from selections of rare mutations in the structural genes of the rice flower. Basudha seems to be the last repository of one such triple-kernel rice landrace, Sateen.

Several landraces also possess resistance to pests and pathogens. Kalo nunia, Kalanamak, Kartik-sal and Tulsi manjari are blast-resistant. Bishnubhog and Rani kajal are resistant to bacterial blight. Kataribhog is moderately resistant to tungro virus. Gour-Nitai, Jashua and Shatia seem to resist caseworm attack, and stemborer attack on Khudi khasa, Loha gorah, Malabati, Sada Dhepa and Sindur mukhi varieties is seldom observed. Such seeds, distributed from Vrihi, have reduced crop losses from pest and disease attacks in thousands of farm fields over the past 25 or so years.

Modern rice breeding is largely focused on enhancing grain yield, but numerous folk rice varieties contain various micronutrients that are absent from modern cultivars. Our recent studies identified at least 80 folk varieties that contain more than 20 mil-

ligrams of iron per kilogram of rice, with the highest levels recorded for Harin kajli, Dudhé bolta and Jhuli rice, which range from 131 to 140 milligrams per kilogram. Compare this range with the 9.8 milligrams of iron per kilogram of the transgenic iron-fortified rice IR68144-2B-2-2-3, developed at IRRI at enormous expense.

Certain landraces may have medicinal uses. Ayurveda, the traditional Indian system of medicine, recommends Nyavara rice from Kerala to help treat a class of neurological disorders. Along with my co-workers, I am examining its chemistry and also hope to study its efficacy for such use. Another medicinal rice, Garib-sal from West Bengal, was prescribed in traditional medicine for treatment of gastroenteric infections. In a 2017 paper in *ACS Sustainable Chemistry and Engineering,* my collaborators and I documented the bioaccumulation of silver in Garib-sal grains to the extent of 15 parts per million. Silver nanoparticles kill pathogenic bacteria, according to a 2017 study in *Chemistry Letters,* so this rice might help fight human gut pathogens. A plethora of such medicinal rice varieties awaits laboratory and clinical testing.

Aesthetics is yet another value that indigenous farmers cherish, cultivating certain landraces simply for their beautiful colors or patterns: gold, brown, purple and black furrows on yellow hulls, purple apexes, black awns, and so on. Many in eastern India take pride in the beauty of the winglike extensions of the sterile lemma in Moynatundi and Ramigali rice. Aromatic varieties are associated with religious ceremonies and cultural festivals in all rice-growing cultures. When these types of rice disappear from fields, numerous culinary delicacies are no more, and the associated ceremonies lose their cultural and symbolic significance. Basudha's collection of 195 aromatic rice landraces has helped revive many evanescent local food cultures and traditional ceremonies.


2

The complexity of ecological interactions has resulted in another set of rice varieties. Smallholding farmers of West Bengal and Jharkhand prefer varieties with long and strong awns (spinelike projections at the end of the hull), which deter grazing by cattle and goats. Indigenous farmers also prefer landraces with erect flag leaves because grain-eating birds cannot perch on them.

Interestingly, some farmers in Odisha grow a combination of awned and awnless varieties on their farms, regardless of any direct benefits. Other rare varieties with no obvious use possess purple stems and leaves. Indeed, South Asian tradition appears to deem biodiversity, at both the genetic and the species level, as so essential to agriculture that it was enshrined in certain religious rituals. For example, some wild relatives of cultivated rice, such as Buno dhan (*Oryza rufipogon*) and Uri dhan (*Hygroryza asiatica*), are associated with local Hindu rites and maintained on many farms in West Bengal and its neighboring state, Jharkhand. Such wild gene pools are becoming ever more important as a source of unusual traits that can be incorporated, as required, into existing cultivars. Further, the presence in rice fields of certain trees such as neem (*Azadirachta indica*), whose leaves serve as a natural pesticide, and of predators such as the owl has been considered auspicious.

SAVING FARMERS

GIVEN THE FAILURE of modern agricultural research to provide marginal farmers with any reliable germ lines of rice, a large collection of folk rice varieties, with their fine-tuned adaptations to adverse conditions, is our best bet. Convinced by the superior yield stability of the landraces, more than 2,000 farmers in Odisha, Andhra Pradesh, West Bengal, Karnataka, Kerala and Maharashtra have adopted several folk rice varieties from Vrihi and abandoned cultivation of HYVs.

When Cyclone Aila hit the Sundarbans coast of West Bengal and Bangladesh in May 2009, it killed almost 350 people and destroyed the homes of more than a million. A storm surge inundated fields with seawater and left them salinated—which meant that quite apart from the immediate devastation, the food security of the region was likely to suffer long-term damage. We distributed a small amount of seeds from the Vrihi seed bank's repertoire of traditional salinity-tolerant landraces, such as Lal Getu, Nona bokra and Talmugur, among a few farmers on island villages of the Sundarbans. These were the only rice varieties that yielded a sizable amount of grain on the salinated farms in that disastrous season. Similarly, in 1999 several folk varieties such as Jabra, Rani kajal and Lakshmi dighal ensured rice production for southern Bengal farmers after a flash flood of the Hugli River. In 2010 Bhutmuri, Kalo gorah, Kelas and Rangi rescued many indigenous farmers in the western district of Puruliya when delayed arrival of monsoon rains caused a severe drought.

Such disasters prove, time and again, that the long-term sustainability of rice farming depends crucially on the restoration of traditional farming practices based on biodiversity and use of the full diversity of crop varieties that have survived the onslaught of industrial farming. SA

MORE TO EXPLORE

Beyond Developmentality: Constructing Inclusive Freedom and Sustainability. Debal Deb. Earthscan, 2009.

Rice: Origin, Antiquity and History. Edited by S. D. Sharma. CRC Press, 2010.

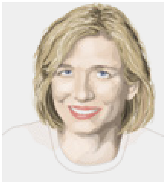
The Imperial Roots of Hunger. Madhusree Mukerjee in *Himal Southasian,* Vol. 26, No. 2, pages 12–25; April 2013.

A Profile of Heavy Metals in Rice (*Oryza sativa* ssp. *indica*) Landraces. Debal Deb et al. in *Current Science,* Vol. 109, No. 3, pages 407–409; August 10, 2015.

FROM OUR ARCHIVES

Sacred Groves: An Ancient Tradition of Nature Conservation. Madhav Gadgil; December 2018.

scientificamerican.com/magazine/sa



Lydia Denworth is a contributing editor for *Scientific American* and is author of *Friendship: The Evolution, Biology, and Extraordinary Power of Life's Fundamental Bond* (W. W. Norton, in press).

THE STATE OF THE WORLD'S SCIENCE

2019

STATISTICS

A Significant Problem

Standard scientific methods are under fire. Will anything change?

By Lydia Denworth

In 1925 British geneticist and statistician Ronald Fisher published a book called *Statistical Methods for Research Workers*. The title doesn't scream "best seller," but the book was a huge success and established Fisher as the father of modern statistics. In it, he tackles the problem of how researchers can apply statistical tests to numerical data to draw conclusions about what they have found and determine whether it is worth pursuing. He references a statistical test that summarizes the compatibility of data with a proposed model and produces a p value. Fisher suggests that researchers might consider a p value of 0.05 as a handy guide: "It is convenient to take this point as a limit in judging whether a deviation ought to be considered significant or not." Pursue results with p values below that threshold, he advises, and do not spend time on results that fall above it. Thus was born the idea that a value of p less

IN BRIEF

The use of *p* values for nearly a century to determine statistical significance of experimental results has contributed to an illusion of certainty and reproducibility crises in many scientific fields.

There is growing determination to reform statistical analysis, but researchers disagree on whether it should be tweaked or overhauled. Some suggest changing statistical methods, whereas others would do away with a threshold for defining "significant" results.

Ultimately the *p* value plays into the human need for certainty. So it may be time for both scientists and the public to embrace the discomfort of being unsure.

Illustration by Mark Allen Miller

than 0.05 equates to what is known as statistical significance—a mathematical definition of "significant" results.

Nearly a century later, in many fields of scientific inquiry, a *p* value less than 0.05 is considered the gold standard for determining the merit of an experiment. It opens the doors to the essentials of academia—funding and publication—and therefore underpins most published scientific conclusions. Yet even Fisher understood that the concept of statistical significance and the *p* value that underpins it has considerable limitations. Most have been recognized for decades. "The excessive reliance on significance testing," wrote psychologist Paul Meehl in 1978, "[is] a poor way of doing science." *P* values are regularly misinterpreted, and statistical significance is not the same thing as practical significance. Moreover, the methodological decisions required in any study make it possible for an experimenter, consciously or unconsciously, to shift a *p* value up or down. "As is often said, you can prove anything with statistics," says statistician and epidemiologist Sander Greenland, professor emeritus at the University of California, Los Angeles, and one of the leading voices for reform. Studies that rely only on achieving statistical significance or pointing out its absence regularly result in inaccurate claims—they show things to be true that are false and things to be false that are true. After Fisher had retired to Australia, he was asked whether there was anything in his long career he regretted. He is said to have snapped, "Ever mentioning 0.05."

