MATHEMATICS
Celebrating Martin Gardner

CELL BIOLOGY
How Forces Create Organs—or Tumors

ENVIRONMENT
Climate and an Inconvenient Ice

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OCTOBER 2014

A Beacon from the Big Bang

It could reveal insights about the early universe and maybe even the "theory of everything"

SPECIAL REPORT
State of the World's Science 2014
HOW DIVERSITY POWERS INNOVATION

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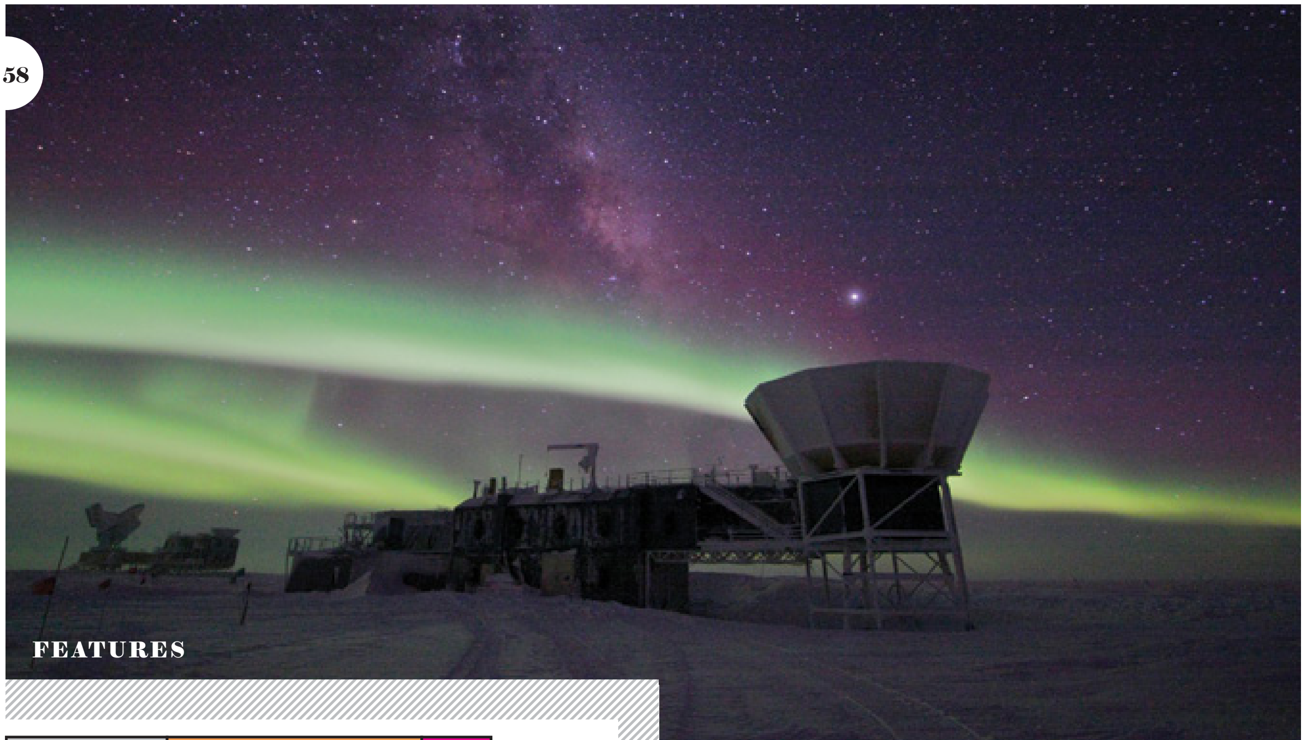
October 2014 Volume 311, Number 4

ON THE COVER

Earlier this year a group of astronomers announced a stunning discovery: evidence of gravitational waves that had originated in the first instant after the big bang. If the finding is confirmed, it will be "one of the most important in decades," according to physicist Lawrence M. Krauss. He explains what the waves might reveal about the birth of our universe—and others. Illustration by Mark Ross.