In the past decade the debate over statistical significance has flared up with unusual intensity. One publication called the flimsy foundation of statistical analysis "science's dirtiest secret." Another cited "numerous deep flaws" in significance testing. Experimental economics, biomedical research and especially psychology have been engulfed in a controversial replication crisis, in which it has been revealed that a substantial percentage of published findings are not reproducible. One of the more notorious examples is the idea of the power pose, the claim that assertive body language changes not just your attitude but your hormones, which was based on one paper that has since been repudiated by one of its authors. A paper on the economics of climate change (by a skeptic) "ended up having almost as many error corrections as data points—no kidding!—but none of these error corrections were enough for him to change his conclusion," wrote statistician Andrew Gelman of Columbia University on his blog, where he regularly takes researchers to task for shoddy work and an unwillingness to admit the problems in their studies. "Hey, it's fine to do purely theoretical work, but then no need to distract us with data," Gelman wrote.

The concept of statistical significance, though not the only factor, has emerged as an obvious part of the problem. In the past three years hundreds of researchers have urgently called for reform, authoring or endorsing papers in prestigious journals on redefining statistical significance or abandoning it altogether. The American Statistical Association (ASA), which put out a strong and unusual statement on the issue in 2016, argues for "moving to a world beyond $p < 0.05$." Ronald Wasserstein, the ASA's executive director, puts it this way: "Statistical significance is supposed to be like a right swipe on Tinder. It indicates just a certain level of interest. But unfortunately, that's not what statistical significance has become. People say, 'I've got 0.05, I'm good.' The science stops."

The question is whether anything will change. "Nothing is new. That needs to sober us about the prospect that maybe this time will be the same as every other time," says behavioral economist

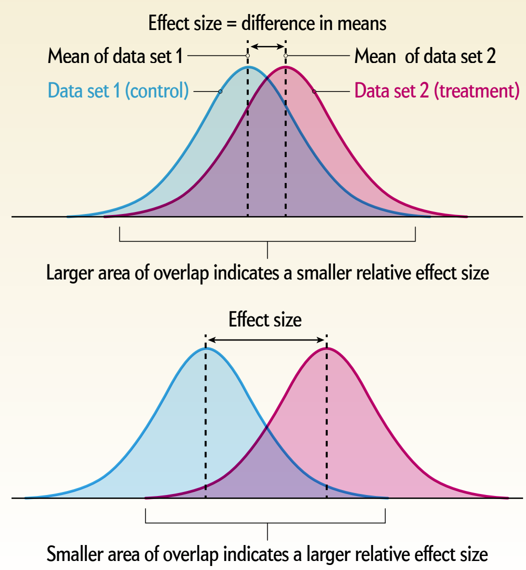
Statistical Significance

Imagine you grow pumpkins in your garden. Would using fertilizer affect their size? Given your long experience without fertilizer, you know how much the weights of pumpkins vary and you know that their average weight is 10 pounds. You decide to grow a sample of 25 pumpkins with fertilizer. The average weight of these 25 pumpkins turns out to be 13.2 pounds. How do you decide whether the difference of 3.2 pounds from the status quo of 10 pounds—the hypothetical "null" value—happened by chance or that fertilizer does indeed grow larger pumpkins?

Statistician Ronald Fisher's solution to this puzzle involves performing a thought experiment: imagine that you were to repeatedly grow 25 pumpkins a very large number of times. Each time you would get a different average weight because of the random variability of individual pumpkins. Then you would plot the distribution of those averages and consider the probability (**p value**) that the data you have generated would be possible if the fertilizer had no effect. By convention, a *p* value of 0.05 became a cut-off to identify significant results—in this case, ones that lead a researcher to conclude the fertilizer does not have an effect. Here we break down some of the concepts that drive the thought experiment for statistical significance.

EFFECT SIZE

The effect size for a treatment is the difference between the average outcome when the treatment is used compared with the average when the treatment is not used. The concept can be used to compare averages in samples or "true" averages for entire distributions. The effect size can be measured in the same units (such as pounds of pumpkins) as the outcome. But for many outcomes—such as responses to some psychological questionnaires—there is not a natural unit. In that case, researchers can use relative effect sizes. One way of measuring relative effect size is based on the overlap between the control and the treatment distributions.

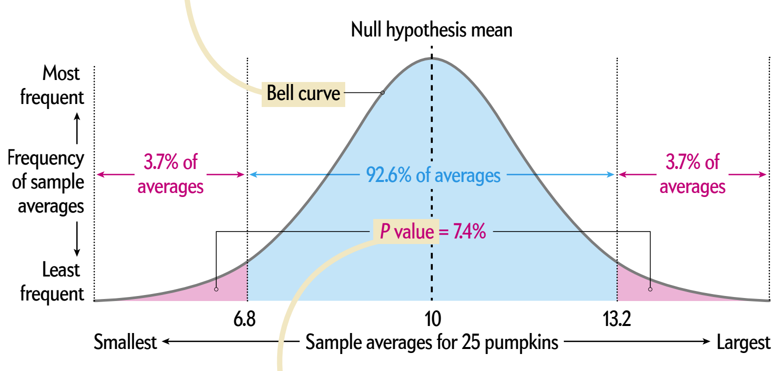


Graphic by Amanda Montañez (graphs) and Heather Krause

P VALUE

To calculate the *p* value, we need to compare the actual average of 13.2 pounds that we observed in our sample of 25 pumpkins with the random distribution of averages if we were to take many new samples of 25 pumpkins.

The bell curve shows the distribution of random average weights for samples of 25 under the null hypothesis that the fertilizer has no effect.

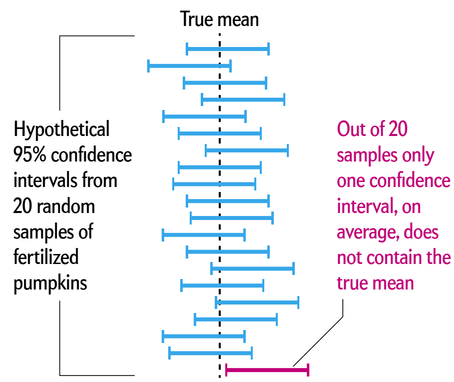


The *p* value is the probability of getting a random average weight as far from 10 as the average you actually observed, 13.2. Since 13.2 – 10 = 3.2, we want the probability of getting an average ≥ 13.2 or ≤ 6.8 (6.8 = 10 – 3.2). In this example, that probability is 0.074, which is the actual observed *p* value for your sample. Because it is greater than 0.05, your result would not be considered significant evidence that the fertilizer makes a difference.

The example shows a "two-tailed test," where the *p* value counts the probability of a weight greater than 13.2 and that of a weight less than 6.8 (10 – 3.2 = 6.8). Under some circumstances, a researcher might choose to perform a "one-tailed test." In that case, the *p* value would be only 0.037, which, being less than 0.05, is considered significant. This illustrates one way in which researchers can modify their stated intention for a study to achieve different *p* values with exactly the same data.

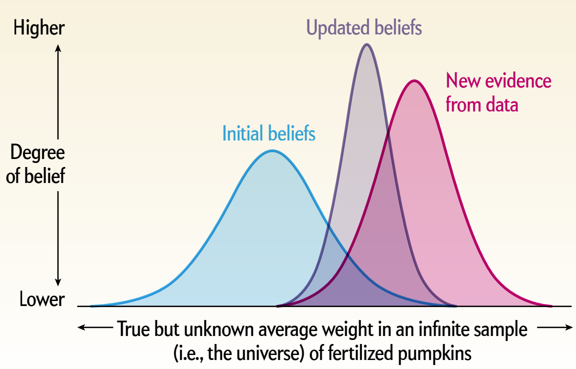
CONFIDENCE INTERVAL

We can calculate a 95 percent confidence interval from our sample of 25 pumpkins. This is a guess for the average weight of fertilized pumpkins. Calculating the 95 percent confidence interval involves inverting the calculation for the *p* value to find all hypothetical values that produce a *p* value ≥ 0.05. With our sample of 25 pumpkins, our 95 percent confidence interval goes from 9.69 to 16.71. The "true" average weight of fertilized pumpkins may or may not be in that interval. We can't be sure, so what does the "95 percent" mean? Imagine what would happen if we repeatedly grew batches of 25 pumpkins and sampled them. Each sample would produce a randomly different confidence interval. We know that in the long run, 95 percent of these intervals would include the true value and 5 percent would not. But what about our particular interval from the first pumpkin sample? We don't know whether it is in the 95 percent that worked or in the 5 percent that missed. It is the *process* that is right 95 percent of the time.



BAYESIAN METHODS

In the Bayesian approach to inference, a person's state of uncertainty about an unknown quantity is represented by a probability distribution. Bayes' theorem is used to combine individuals' initial beliefs—their distribution before looking at data—with the information they receive from the data, which produces a mathematically implied distribution for their updated beliefs. The updated beliefs from one study become the new initial beliefs for the next study, and so on. A major area of discussion and controversy concerns attempts to find "objective" criteria for initial beliefs. The goal is to find ways of constructing initial beliefs, known as prior distributions, that can be widely accepted by researchers as reasonable.



SURPRISAL

The *p* value conveys how surprising our pumpkin data are if we suppose that, in reality, fertilizing has no effect on growth. Some researchers have suggested that the *p* values do not convey surprisingness in a way that is intuitive for most people. Instead they suggest a mathematical quantity called a surprisal, also known as an *s* value or Shannon transform, that adjusts *p* values to produce bits (as in computer bits). Surprisal can be interpreted through the example of tossing coins.

Two heads in a row = **2** bits of surprisal = *p* value of $1/2^2$ = **0.25**

Four heads in a row = **4** bits of surprisal = *p* value of $1/2^4$ = **0.0625**

Five heads in a row = **5** bits of surprisal = *p* value of $1/2^5$ = **0.03215**

Our sample of 25 pumpkins with an average weight of 13.2 and a *p* value of 0.074 produces between 3 and 4 bits of surprisal. To be exact: 3.76 bits of surprisal since $3.76 = -\log_2 (0.074)$.

Daniel Benjamin of the University of Southern California, another voice for reform. Still, although they disagree over the remedies, it is striking how many researchers do agree, as economist Stephen Ziliak wrote, that "the current culture of statistical significance testing, interpretation, and reporting has to go."

THE WORLD AS IT IS

THE GOAL OF SCIENCE is to describe what is true in nature. Scientists use statistical models to infer that truth—to determine, for instance, whether one treatment is more effective than another or whether one group differs from another. Every statistical model relies on a set of assumptions about how data are collected and analyzed and how the researchers choose to present their results.

Those results nearly always center on a statistical approach called null hypothesis significance testing, which produces a *p* value. This testing does not address the truth head-on; it glances at it obliquely. That is because significance testing is intended to indicate only whether a line of research is worth pursuing further. "What we want to know when we run an experiment is how likely is it [our] hypothesis is true," Benjamin says. "But [significance testing] answers a convoluted alternative question, which is, if my hypothesis were false, how unlikely would my data be?"

Sometimes this works. The search for the Higgs boson, a particle first theorized by physicists in the 1960s, is an extreme but useful example. The null hypothesis was that the Higgs boson did not exist; the alternative hypothesis was that it must exist. Teams of physicists at CERN's Large Hadron Collider ran multiple experiments and got the equivalent of a *p* value so vanishingly small that it meant the possibility of their results occurring if the Higgs boson did not exist was one in 3.5 million. That made the null hypothesis untenable. Then they double-checked to be sure the result wasn't caused by an error. "The only way you could be assured of the scientific importance of this result, and the Nobel Prize, was to have reported that [they] went through hoops of fire to make sure [none] of the potential problems could have produced such a tiny value," Greenland says. "Such a tiny value is saying that the Standard Model without the Higgs boson [can't be correct]. It's screaming at that level."

But physics allows for a level of precision that isn't achievable elsewhere. When you're testing people, as in psychology, you will never achieve odds of one in three million. A *p* value of 0.05 puts the odds of repeated rejection of a correct hypothesis across many tests at one in 20. (It does not indicate, as is often believed, that the chance of error on any single test is 5 percent.) That's why statisticians long ago added "confidence intervals," as a way of providing a sense of the amount of error or uncertainty in estimates made by scientists. Confidence intervals are mathematically related to *p* values. *P* values run from 0 to 1. If you subtract 0.05 from 1, you get 0.95, or 95 percent, the conventional confidence interval. But a confidence interval is simply a useful way of summarizing the results of hypothesis tests for many effect sizes. "There's nothing about them that should inspire any confidence," Greenland says. Yet over time both *p* values and confidence intervals took hold, offering the illusion of certainty.

P values themselves are not necessarily the problem. They are a useful tool when considered in context. That's what journal editors and scientific funders and regulators claim they do. The concern is that the importance of statistical significance might be exaggerated or overemphasized, something that's especially easy to do with

small samples. That's what led to the current replication crisis. In 2015 Brian Nosek, co-founder of the Center for Open Science, spearheaded an effort to replicate 100 prominent social psychology papers, which found that only 36.1 percent could be replicated unambiguously. In 2018 the Social Sciences Replication Project reported on direct replications of 21 experimental studies in the social sciences published in *Nature* and *Science* between 2010 and 2015. They found a significant effect in the same direction as in the original study for 13 (62 percent) of the studies, and the effect size of the replications was on average about half the original effect size.

Genetics also had a replication crisis in the early to mid-2000s. After much debate, the threshold for statistical significance in that field was shifted dramatically. "When you find a new discovery of a genetic variance related to some disease or other phenotype, the standard for statistical significance is 5×10^{-8}, which is basically 0.05 divided by a million," says Benjamin, who has also worked in genetics. "The current generation of human genetics studies is considered very solid."

The same cannot be said for biomedical research, where the risk tends toward false negatives, with researchers reporting no statistical significance when effects exist. The absence of evidence is not evidence of absence, just as the absence of a wedding ring on someone's hand is not proof that the person isn't married, only proof that the person isn't wearing a ring. Such cases sometimes end up in court when corporate liability and consumer safety are at stake.

BLURRING BRIGHT LINES

JUST HOW MUCH TROUBLE is science in? There is fairly wide agreement among scientists in many disciplines that misinterpretation and overemphasis of *p* values and statistical significance are real problems, although some are milder in their diagnosis of its severity than others. "I take the long view," says social psychologist Blair T. Johnson of the University of Connecticut. "Science does this regularly. The pendulum will swing between extremes, and you've got to live with that." The benefit of this round, he says, is

that it is a reminder to be modest about inferences. "If we don't have humility as scholars, we're not going to move forward."

To truly move forward, though, scientists must agree on solutions. That is nearly as hard as the practice of statistics itself. "The fear is that taking away this long-established practice of being able to declare things as statistically significant or not would introduce some kind of anarchy to the process," Wasserstein says. Still, suggestions abound. They include changes in statistical methods, in the language used to describe those methods and in the way statistical analyses are used. The most prominent ideas have been put forth in a series of papers that began with the ASA statement in 2016, in which more than two dozen statisticians agreed on several principles for reform. That was followed by a special issue of one of the association's journals that included 45 papers on ways to move beyond statistical significance.

In 2018 a group of 72 scientists published a commentary called "Redefine Statistical Significance" in *Nature Human Behaviour* endorsing a shift in the threshold of statistical significance from 0.05 to 0.005 for claims of new discoveries. (Results between 0.05 and 0.005 would be called "suggestive.") Benjamin, the lead author of that paper, sees this as an imperfect short-term solution but as one that could be implemented immediately. "My worry is that if we don't do something right away, we'll lose the momentum to do the kind of bigger changes that will really improve things, and we'll end up spending all this time arguing over the ideal solution. In the meantime, there will be a lot more damage that gets done." In other words, don't let the perfect be the enemy of the good.

Others say redefining statistical significance does no good at all because the real problem is the very existence of a threshold. In March, U.C.L.A.'s Greenland, Valentin Amrhein, a zoologist at the University of Basel, and Blakeley McShane, a statistician and expert in marketing at Northwestern University, published a comment in *Nature* that argued for abandoning the concept of statistical significance. They suggest that p values be used as a continuous variable among other pieces of evidence and that confidence intervals be renamed "compatibility intervals" to reflect what they actually signal: compatibility with the data, not confidence in the result. They solicited endorsements for their ideas on Twitter. Eight hundred scientists, including Benjamin, signed on.

Clearly, better—or at least more straightforward—statistical methods are available. Gelman, who frequently criticizes the statistical approaches of others, does not use null hypothesis significance testing in his work at all. He prefers Bayesian methodology, a more direct statistical approach in which one takes initial beliefs, adds in new evidence and updates the beliefs. Greenland is promoting the use of a surprisal, a mathematical quantity that adjusts p values to produce bits (as in computer bits) of information. A p value of 0.05 is only 4.3 bits of information against the null. "That's the equivalent to seeing four heads in a row if someone tosses a coin," Greenland says. "Is that much evidence against the idea that the coin tossing was fair? No. You'll see it occur all the time. That's why 0.05 is such a weak standard." If researchers had to put a surprisal next to every p value, he argues, they would be held to a higher standard. An emphasis on effect sizes, which speak to the magnitude of differences found, would also help.

Improved education about statistics for both scientists and the public could start with making the language of statistics more accessible. Back when Fisher embraced the concept of "significance," the word carried less weight. "It meant 'signifying' but not 'important,'" Greenland says. And it's not surprising that the term "confidence intervals" tends to instill undue, well, confidence.

EMBRACE UNCERTAINTY

STATISTICAL SIGNIFICANCE has fed the human need for certainty. "The original sin is people wanting certainty when it's not appropriate," Gelman says. The time may have come for us to sit with the discomfort of not being sure. If we can do that, the scientific literature will look different. A report about an important finding "should be a paragraph, not a sentence," Wasserstein says. And it shouldn't be based on a single study. Ultimately a successful theory is one that stands up repeatedly to decades of scrutiny.