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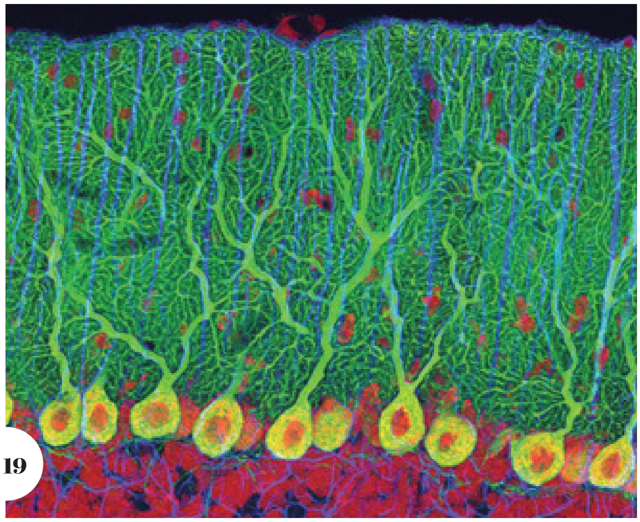

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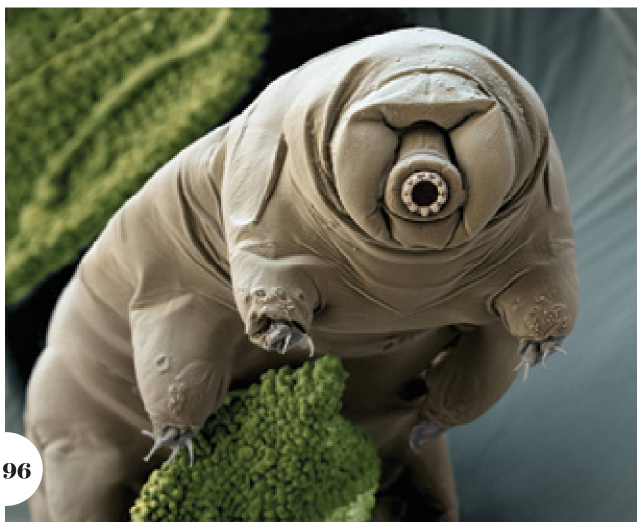

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2014 Nobel Prize Winners
Scientific American covers this year's prizes, awarded in October, across all science categories, including who won and the impact of their award-winning contributions.
Go to www.ScientificAmerican.com/oct2014/nobel

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Life Photonics

Right now, the earth's populations are facing a multitude of challenges such as global warming and biodiversity issues, that are beginning to upset the balance of life itself on a global scale. At Hamamatsu Photonics, we use the term Life Photonics to describe research and development topics that embrace sustainability as a core value. We conduct our activities with an emphasis on diverse viewpoints and mutual interactions among individual engineers and researchers, so as to ultimately ensure a lasting future for every form of life on earth.

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

You're Invited

"WHAT IS YOUR VISION?" IT WAS 2009, AND MY NEW BOSS, Steven Inchcoombe, had just inspired me with the most wonderful invitation. I was executive editor of *Scientific American* at the time, and what did I want to do if I could earn the privilege of becoming editor in chief? In my mind's eye, the future opened before me. What did *Scientific American* need to become *now* that it had not been in the past, and how could it do that?

Like the seven editors in chief who preceded me since 1845, I believe science is an engine of prosperity. The laptop I'm using right now, our food, clothing, buildings—the expanse of human knowledge itself—all these things were improved through the process we call science. And science underpins the critical challenges that humanity wrestles with today, from cures for our ailments to living sustainably in a finite world. It's just that, as I realized, people don't always call it science, or they don't see the connection between the things they care about and science. My job, I decided, would be about inviting people into science through *Scientific American,* so they could understand.

Immediately, I asked scientists to join as advisers, to help steer our course; you see them listed below this letter. We redesigned the magazine and Web site in 2010, the better to engage our audiences. We launched a series of education initiatives in 2011 for families and educators. That year we also started our network of lively, independent bloggers to widen the community discussion. In 2012 we added the *Scientific American* Science in Action Award, powered by the Google Science Fair. I began attending the World Economic Forum meetings in Davos, Switzerland, and in China to share news about innovation with leaders in policy and business, who have always been part of our readership. In July, I also spoke to the Senate Committee on Commerce, Science, and Transportation about the value of funding basic research.

SENATE SCIENCE witnesses Vint Cerf, Google's Internet evangelist, and DiChristina look at a facsimile of *Scientific American*'s first 1845 issue before their testimony.

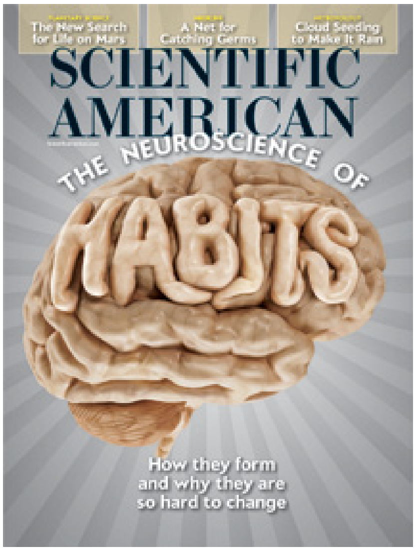
ALEX WONG *Getty Images*

In our new Voices blog, edited by blogs editor Curtis Brainard, and in this issue's annual "State of the World's Science," organized by executive editor Fred Guterl, we take a special look at diversity—how bringing in different perspectives can power science innovation still more for a better future for us all. Turn to page 38.

And it all started when I realized how inspiring an invitation could be. (Thanks, Steven.) SA

Illustration by Nick Higgins

editors@sciam.com



June 2014

"The dominant global economic paradigm is itself a mega-Ponzi scheme."

JOHN O'HARA *MOUNT WAVERLEY, AUSTRALIA*

DILEMMAS OF FREE WILL

In "The World without Free Will," Azim F. Shariff and Kathleen D. Vohs assert that a survey revealed that "the more people doubt free will, the less they favor 'retributive' punishment" and indicate that the notion of free will is necessary to social order. What constitutes human freedom is a complex matter, fraught with ambiguities that have been debated for millennia. The authors don't clarify the survey's questions. For instance, what if it had asked respondents to rate the relative influence of several factors, such as physical laws, biological impulses, life experiences, the cultural environment, rational deliberation or a sense of self-determination? Wouldn't that have elicited a more nuanced response?

Richard M. Rubin
Adjunct lecturer in philosophy
Washington University in St. Louis

Shariff and Vohs ask the question "What will our society do if it finds itself without the concept of free will?" But they do little to clarify the issue. They show, at best, that there is a temporary disturbance in the moral compass of people freshly exposed to the idea that free will does not exist. Many things have the same temporary effect, including emotional states such as love or hate and war or abuse. The important question is whether a prolonged exposure to a different view of free will changes us. To answer that, there are plenty of historical and anthropological data to prioritize over those they discuss.

Raymond Duchesne
Round Hill, Va.

HIDDEN PONZIS

In "The Ponzi Economy," Kaushik Basu does a great disservice to those of us involved in the day-to-day operations of the economy by implying that many of the activities we undertake are no different from a scam. His article easily fits with preconceived notions that actively engaging in commerce is somehow demeaning and morally bankrupt. (Witness that the only emotion allowed private-sector participants is greed.)

Thomas A. Fink
North Caldwell, N.J.

Despite the title of Basu's article, he doesn't draw what seems to me the inevitable conclusion that the dominant global economic paradigm (neoliberal capitalism) is itself a mega-Ponzi scheme. It is predicated on infinite growth, there is no graceful way to a soft landing, the system collapses when growth is no longer possible, and we can't predict a well-defined point at which the crash occurs.

John O'Hara
Mount Waverley, Australia

BAD HABITS

In addition to the excellent points Ann M. Graybiel and Kyle S. Smith make about the difficulties people face as they try to change habits in "Good Habits, Bad Habits," there are the social barriers such individuals face from the social groups they are a part of. Working in a part of health care that deals with this constantly, I have had some patients who had to change friends because they were no longer accepted because of their healthier behavior and others chastised by their boss for not participating in every pizza party or early-morning doughnut meeting. Most people with bad habits are just well adapted to a social environment of bad habits.

Mike Taylor
via e-mail

DNA ARITHMETIC

In his article describing biosensors that can quickly identify viral, bacterial or fungal origins of disease ["Germ Catcher"], David J. Ecker asserts that 43 adenine, 28 guanine, 19 cytosine and 35 thymine nucleotide subunits constitute a unique solution for a DNA strand weighing 38,765.05 daltons. I tried to duplicate the result and got about 10 possible solutions. Can you shed some further light on this very interesting technique?