Small changes are occurring among the powers that be in science. "We agree that p values are sometimes overused or misinterpreted," says Jennifer Zeis, spokesperson for the *New England Journal of Medicine*. "Concluding that a treatment is effective for an outcome if $p < 0.05$ and ineffective if $p > 0.05$ is a reductionist view of medicine and does not always reflect reality." She says their research reports now include fewer p values, and more results are reported with confidence intervals without p values. The journal is also embracing the principles of open science, such as publishing more detailed research protocols and requiring authors to follow prespecified analysis plans and to report when they deviate from them.

At the U.S. Food and Drug Administration, there hasn't been any change to requirements in clinical trials, according to John Scott, director of the Division of Biostatistics. "I think it's very unlikely that p values will disappear from drug development anytime soon, but I do foresee increasing application of alternative approaches," he says. For instance, there has been greater interest among applicants in using Bayesian inference. "The current debate reflects generally increased awareness of some of the limitations of statistical inference as traditionally practiced."

Johnson, who is the incoming editor at *Psychological Bulletin,* has seen eye to eye with the current editor but says, "I intend to force conformity to fairly stringent standards of reporting. This way I'm sure that everyone knows what happened and why, and they can more easily judge whether methods are valid or have flaws." He also emphasizes the importance of well-executed meta-analyses and systematic reviews as ways of reducing dependence on the results of single studies.

Most critically, a p value "shouldn't be a gatekeeper," McShane says. "Let's take a more holistic and nuanced and evaluative view." That was something that even Ronald Fisher's contemporaries supported. In 1928 two other giants of statistics, Jerzy Neyman and Egon Pearson, wrote of statistical analysis: "The tests themselves give no final verdict but as tools help the worker who is using them to form his final decision." SA

MORE TO EXPLORE

Evaluating the Replicability of Social Science Experiments in *Nature* and *Science* between 2010 and 2015. Colin F. Camerer et al. in *Nature Human Behaviour,* Vol. 2, pages 637–644; September 2018.

Moving to a World beyond "p< 0.05." Ronald L. Wasserstein, Allen L. Schirm and Nicole A. Lazar in *American Statistician,* Vol. 73, Supplement 1, pages 1–19; 2019.

FROM OUR ARCHIVES

Make Research Reproducible. Shannon Palus; October 2018.

scientificamerican.com/magazine/sa

EDUCATION

SMART START

Kids in preschools that encourage them to play with language and focus their attention do better in school and later life

By Lisa Guernsey

Illustration by Alison Seiffer

Lisa Guernsey is director of the Teaching, Learning, and Tech program and senior adviser to the Early and Elementary Education Policy program at New America, a Washington, D.C.–based think tank.

DAWN BRADLEY, AN EARLY-CHILDHOOD TEACHER, HAS SPENT enough time with three-, four- and five-year-olds to know that they often do not get the credit they deserve. Children "are just told to follow orders or are told to only answer yes-and-no questions," she says. But in five years of teaching at Libertas School of Memphis in Tennessee, Bradley has seen kids persistently try to solve math problems until they get them right, learn to show courtesy when they accidentally bump into a friend, and ask astute questions about parts of insects or features of the nearby Mississippi River.

In many preschool classrooms in the U.S., children are asked to do little more than identify shapes and letters and sit quietly on rugs during story time. But a growing body of research is overturning assumptions about what early education can look like. The studies back up what Bradley sees in her work: when children learn certain skills, such as the ability to focus attention—skills that emerge when teachers employ games and conversations that prompt kids to think about what they are doing—the children do better socially and academically for years afterward. A study published last year, which tracked kids for a decade starting in preschool, found some evidence that children with teachers trained to foster such abilities may get better grades compared with children who did not get this type of education.

Politicians routinely promise to give more money to prekindergarten schooling, but there is now a new player on the scene with a particular interest in this kind of approach. About a year ago Jeff Bezos, the world's richest man, pledged to donate at least $1 billion to build a network of preschools accessible to children in low-income families and inspired by the Montessori program he attended in Albuquerque, N.M., as a child. Many Montessori programs emphasize this type of playful activity and choice making. His initiative is still taking shape, and it has not yet been announced how the money will be spent. But experts say that to do right for kids, any program will need to focus on at least two foundational skills: executive functioning and oral language.

Executive function involves a suite of cognitive skills, such as being able to hold an idea in one's head and recall it a short time later (working memory), the ability to control impulses and emotions, and the flexibility to shift attention between tasks. Oral language skills mean not just expressing sounds and words but using them in meaningful conversations that involve increasingly complex sentences.

"These are the fundamentals that lead to later success," says Robert C. Pianta, dean of the Curry School of Education and Human Development at the University of Virginia. "And the more we learn about them, the more we learn what underpins the academic skills that we value." The long-term benefits carry tremendous significance for children in low-income families. Not only are they the intended recipients of many public pre-K programs, but studies show they are more likely to enter first grade behind their peers in terms of their early literacy and math skills.

FOCUS FACTOR

EARLIER THIS YEAR a little girl in pink, age three and a half, with neat cornrows in her hair, stood at a wood table at Breakthrough Montessori, a public charter school in Washington, D.C. It was 10 o'clock in the morning. The little girl was cradling a fresh pomegranate and looking at an empty glass bowl that her teacher, Marissa Howser, had set up along with other carefully designed activities children could choose to do. Each one was meant to foster new competencies, such as completing tasks without an adult's help and developing fine-motor coordination.

The pomegranate activity provides the incentive of making a midmorning snack, and the girl eagerly embarked on the challenge of separating the fruit's glossy red seeds from the white pulp. Her tiny fingers pushed and pulled. Her face was set in concentration. "Oh, yeah, I got one!" she suddenly exclaimed. She dropped the seed into the bowl, then began to pry out another and another,

IN BRIEF

Many preschools teach children to memorize letters and numbers, but new research indicates early education should have other priorities.

Language skills, which are taught via conversation and guided play, form a strong foundation for later educational achievement.

The ability to focus and control impulses, which can be developed through games that require choices, also has a positive and long-lasting impact.

PULLING SEEDS from a fruit pod, a youngster at a Montessori public school boosts his ability to focus and learn while having fun.

In a 2015 study of 276 children in Head Start, the federally funded preschool program for low-income families, Sara Schmitt of Purdue University, along with her colleagues, including McClelland, found that playing the games twice a week led to higher executive functioning than that observed in a control group. They also found a significant link between better executive function scores and better math scores among Spanish-speaking English-language learners.

Opportunities to practice independence and autonomy may be another key ingredient. A 2018 study in the *Journal of Applied Developmental Psychology* links improvements in children's executive function to the extent to which adults give them a little autonomy. Such results are driving interest in the Montessori model, which gives children chances to choose activities that show what they are capable of, whether it is matching similar colors or preparing snacks for the group. And several studies comparing low-income children in Montessori with other low-income children have shown that Montessori students score better on tests of executive function. Researchers have hypothesized that the schools' emphasis on independent choices is one reason.

working for at least 20 minutes without interruption or coaching.

Standing at a table deseeding fruit might not seem like an obvious first step on the path to success in school and life. But a few decades ago cognitive scientists and behavioral researchers began to examine how and when children develop the ability to "self-regulate"—to know when to control emotions and how to follow through on tasks even when they might be difficult. The girl's persistent attempts to separate the slippery seeds showed that kind of follow-through. (The term "self-regulation" sometimes is used interchangeably with "executive function.")

Clancy Blair, a developmental psychology professor at New York University, was one of the first researchers to design experiments to understand how executive function works in young kids. "I began by looking at what is influencing the development of executive function," Blair says. "Could we cultivate it? Could we develop it?"

In some of the experiments by Blair and others, children were asked to play games that required them to remember rules and resist impulses to do other things. For example, one game was a peg-tapping game in which children were supposed to tap twice when a researcher tapped once, or vice versa. In 2005 Blair reported that stress had a marked impact on performance in this task. He tested the amount of the stress hormone cortisol in the saliva of game players. When levels climbed but then dropped—a sign that stress was dropping, too—children were better able to remember the game rules. Success at a task came not only from repetition but also from reducing stress during performance.

In addition to environments that allow them to be calm enough to focus, young children also need chances to practice this kind of concentration. Megan McClelland, a child development researcher at Oregon State University, and her colleague Shauna Tominey developed a suite of six games called Red Light, Purple Light to see whether playing them could help. One of the games is roughly similar to Simon Says—the rule is that you don't do something until you get the proper signal. Another asks children to dance when the music plays and freeze when it stops.

Another approach under study is Tools of the Mind, which employs a combination of literacy and math activities, dedicated time for children to talk about their plans for learning, and pretend play with costumes and props. Deborah Leong, a professor emerita at Metropolitan State University of Denver, who designed the program with developmental psychologist Elena Bodrova, said they wanted to push learning but make school "more playful and avoid 'drill and kill.'"

One version being used in kindergarten involves the Magic Tree House series of books, which feature Jack and Annie, two time-traveling kids who have adventures visiting landmarks and natural settings around the world at different times in history. Students can pretend they are Jack and Annie exploring the rain forest. While putting on costumes and strapping on backpacks, they talk about plans for their adventures and assign themselves roles. The Tools approach is also used in pre-K, but there it does not rely on the books. Instead kids might be asked to play roles in familiar settings such as managing a restaurant in their community or sending letters through a post office, loosely guided by a teacher but coming up with specific ways to accomplish the tasks themselves. "The level of engagement in a Tools classroom is off the charts," says Leslie Pekarek, a pre-K teacher at Gillett Elementary School in Wisconsin, who has used this method for the past four years. "When they are part of planning their play, they own it so much more. It feels like, it is, their idea."

Adele Diamond, a developmental cognitive neuroscientist at the University of British Columbia, is one of several researchers who have studied the impact of the Tools approach. In a 2007 *Science* article, she and her co-authors compared 147 children, about five years old on average, who were from the same urban neighborhood and had teachers with the same resources and level of training. But one group of these kids had teachers who used

Tools, and the other group received a more traditional, literacy-oriented curriculum. After one year, the children in the Tools classrooms were testing better compared with the literacy group on tasks related to executive function. The program has since been redesigned to make it easier for teachers to use and customize. A 2014 study of the revamped version by Blair and C. Cybele Raver, also at N.Y.U., showed Tools children in 29 schools also gained skills in academics.

TALKING POINTS

THE CHILDREN using Tools or similar approaches are doing more than learning to plan and play roles. They are also developing language skills—the second set of foundational abilities highlighted by research. Teachers and parents notice these skills when frustrated children stop—or at least shorten—a tantrum and begin to "use their words." The ability does not simply make adults' lives easier. It also enables children to speak with and listen to peers in ways that help build friendships, and it gives them the ability to ask teachers and other adults questions about new content they see in books or videos. As children move into kindergarten and first grade, these language skills are linked to their ability to read and comprehend texts.

Sonia Q. Cabell, a literacy researcher at Florida State University, says it is critical to develop these skills early because they give rise to later, more sophisticated approaches to language and to learning. And after a slow start, she adds, it is hard to make up ground, and achievement gaps get wider: "The ones who are behind don't tend to catch up."

Insights about oral language and literacy are rooted in older studies on ways to help children learn to read. Starting in the late 1980s, studies showed that simply reading a picture book to a young child was not as effective as pausing to engage in "dialogic" reading. Interactive dialogue about the book helped children learn new words and follow the meaning of the stories. An oft-cited 2002 study showed that differences in the way a teacher talked in class—whether reading a book or not—could change how children in preschool learned language. In that study, which tested more than 300 kids from different socioeconomic backgrounds across Chicago, the children with teachers who spoke in complex sentences showed significant growth after one year in their own use of complex sentences. Those with teachers whose language was not as complex (less likely to use multiple clauses, for example) did not show the same growth.

Today the evidence continues to pile up: a higher quality and quantity of children's turn-taking conversations helps them build their oral language skills, laying a foundation for reading and writing. For example, a study by Cabell and her colleagues, published this year in *Early Education and Development,* examined how teachers read books to 417 pre-K children in multiple locations around the U.S. It showed that what is called "extratextual" talk—moments when a teacher pauses to remark on the story and ask the children some informal questions about it—makes a big difference in children's overall literacy and language skills. Some scientists are now applying these findings about teachers' talking styles to experiments on how to help children with developmental delays.

Susan C. Levine, a professor of psychology at the University of Chicago, was one of the researchers who conducted the 2002 study of in-class language complexity. She also has been exploring how adults' talk about math—whether by parents or teachers—affects how children learn to handle numbers. For a 2006 study, she monitored hours of teacher-preschooler interactions. After a year, the more teachers used words associated with math—phrases such as "we share by dividing equally" and "all three of you can help me"—the higher the children scored on math tests.

Strategies to encourage more conversation are part of Tools of the Mind, too. Leong says the program was designed so children "talk to each other, and *then* the teacher calls on them. And by then they have had much more practice." The kids are not only learning how to express themselves and use new vocabulary but also listening to each other: "It equalizes the classroom and creates a community of learners where kids value each other's opinions," she says.

To encourage this kind of conversation, teachers have to plan ahead and set up routines that provide a sense of order and fairness in the classroom. In her study of extratextual talk, Cabell and her colleagues discovered that it was only in highly organized reading sessions that conversation around the content of books appeared to affect how well children learned vocabulary. When classrooms were more chaotic, teachers were less likely to engage in conversation with children that stimulated their language development.

Regardless of the exact methods used, McClelland says, it is possible that many of these strategies for oral language and executive function work together and build on one another. Teachers who give kids opportunities to make choices can help to develop children's executive function skills, which then helps them stay focused and keep their emotions under control. That in turn may aid children in figuring out math problems and lead them to try new words and complex sentences, which helps them learn to read and succeed in school. And all of that helps the kids feel less stressed and more able to regulate their behavior. The interwoven connections may also be what makes these skills so important throughout one's lifetime. "All of this codevelops," McClelland says.

LEVELING THE PLAYING FIELD

THE LIFELONG BENEFITS highlight just how unfortunate it is that the majority of low-income children do not have access to good preschool programs. A few states have rolled out free preschool for almost any resident who wants to enroll their children (Oklahoma, West Virginia and Washington, D.C., for example), but most states have more limited programs, and some states provide no preschool option at all. Head Start, which is aimed at families in poverty, children in foster care, homeless children and children with special needs, is currently accessible to only 31 percent of the eligible population, according to the National Head Start Association. The National Institute for Early Education Research at Rutgers University, which tracks teachers' level of preparedness, as well as other indicators of quality in state-funded pre-K, found that just 9 percent of enrollees nationwide are in state programs with high marks on all or almost all indicators of quality.

This shortfall has long-term consequences. Research on educational outcomes for young children shows that the higher the quality of the program, the better children do by the end of high school and in their adult lives. A recent analysis of the effectiveness of 21 public pre-K programs, published this year by the nonprofit Learning Policy Institute, reported that high-quality programs "help close the gap in school and life outcomes between those raised in

INSTRUCTIONAL GAMES called Red Light, Purple Light, which include a dance activity, help kids learn to manage impulses and emotions.

low-income families and their wealthier peers." These outcomes include a higher likelihood of graduating from high school and a lower likelihood of unemployment or spending time in jail.

Now there is evidence that a good preschool program may have effects that span generations. A new study by Nobel Prize–winning economist James J. Heckman of the University of Chicago and economist Ganesh Karapakula of Yale University tracked the effect of a Michigan program started in the 1960s known as the Perry Preschool Project. Perry used a curriculum called High-Scope that continues to be implemented in some preschools today and, as with Montessori and Tools of the Mind, puts a premium on executive function and language development. Heckman and Karapakula found that when the Perry children grew up and had kids of their own, those youngsters went further in school, had fewer discipline and legal troubles, and, for some, even had better health than children in a comparison group.

TEACHING TEACHER

THIS KIND OF QUALITY preschool experience, the research also indicates, requires a quality preschool teacher. The implication is that if governments ever follow through and invest more in pre-K and if Bezos's preschool network comes into being, leaders will need to focus on training adults as much as teaching children. "These oral language and executive function skills have to be more explicitly part of the instruction in the classroom and not something that happens by accident," University of Virginia's Pianta says. "This is not just 'let them play,' nor is it 'drill them on their letters.'"

Scientists highlighted this teaching effect in studies that began in the mid-2000s. They tracked hundreds of children in Chicago facilities that administer Head Start. Half of the children had teachers trained in ways of encouraging executive functions, and half had teachers who had not. Training included lessons on how to support children in managing their emotions and how to organize a classroom without being a dictator. By testing the children before and after their pre-K year, the researchers, led by N.Y.U.'s Raver, found that the kids with trained teach-ers had better self-regulation and academic skills than those without. Ten years later researchers followed up with the children, now teenagers, to see whether the effects had lasted. The answer, published in 2018 in *PLOS ONE,* was yes. The students still had higher grades.

Other efforts to train teachers involve methods that prompt the adults to reflect on exactly what they are doing each day as they interact with children. Observers sit in the back of classrooms and take notes on a teacher's ability to elaborate on children's remarks while introducing new vocabulary, to redirect students' attention when they become distracted, to recognize their individual needs, to respond thoughtfully to their questions or concerns, and more. The notes then get applied to one of several rating scales that score the classroom environment. One, now required in Head Start, is the Classroom Assessment Scoring System, developed by researchers at the University of Virginia. It measures interactions—including back-and-forth conversation—between teachers and children.

Coaching programs are also gaining traction as a way to give teachers support that is specific to the context of their classrooms. The coaches use data gathered from environment-rating scales and go into a classroom to physically demonstrate new techniques. "If the adult is scattered and doing 10 different things at once, that's [likely] what the child will be doing," says Elizabeth Slade, lead coach for the National Center on Montessori in the Public Sector. But when a teacher is focused on a child, one-on-one, Slade says, that teacher is showing "that this is what paying attention looks like."

Perhaps that kind of behavior modeling is why the little girl with the pomegranate could work so diligently for so long. Earlier that morning her teacher had had several one-on-one conversations with other kids, letting the three-and-a-half-year-old work on the fruit by herself. By snack time, the girl had a full bowl of tasty, sweet seeds to offer to her classmates. She brought it over to a boy kneeling next to a shelf of blocks. "Pom-grat," she said out loud, practicing the word, which she had just learned. "Do you like that?" SA

MORE TO EXPLORE

Closing the Achievement Gap through Modification of Neurocognitive and Neuroendocrine Function: Results from a Cluster Randomized Controlled Trial of an Innovative Approach to the Education of Children in Kindergarten. Clancy Blair and C. Cybele Raver in *PLOS ONE,* Vol. 9, No. 11, Article e112393; November 12, 2014.