David Mawdsley
Danbury, Conn.

Would it be possible to use the technological machinery Ecker describes to determine the differences in the flora of the digestive tract between people who are of a healthy weight and those who suffer from morbid obesity? If this is a possibility, then a probiotic could be specifically developed for particular individuals' needs, improving their digestive flora to make weight loss an easier process.

Ron Rega
Marietta, Ga.

ECKER REPLIES: Mawdsley is correct. Referring to 38,765.05 daltons as corresponding uniquely to a DNA strand containing the subunits 43 adenine, 28 guanine, 19 cytosine and 35 thymine was a simplification for illustrative purposes. With additional decimal points in the measurement, however, the solution does become unique. But this ignores the fact that there is a 10-parts-per-million (ppm) error in the measurement, which would actually enable nearly 1,000 possible base compositions as correct solutions!

But because our system separates the double-stranded DNA and independently measures each of the single strands and because we know that the A count in one strand must equal the T count in its double-helical partner (same for G and C), at a measurement deviation tolerance of 10 ppm, there is only one solution that fits for both strands. Constraining the prob-

lem by considering both strands in conjunction with Watson-Crick rules is part of the algorithm used by the technology.

In reply to Rega: Indeed, the system could, in theory, be used to characterize intestinal flora and might be used to provide a picture of the "enterotype," or microbiota, of individuals and then to measure perturbations that result from prebiotic or probiotic therapy.

BIRTH BACTERIA

The question of how newborns acquire their flora at birth, brought up in "Gut Reactions," by Claudia Wallis [The Science of Health], remains fascinating and unanswered. As a midwife, I do not rupture the sealed fetal sac. It usually spontaneously ruptures, but in 5 percent of my births, the baby emerges in the intact sac, never directly exposed to the mother's vaginal or intestinal flora. Breast-feeding is a possible route for the immediate colonization of the intestines after birth. If so, how do intestinal bacteria get into the milk?

JUDY SLOME COHAIN
Certified nurse midwife
Alon Shvut, Israel

WALLIS REPLIES: To begin with, the uterine environment is not the pristine place it was once thought to be; microbes are present there and in the placenta. Second, during birth it is likely there would be some contact with the mother's microbes even when the sac is unbroken. Third, according to Maria Gloria Dominguez-Bello of the New York University School of Medicine, the mother's nipples and milk ducts very likely harbor bacteria that thrive in milk and that these then colonize the infant gut.

ERRATA

"Full Disclosure," by the Editors [Science Agenda], gives the generic name of Vioxx as celecoxib. It is rofecoxib.

"A Milestone on the Long and Winding Road to Fusion," by David Biello, states that lasers at Lawrence Livermore National Laboratory used to produce fusion require about 500 trillion joules. The figure should be at least 190 million joules.

"Summon the Rain," by Dan Baum, incorrectly refers to the volume of a small cloud as topping 750 cubic kilometers. A typical cloud is one cubic kilometer.

LETTERS TO THE EDITOR

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Letters may be edited for length and clarity. We regret that we cannot answer each one. Post a comment on any article at ScientificAmerican.com/oct2014

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Preferential Treatment

Good intentions are not enough to end racial and gender bias

Scientists pride themselves on their objectivity, yet when it comes to gender and race, they are as partial as everyone else. A 1999 study, for example, found that academic psychologists were more likely to recommend hiring a male job applicant than a female one with an identical record. A résumé assigned the name Brad Baker is more likely to lead to a job interview than one from Rasheed Jones. Numerous studies have shown that women scientists get weaker letters of recommendation. Whereas female applicants to a faculty position at a medical school were called "teachers" and "students," men were "researchers" and "professionals."

These kinds of biases are unconscious and subtle but invidious enough to suppress the diversity of students and faculty in many university science, engineering and math departments and in the scientific workforce at large. As of 2010, white men made up 51 percent of all working scientists and engineers, in contrast to white women (18 percent) and black and Hispanic men and women, who each held 4 percent or fewer of these jobs. As Katherine W. Phillips shows in "How Diversity Works," starting on page 42, diversity is not only socially just, it is an essential ingredient in high-quality scientific work.

Asking individuals to check their own predispositions is a worthy step, but it is insufficient. Unconscious biases cannot be wished away. Institutions must strive to eliminate opportunities for implicit bias to affect decisions on hiring and promotions. Systemic changes are crucial.