Montessori Preschool Elevates and Equalizes Child Outcomes: A Longitudinal Study. Angeline S. Lillard et al. in *Frontiers in Psychology,* Vol. 8, Article 1783; October 2017.

The Chicago School Readiness Project: Examining the Long-Term Impacts of an Early Childhood Intervention. Tyler W. Watts et al. in *PLOS ONE,* Vol. 13, No. 7, Article e0200144; July 12, 2018.

Prekindergarten Interactive Book Reading Quality and Children's Language and Literacy Development: Classroom Organization as a Moderator. Sonia Q. Cabell et al. in *Early Education and Development,* Vol. 30, No. 1, pages 1–18; January 2019.

FROM OUR ARCHIVES

The Serious Need for Play. Melinda Wenner; *Scientific American Mind,* February 2009.

scientificamerican.com/magazine/sa

Caiaimage/Trevor Adeline

Millie Hughes-Fulford, Ph.D.
Professor of Medicine University of California Medical Center

Millie Hughes-Fulford was selected as a Scientist-Astronaut on the first Spacelab mission dedicated to biomedical studies in 1991 and has since continued her research into the mechanisms of cell growth and activation in spaceflight, winning an award from NASA in 2012 for discovering why the immune system is weakened in zero gravity.

Space: An Astronaut's Perspective

- Living and Working in Space
- ISS and Science
- The Right Stuff — Revised 2020 Edition
- The Future

Jill Tarter, Ph.D.
Emeritus Chair for SETI Research, SETI Institute

Jill Tarter achieved recognition for her work searching for evidence of extraterrestrial life, which entered public consciousness through the movie *Contact*, and has won several awards including the Lifetime Achievement Award from Women in Aerospace, two NASA Public Service Medals, *Time* Magazine's Top 100 Most Influential People in 2004 and many more for her dedication to communicating science to the public.

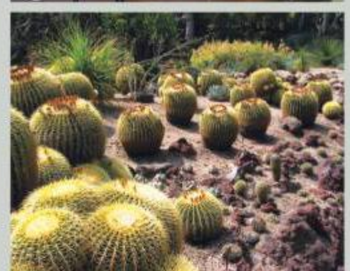
Habitable Worlds: The Search for Life

- Extremophiles on Earth
- Exoplanets
- Biosignatures
- Technosignatures

For speakers' complete bios, visit http://InsightCruises.com/events/sa39/#SPEAKERS.html

Post-Cruise Land Tour March 30 – April 3, 2020

Join us in Los Angeles to visit the most exciting science sites that SoCal has to offer. We'll go behind the scenes into the prep lab at the Natural History Museum to learn how scientists process fossils. We'll also enjoy private tours at NASA's Jet Propulsion Lab, CalTech and the Mount Wilson Observatory, where we'll stay until after dark to observe the stars through the same Hooker telescope that Edwin Hubble used in 1923 to discover the Andromeda galaxy.*



NOTES: Maximum of 40 for our private telescope reservation. Mt. Wilson Observatory is at 5,700 feet of elevation and not ADA compliant.

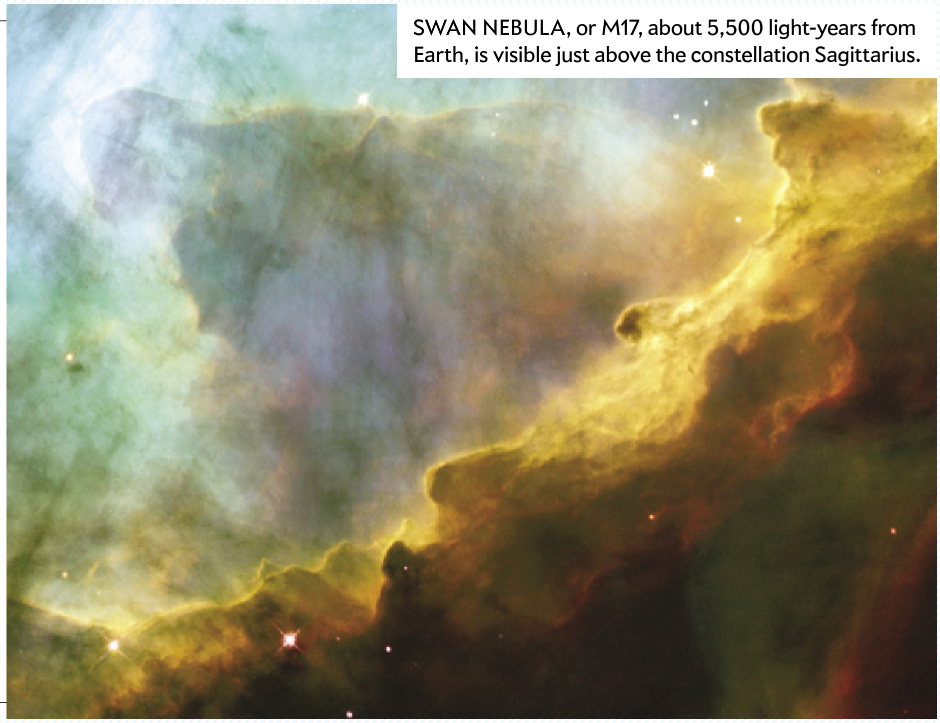
CST# 2065380-40

For more info please email: Info@InsightCruises.com or visit: ScientificAmerican.com/Travel

By Andrea Gawrylewski

50 Things to See in the Sky

by Sarah Barker.
Princeton Architectural Press, 2019 ($16.95)



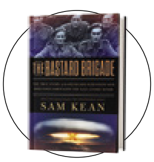
SWAN NEBULA, or M17, about 5,500 light-years from Earth, is visible just above the constellation Sagittarius.

NASA, ESA AND J. HESTER *Arizona State University*

In this stargazer's guide (with a glow-in-the-dark cover), astrophysicist Barker gives tips for finding celestial phenomena with or without a telescope. She shares practical tips and tricks to navigate the boundless sky, such as how to identify the constellation Orion, spot the red supergiant star Betelgeuse and even locate the *Apollo 11* moon landing site. The amusing illustrations and maps come in handy to identify the right time and place for observing. Although only 50 sights are highlighted, there is much more to explore out there. As Barker writes, "the sky isn't the limit—the sky has no limit." *—Sunya Bhutta*

The Bastard Brigade: The True Story of the Renegade Scientists and Spies Who Sabotaged the Nazi Atomic Bomb

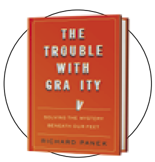
by Sam Kean. Little, Brown, 2019 ($30)



As World War II enveloped Europe and the Pacific, a battle was playing out between a group of Nazi physicists dubbed the Uranium Club and the Alsos Mission, a clandestine faction of the Manhattan Project. Writer Kean breaks down the sabotage efforts of Alsos members such as baseball-player-turned-spy Moe Berg, as well as others who got drawn in, including Joseph Kennedy, Jr., and Nobel Prize–winning chemist Irène Joliot-Curie. Together they prevented the Nazis from developing nuclear weapons. Kean traces the scientific discoveries that led to the creation of the bomb and includes illustrations that take on challenging concepts. The world might be vastly different had Germany harnessed nuclear weapons first. *—Jennifer Leman*

The Trouble with Gravity: Solving the Mystery beneath Our Feet

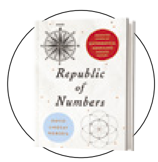
by Richard Panek.
Houghton Mifflin Harcourt, 2019 ($28)



The reason rain falls down, not up, and why balls inevitably reach the ground: gravity. This most familiar force seems simple—even babies get the concept. Yet gravity is fundamentally a mystery, writer Panek reveals in this beautiful and philosophical investigation of nature's weakest force. He surveys creation myths for a cultural understanding of gravity, interviews physicists about why the multiverse might explain gravity's strangeness and even meditates on the force of gravity pulling the waves off Italy's Amalfi Coast. Readers will not emerge from this book with the answer to the question "What is gravity?"—a so far unanswerable quandary—but they will gain many and varied insights from the asking. *—Clara Moskowitz*

Republic of Numbers: Unexpected Stories of Mathematical Americans through History

by David Lindsay Roberts.
Johns Hopkins University Press, 2019 ($29.95)



The U.S. was once a backwater for mathematical research, but over the past 200 years it has become a powerhouse, writes math professor Roberts. He explores this transition through stories of lesser-known thinkers, such as Catharine Beecher, who founded schools for women and wrote arithmetic textbooks, and famous ones such as John Nash. Perhaps most unexpected is a chapter on Abraham Lincoln, who gained math experience surveying land and studying geometry. Roberts calls into question Lincoln's heroic status, describing the surveying's role in forcing Native Americans off their land. Later chapters offer a similar dose of honesty, entwining mathematics with social realities. *—Leila Sloman*

Zeynep Tufekci is an associate professor at the University of North Carolina School of Information and Library Science and a regular contributor to the *New York Times*. Her book, *Twitter and Tear Gas: The Power and Fragility of Networked Protest,* was published by Yale University Press in 2017.

Has Google Maps Rotted My Brain?

Maybe, but it's also made me a more confident traveler

By Zeynep Tufekci

More than a billion people around the world have smartphones, almost all of which come with some kind of navigation app such as Google or Apple Maps or Waze. This raises the age-old question we encounter with any technology: What skills are we losing? But also, crucially: What capabilities are we gaining?

Talking with people who are good at finding their way around or adept at using paper maps, I often hear a lot of frustration with digital maps. North/south orientation gets messed up, and you can see only a small section at a time. And unlike with paper maps, one loses a lot of detail after zooming out.

I can see all that and sympathize that it may be quite frustrating for the already skilled to be confined to a small phone screen. (Although map apps aren't really meant to be replacements for paper maps, which appeal to our eyes, but are actually designed to be *heard:* "Turn left in 200 feet. Your destination will be on the right.")

But consider what digital navigation aids have meant for someone like me. Despite being a frequent traveler, I'm so terrible at finding my way that I still use Google Maps almost every day in the small town where I have lived for many years. What looks like an inferior product to some has been a significant expansion of my own capabilities. I'd even call it life-changing.

Part of the problem is that reading paper maps requires a specific skill set. There is nothing natural about them. In many developed nations, including the U.S., one expects street names and house numbers to be meaningful referents, and instructions such as "go north for three blocks and then west" make sense to those familiar with these conventions. In Istanbul, in contrast, where I grew up, none of those hold true. For one thing, the locals rarely use street names. Why bother when a government or a military coup might change them—again. House and apartment numbers often aren't sequential either because after buildings 1, 2 and 3 were built, someone squeezed in another house between 1 and 2, and now that's 4. But then 5 will maybe get built after 3, and 6 will be between 2 and 3. Good luck with 1, 4, 2, 6, 5, and so on, sometimes into the hundreds, in jumbled order. Besides, the city is full of winding, ancient alleys that intersect with newer avenues at many angles. Instructions as simple as "go north" would require a helicopter or a bulldozer.

In such places, you navigate by making your way to a large, well-known landmark and asking whomever is around how to get to your destination—which involves getting to the next big landmark and asking again. In American suburbs, however, there is often nobody outside to ask—and even when there is, "turn right at the next ornate mosque" is a different level of specificity than "turn right at the next strip mall."

All of this means that between my arrival in more developed nations and the arrival of Google Maps, I got lost all the time, searching in vain for someone to ask. Even when I traveled to cities that were old like Istanbul, I still felt uncomfortable. I didn't necessarily speak the language well enough or know the major landmarks so my skills didn't transfer.

I tried many techniques, and maybe I would have gotten eventually better—who knows? But along came Google Maps, like a fairy grandmother whispering directions in my ear.

Since then, I travel with a lot more confidence, and my world has opened up. Maybe it is true that I am especially directionally challenged, but I cannot be the only one. And because I go to more places more confidently, I believe my native navigation skills have somewhat improved, too.

Which brings me back to my original question: while we often lose some skills after outsourcing the work to technology, this new setup may also allow us to expand our capabilities. Consider the calculator: I don't doubt that our arithmetic skills might have regressed a bit as the little machines became ubiquitous, but calculations that were once tedious and error-prone are now much more straightforward—and one can certainly do more complex equations more confidently. Maybe when technology closes a door, we should also look for the doors it opens. SA

JOIN THE CONVERSATION ONLINE
Visit *Scientific American* on Facebook and Twitter
or send a letter to the editor: editors@sciam.com

Illustration by James Olstein

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.

Bad Bites

Mosquitoes may have killed about half of all *Homo sapiens* who ever existed

By Steve Mirsky

In the middle of a humid night in November 1997, two scientists and I donned waders and walked into the water of a half-acre test pond about 20 miles west of West Palm Beach, Fla. The researchers were there to set up egret decoys before the real birds flew over at dawn. I'd been warned about the snakes we might encounter while I was reporting on their research for this magazine [see "The Painted Bird"; February 1998]. Our flashlights illuminated the eyes of not too distant alligators. But despite the potential for venomous and/or crushing reptile bites, the most pressing safety concern explained my long sleeves and head netting—preventing the pinprick puncture of encephalitis-carrying mosquitoes.

I was reminded of my 4 A.M. tromp upon the arrival of the new book *The Mosquito: A Human History of Our Deadliest Predator*. Most people are probably more frightened of sharks than they are of mosquitoes—it's tough to get too worked up over something you can swat. But as author Timothy Winegard points out, sharks kill fewer than 10 people annually, whereas the average yearly mosquito-related death toll over the past two decades is about two million. Mosquitoes *are* the deadliest predator of people on the planet.

The runner-up killer of human beings is—you guessed it—human beings. In that same stretch, we've offed about 475,000 of our fellows on average annually, Winegard reports. Granted, it would be tough for 7.7 billion humans to outkill the 110 *trillion* mosquitoes that are alive at any time. That's more than 14,000 of them for every person. In the Arctic during the summer, they can completely cover something (or someone) edible in a flash. "Ravenous mosquito swarms," Winegard writes, "literally bleed young caribou to death at a bite rate of 9,000 per minute, or by way of comparison, they can drain half the blood from an adult human in just two hours."

Of course, human expiration via exsanguination by mosquito is exceedingly rare. "It is the toxic and highly evolved diseases she transmits that cause an endless barrage of desolation and death," Winegard writes. He uses "she" because only females bite, attracted to us mostly by the carbon dioxide exhalations that they can detect up to 200 feet away. They also like really smelly feet. So if you think you can hide in plain sight by holding your breath, be sure to also wash between your toes before you pass out.

Of the more than 15 diseases mosquitoes transmit, the deadliest—malaria—has been sickening animals for an exceedingly long time. "Amber-encased mosquito specimens contain the blood of dinosaurs infected with various mosquito-borne diseases, including malaria," Winegard writes. He notes that the 1993 movie *Jurassic Park* gets it wrong because the mosquito depicted as having supplied the dinosaur blood, and thus its DNA, is one of the few species for which blood meals are not required for reproduction. Indeed, that egregious error is what blew the movie's verisimilitude for me.

The book claims that mosquito diseases played a critical role in the American colonists' underdog win in 1783 against the British in the Revolutionary War. George Washington, himself a malaria sufferer, "had the advantage of commanding acclimated, malaria-seasoned colonial troops." Meanwhile many British troops had never been exposed and were mowed down by the kill-buzz.

Washington was first in war, first in peace and the first of eight presidents to be afflicted with malaria, according to Winegard. The others were Lincoln, Monroe, Jackson, Grant, Garfield, Teddy Roosevelt and John F. Kennedy. Roosevelt caught his in the Amazon, and Kennedy got it in the South Pacific, but the first six all got the disease in the U.S. when malaria and yellow fever were still common here.

In 2018 Climate Central reported that higher temperatures could mean more "disease danger days," in the temperature range that disease-carrying mosquitoes prefer. But take heart: "Climate change may also actually make some locations too hot for mosquito survival and disease transmission," Climate Central acknowledged. Finally, some good news. ■

JOIN THE CONVERSATION ONLINE
Visit *Scientific American* on Facebook and Twitter or send a letter to the editor: editors@sciam.com

Illustration by Matt Collins

50, 100 & 150 YEARS AGO

INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Daniel C. Schlenoff

OCTOBER

1969 Bubble Computers

"The Bell Telephone Laboratories have disclosed a new way to build electronic data-processing circuits by manipulating the flow of tiny magnetic 'bubbles'—actually magnetic domains in the form of microscopic cylinders embedded in thin sheets of ferrite. The bubbles can be moved around with less energy than is needed to switch a transistor and, being only a few wavelengths of light across, they can be packed with a density of a million or more to the square inch. The bubbles can be created, erased and shunted around to perform a variety of functions: logic, memory, switching and counting. Data rates of three million bits per second have been demonstrated."

The system was made obsolete by faster semiconductor chips with more memory density and efficient flash memory.

1919 Stalking Polio

"In the United States we are becoming increasingly familiar with epidemics of polio myelitis. Prior to 1907, infantile paralysis was a rare disease in this country. Since then it has prevailed fitfully every summer and autumn. Fundamental knowledge of poliomyelitis may be said to have grown rapidly since Ivar Wickman's epochal clinical studies published in 1907. We are today in possession of precise information with regard to the nature of the inciting micro-organism, and the manner in which it leaves the infected body within the secretions of the nasopharynx chiefly and gains access to another human being by means of the corresponding mucous membranes, and apparently in no other way."

Less Horse Power

"The postmaster at Madras, India, recently experimented with three autos in the place of horse-drawn vehicles for the conveyance of mail. The experiment was said to be the first of its kind in India and to be so successful that the entire horse service is now to be abolished."

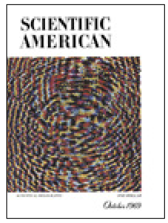
A Fair Hunt

"In the report of the Departmental Committee which has been considering the protection of wild birds in Great Britain, it is pointed out that a novel danger to bird life has been introduced, in shooting and bombing from aircraft. The Committee recommends that the use of aircraft against wild birds be prohibited."