One simple way to help ensure that rewards go to the most deserving applicants—not just the ones with the right names—is to strip critical documents of identifying information. Hiring committees cannot favor white and male applicants if résumés have only a number at the top. Peer reviewers cannot disproportionately reject journal papers from women and ethnic minorities if author identities are hidden.

A 2012 study of Swedish data on real-life job applications showed that anonymous hiring practices increased the chances that women and minorities made it to the interview stage. The same thing happened in a 2010–2011 German pilot program when participating companies removed personal details such as age and gender from job applications. Symphony orchestras have found that they are more likely to hire women when musicians audition from behind a screen.

University science departments can and should obscure the identities of applicants on curricula vitae (CVs) and other materials during the first round of screening for new faculty members and graduate students. That won't be a panacea, of course: in some circumstances, the identity of an applicant can be sussed out from the details and collaborators on the CV. Still, "anonymization" introduces an element of doubt that helps reviewers strive for objectivity. By the time a candidate shows up for the interview, the hiring board will have had a better chance of forming a first impression on the basis of work and experience, with no stereotypes attached. Anonymity can also help in grading classwork and reviewing grants. It should be mandatory in universities and grant-giving institutions.

Keeping authors of scientific papers anonymous has been shown to improve women's odds of acceptance. The practice can also block bias against minorities and in favor of authors and institutions with big reputations. Double-blind peer review, in which the identities of both authors and reviewers are hidden from one another, is already common in the social sciences and humanities, and now science journals are starting to pick it up. A trial of double-blind peer review began in June 2013 at *Nature Geoscience* and *Nature Climate Change,* and *Conservation Biology* is considering adopting the practice. (*Scientific American* is part of Nature Publishing Group.) More science journals should follow their example.

Language is also important. When a National Institutes of Health award emphasized "aggressive risk taking" among its criteria, all nine of the first winners were men; later, terms such as "pioneering" and "high impact" attracted and rewarded more women. Training in identifying and compensating for implicit bias should be mandatory in scientific organizations. And because training is never perfect, documents under review should be anonymous. Awards must be based on merit—not a name. SA

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Illustration by Davide Bonazzi

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Cooperstown, N.Y.

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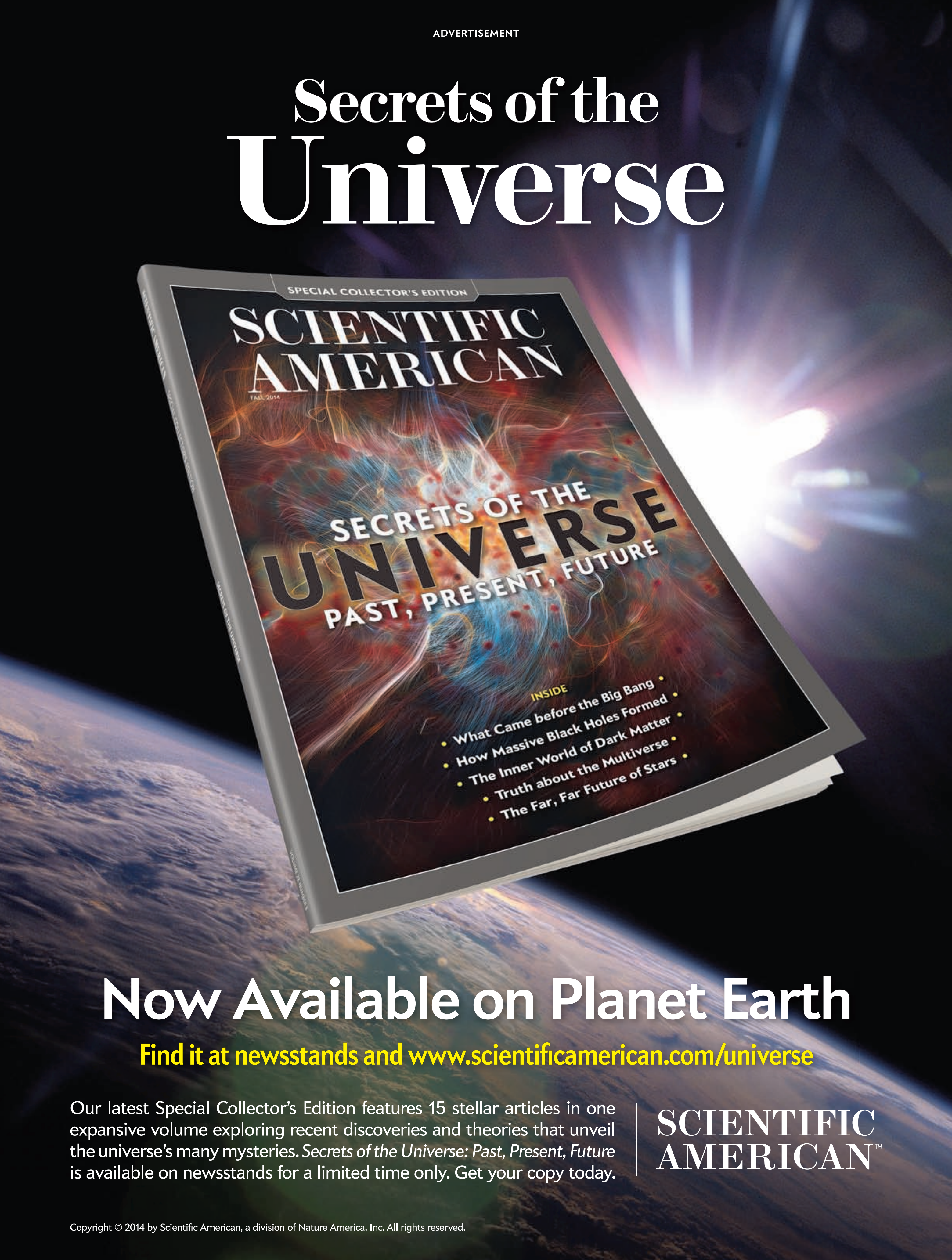
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Ben Nelson is founder and CEO of the Minerva Project.

Passing the Midterm

Educators need to think long-term about the role of technology in learning

The rampant spread of technology-mediated learning has set off fits of hype and hand-wringing—yet the U.S.'s traditional centers of higher education have mostly failed to confront the pace of change and the implications for students. There is probably no way anyone can keep up with this transformation: the technology is simply evolving too rapidly. Nevertheless, we keep trying. Will these developments truly serve our goals for advanced education? We need to know urgently.

But reacting too quickly could be as bad as adapting too slowly. As soon as the newest experiment in higher-learning technology is announced, would-be experts race to declare its success or failure. Even if their snap guesses prove correct in the near term, any alleged breakthrough will likely be sent to the scrapyard before long to make way for the next educational techno-marvel. Given what we know about the progress of technology, we need to ask which advances will persist longer than a few months.

Higher learning has three fundamental objectives: knowledge dissemination, intellectual development and "experiential growth"—mental maturation, in other words. As the field of educational technology grows, these functions must all be addressed.

The first item—dissemination of knowledge—has traditionally been the province of classrooms and lecture halls. Nowadays even the most venerated names in education are touting what they call MOOCs. These "massive open online courses" are the online equivalent of brick-and-mortar lecture halls, only with better functionality (such as the ability to pause and rewind), free tuition and unlimited seating.

That sounds good, but to see the real future of knowledge dissemination, we must look even farther ahead. Although adaptive learning technologies are still in their infancy, they are already displaying huge promise. The idea is to tailor the teaching process to each student's progress. As the tools develop, adaptive learning will bring seismic shifts to the instruction process. Companies such as Knewton and systems such as the Open Learning Initiative at Carnegie Mellon University are just a hint of what's to come. These technologies will provide a whole new mode of instruction, and it will be less expensive and more effective than the old "sage on a stage" model. Although many traditional universities are addicted to the tuitions they draw with big lecture halls, online institutions and companies such as Western Governors University, UniversityNow and StraighterLine have begun demonstrating a viable alternative. The mainstream academic world should take notice.

The second priority is students' intellectual development. People often assume, mistakenly, that this area is beyond the scope of technological improvement. They see no substitute for the one-on-one student-teacher bond exemplified by the high-touch methods of the so-called Oxbridge tutorial system. But can even a very good mentor offset the shortcomings of most present-day institutions, where instruction is delivered course by course, with no core curriculum? The scaffolded curriculum at Minerva Schools at the Keck Graduate Institute, the San Francisco–based university that I helped to found in 2013, teaches a core set of concepts and exercises them throughout all classes in every subject.