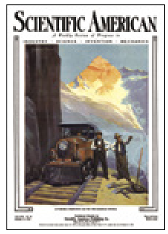
1869 Arsenic Eaters

"Men of science who traversed Styria, in Austria, have long reported that there were people in Styria who consumed arsenic. However, this statement was denied by others, who affirmed that the white mineral they ate was nothing but chalk. Prompted by the importance of this subject, the royal medical counsel, Dr. Von Vest, issued a circular to the physicians of Styria, requesting them to communicate their experiences with regard thereto. Seventeen reports were obtained. The district of Hartberg counts not less than forty individuals who indulge in that habit. From the various sorts of arsenic, the white arsenic, or ratsbane, is mostly taken, less so the commercial yellow, and still less the natural red arsenic. The arsenic eaters begin with the dose of the size of a millet, and increase this quantity gradually. These doses are either taken daily, or every other day, or only once or twice a week. In the district of Hartberg the custom prevails to suspend this unwise usage at the time of the new moon."

The question of whether humans can acquire tolerance to this toxic substance seems to be still open.



1969

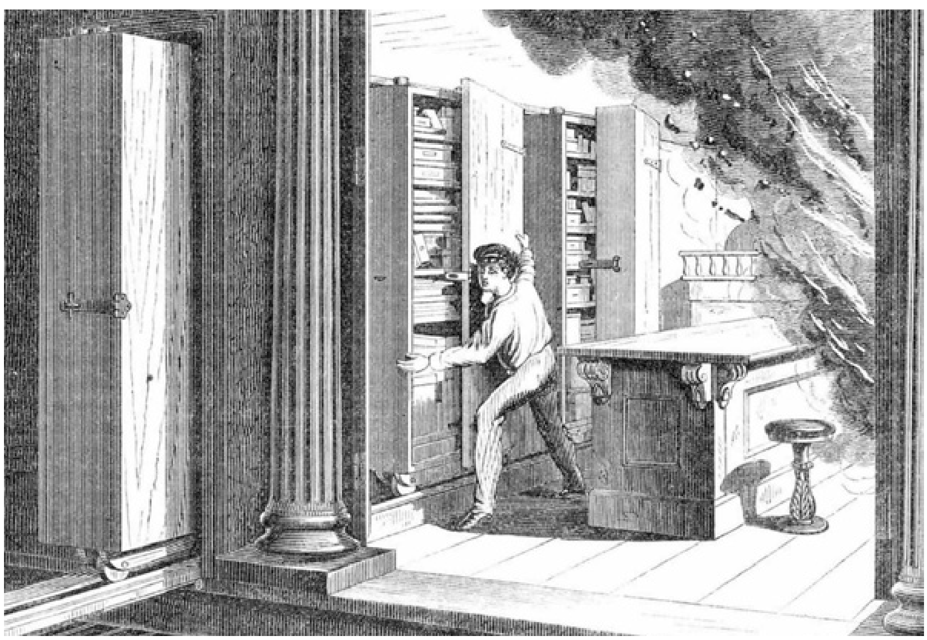


1919

1869

In Case of Fire

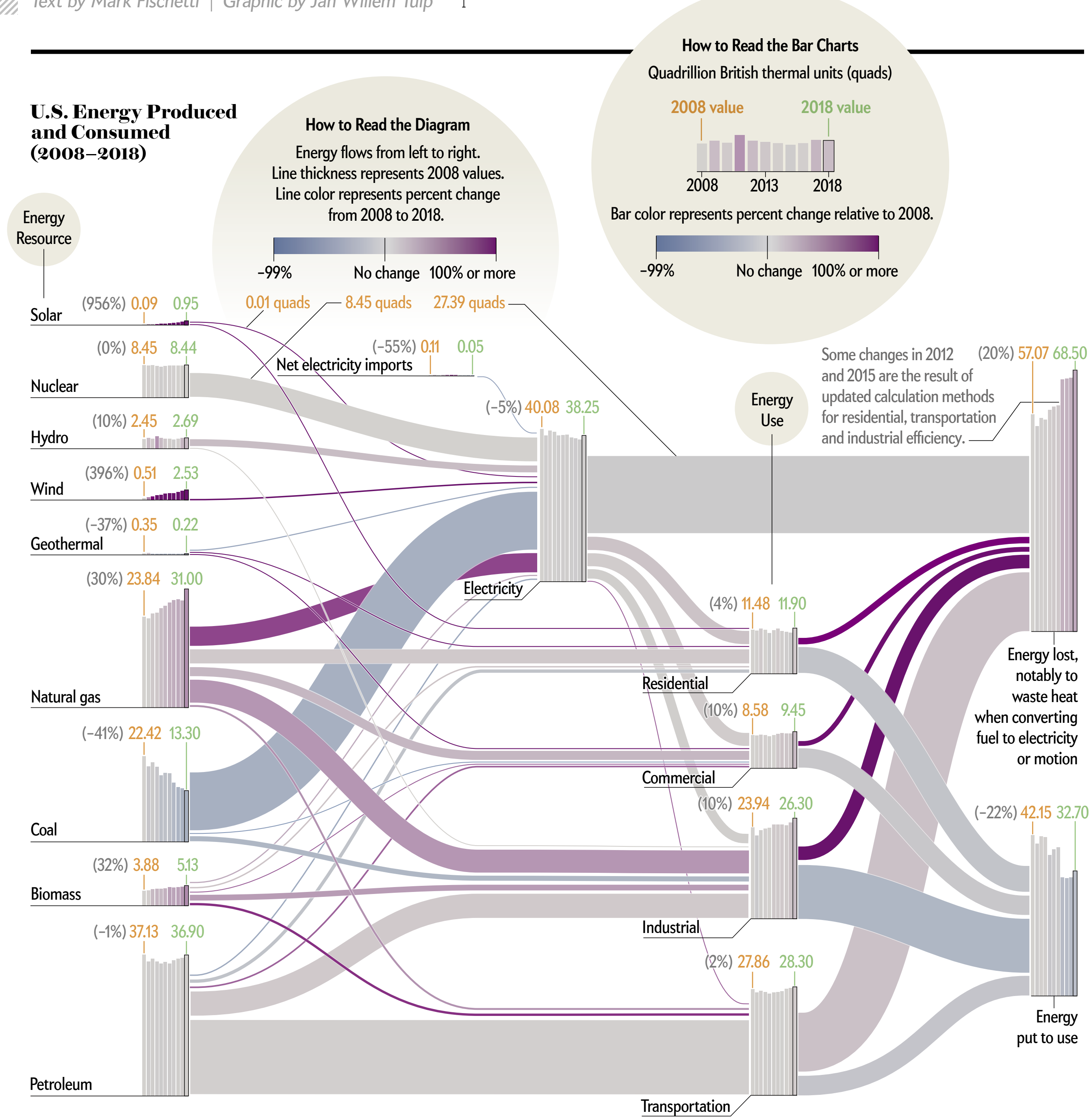
"Improved shelving provides means whereby valuable stocks of goods, books in public libraries and cabinets, letter cases in post offices, etc., can be readily rescued in case of fire. The accompanying engraving tells the whole story. The shelving is made in sections which can be closed with great rapidity, and run out of a building without moving goods or books. The sections are provided at the bottom with rollers or wheels which rest upon tracks. This improvement merits general consideration."



1869: Save the stock! The duties of a clerk during a fire.

SCIENTIFIC AMERICAN, VOL. XXI, NO. 14; OCTOBER 2, 1869

Text by Mark Fischetti | Graphic by Jan Willem Tulp



Cleaning Up

Shifts in the U.S. power supply may be sharper than you think

It can be tricky to resolve different tales that are told about which U.S. energy sources are growing or fading. But now we have hard numbers. Annual flowcharts from Lawrence Livermore National Laboratory show that over the past decade, wind power has increased 396 percent and solar power is up 956 percent. Of course, a very small share can rise by many percentage points and still be small, but that traditional narrative about wind and solar is nearly over: together they now provide 3.48 quads (quadrillion BTU) of electricity—more than hydropower. The natural gas story is clearer, too: it has not surged "recently" but rather has grown steadily for 10 years, and this trend is the main cause of a continual decrease in coal consumption. If these trends persist, says A. J. Simon, Livermore's energy group leader, "we can expect our energy economy to continue to get cleaner."

SOURCE: LAWRENCE LIVERMORE NATIONAL LABORATORY (*data*)


©2019 UPMC
UN
COM
MON
is
CHANGING MEDICINE
AS WE KNOW IT.
Uncommon is daring to question the established way.
At UPMC, we're transforming health care,
one fearless idea at a time. Welcome to change.
UPMC
LIFE CHANGING MEDICINE
UPMCNext.com

ERRORS

editors@sciam.com

SCIENTIFIC AMERICAN,
OCTOBER 2019: PAGE 36

"Is Death Reversible?" by Christof Koch, should have described modern fields such as machine learning as creating an illusion of understanding the "vegetative soul" rather than the "sensitive soul." The vegetative soul defines the body's basic physical functions.