The third and final task remains the big challenge for educational technology: personal development via experiential learning. For students, this is the lifelong process of becoming a more cultured, accomplished and compassionate human being. Traditional universities try to help students along through hands-on work in laboratories and apprenticeships, and they encourage undergraduates to take summer internships and spend semesters abroad. Nevertheless, students mostly remain anchored to their campuses. Even now technology should make it possible for a student to use the world as her or his campus.

Given the technological transformation taking place on all sides, universities need to think seriously about their medium-term strategic plans. What will universities look like in 2025? The changes will be consequential—so consequential, in fact, that stalling could jeopardize the future of higher education. SA

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Illustration by Peter and Maria Hoey

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Atrial Fibrillation (AFib) not caused by a heart valve problem

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Ask your doctor if ELIQUIS is right for you.

This risk is higher if, an epidural catheter is placed in your back to give you certain medicine, you take NSAIDs or blood thinners, you have a history of difficult or repeated epidural or spinal punctures. Tell your doctor right away if you have tingling, numbness, or muscle weakness, especially in your legs and feet.

- **Before you take ELIQUIS,** tell your doctor if you have: kidney or liver problems, any other medical condition, or ever had bleeding problems. Tell your doctor if you are pregnant or breastfeeding, or plan to become pregnant or breastfeed.

- **Do not take ELIQUIS if you** currently have certain types of abnormal bleeding or have had a serious allergic reaction to ELIQUIS. A reaction to ELIQUIS can cause hives, rash, itching, and possibly trouble breathing. Get medical help right away if you have sudden chest pain or chest tightness, have sudden swelling of your face or tongue, have trouble breathing, wheezing, or feeling dizzy or faint.

You are encouraged to report negative side effects of prescription drugs to the FDA. Visit www.fda.gov/medwatch, or call 1-800-FDA-1088.

Please see additional Important Product Information on the adjacent page.

Individual results may vary.

Visit ELIQUIS.COM
or call 1-855-ELIQUIS

Eliquis®
(apixaban) tablets 5mg 2.5mg

IMPORTANT FACTS about ELIQUIS® (apixaban) tablets

℞ ONLY

The information below does not take the place of talking with your healthcare professional. Only your healthcare professional knows the specifics of your condition and how ELIQUIS may fit into your overall therapy. Talk to your healthcare professional if you have any questions about ELIQUIS (pronounced ELL eh kwiss).

What is the most important information I should know about ELIQUIS (apixaban)?

For people taking ELIQUIS for atrial fibrillation: Do not stop taking ELIQUIS without talking to the doctor who prescribed it for you. Stopping ELIQUIS increases your risk of having a stroke. ELIQUIS may need to be stopped, prior to surgery or a medical or dental procedure. Your doctor will tell you when you should stop taking ELIQUIS and when you may start taking it again. If you have to stop taking ELIQUIS, your doctor may prescribe another medicine to help prevent a blood clot from forming.

ELIQUIS can cause bleeding which can be serious, and rarely may lead to death. This is because ELIQUIS is a blood thinner medicine that reduces blood clotting.

You may have a higher risk of bleeding if you take ELIQUIS and take other medicines that increase your risk of bleeding, such as aspirin, nonsteroidal anti-inflammatory drugs (called NSAIDs), warfarin (COUMADIN®), heparin, selective serotonin reuptake inhibitors (SSRIs) or serotonin norepinephrine reuptake inhibitors (SNRIs), and other medicines to help prevent or treat blood clots.

Tell your doctor if you take any of these medicines. Ask your doctor or pharmacist if you are not sure if your medicine is one listed above.

While taking ELIQUIS:

- you may bruise more easily
- it may take longer than usual for any bleeding to stop

Call your doctor or get medical help right away if you have any of these signs or symptoms of bleeding when taking ELIQUIS:

- unexpected bleeding, or bleeding that lasts a long time, such as:
  - unusual bleeding from the gums
  - nosebleeds that happen often
  - menstrual bleeding or vaginal bleeding that is heavier than normal
- bleeding that is severe or you cannot control
- red, pink, or brown urine
- red or black stools (looks like tar)
- cough up blood or blood clots
- vomit blood or your vomit looks like coffee grounds
- unexpected pain, swelling, or joint pain
- headaches, feeling dizzy or weak

ELIQUIS (apixaban) is not for patients with artificial heart valves.

Spinal or epidural blood clots or bleeding (hematoma). People who take a blood thinner medicine (anticoagulant) like ELIQUIS, and have medicine injected into their spinal and epidural area, or have a spinal puncture have a risk of forming a blood clot that can cause long-term or permanent loss of the ability to move (paralysis). Your risk of developing a spinal or epidural blood clot is higher if:

- a thin tube called an epidural catheter is placed in your back to give you certain medicine
- you take NSAIDs or a medicine to prevent blood from clotting
- you have a history of difficult or repeated epidural or spinal punctures
- you have a history of problems with your spine or have had surgery on your spine

If you take ELIQUIS and receive spinal anesthesia or have a spinal puncture, your doctor should watch you closely for symptoms of spinal or epidural blood clots or bleeding. Tell your doctor right away if you have tingling, numbness, or muscle weakness, especially in your legs and feet.

What is ELIQUIS?

ELIQUIS is a prescription medicine used to:

- reduce the risk of stroke and blood clots in people who have atrial fibrillation.
- reduce the risk of forming a blood clot in the legs and lungs of people who have just had hip or knee replacement surgery.

It is not known if ELIQUIS is safe and effective in children.

Who should not take ELIQUIS (apixaban)?

Do not take ELIQUIS if you:

- currently have certain types of abnormal bleeding
- have had a serious allergic reaction to ELIQUIS. Ask your doctor if you are not sure

What should I tell my doctor before taking ELIQUIS?

Before you take ELIQUIS, tell your doctor if you:

- have kidney or liver problems
- have any other medical condition
- have ever had bleeding problems
- are pregnant or plan to become pregnant. It is not known if ELIQUIS will harm your unborn baby
- are breastfeeding or plan to breastfeed. It is not known if ELIQUIS passes into your breast milk. You and your doctor should decide if you will take ELIQUIS or breastfeed. You should not do both

Tell all of your doctors and dentists that you are taking ELIQUIS. They should talk to the doctor who prescribed ELIQUIS for you, before you have **any** surgery, medical or dental procedure. **Tell your doctor about all the medicines you take, including** prescription and over-the-counter medicines, vitamins, and herbal supplements. Some of your other medicines may affect the way ELIQUIS works. Certain medicines may increase your risk of bleeding or stroke when taken with ELIQUIS.

How should I take ELIQUIS?

Take ELIQUIS exactly as prescribed by your doctor. Take ELIQUIS twice every day with or without food, and do not change your dose or stop taking it unless your doctor tells you to. If you miss a dose of ELIQUIS, take it as soon as you remember, and do not take more than one dose at the same time. **Do not run out of ELIQUIS (apixaban). Refill your prescription before you run out.** When leaving the hospital following hip or knee replacement, be sure that you will have ELIQUIS available to avoid missing any doses. **If you are taking ELIQUIS for atrial fibrillation, stopping ELIQUIS may increase your risk of having a stroke.**

What are the possible side effects of ELIQUIS?

- See **"What is the most important information I should know about ELIQUIS?"**
- ELIQUIS can cause a skin rash or severe allergic reaction. Call your doctor or get medical help right away if you have any of the following symptoms:
  - chest pain or tightness
  - swelling of your face or tongue
  - trouble breathing or wheezing
  - feeling dizzy or faint

Tell your doctor if you have any side effect that bothers you or that does not go away.

These are not all of the possible side effects of ELIQUIS. For more information, ask your doctor or pharmacist.

Call your doctor for medical advice about side effects. You may report side effects to FDA at 1-800-FDA-1088.

This is a brief summary of the most important information about ELIQUIS. For more information, talk with your doctor or pharmacist, call 1-855-ELIQUIS (1-855-354-7847), or go to www.ELIQUIS.com.

Manufactured by:
Bristol-Myers Squibb Company
Princeton, New Jersey 08543 USA
Marketed by:
Bristol-Myers Squibb Company
Princeton, New Jersey 08543 USA
and
Pfizer Inc
New York, New York 10017 USA

Bristol-Myers Squibb | PATIENT ASSISTANCE FOUNDATION

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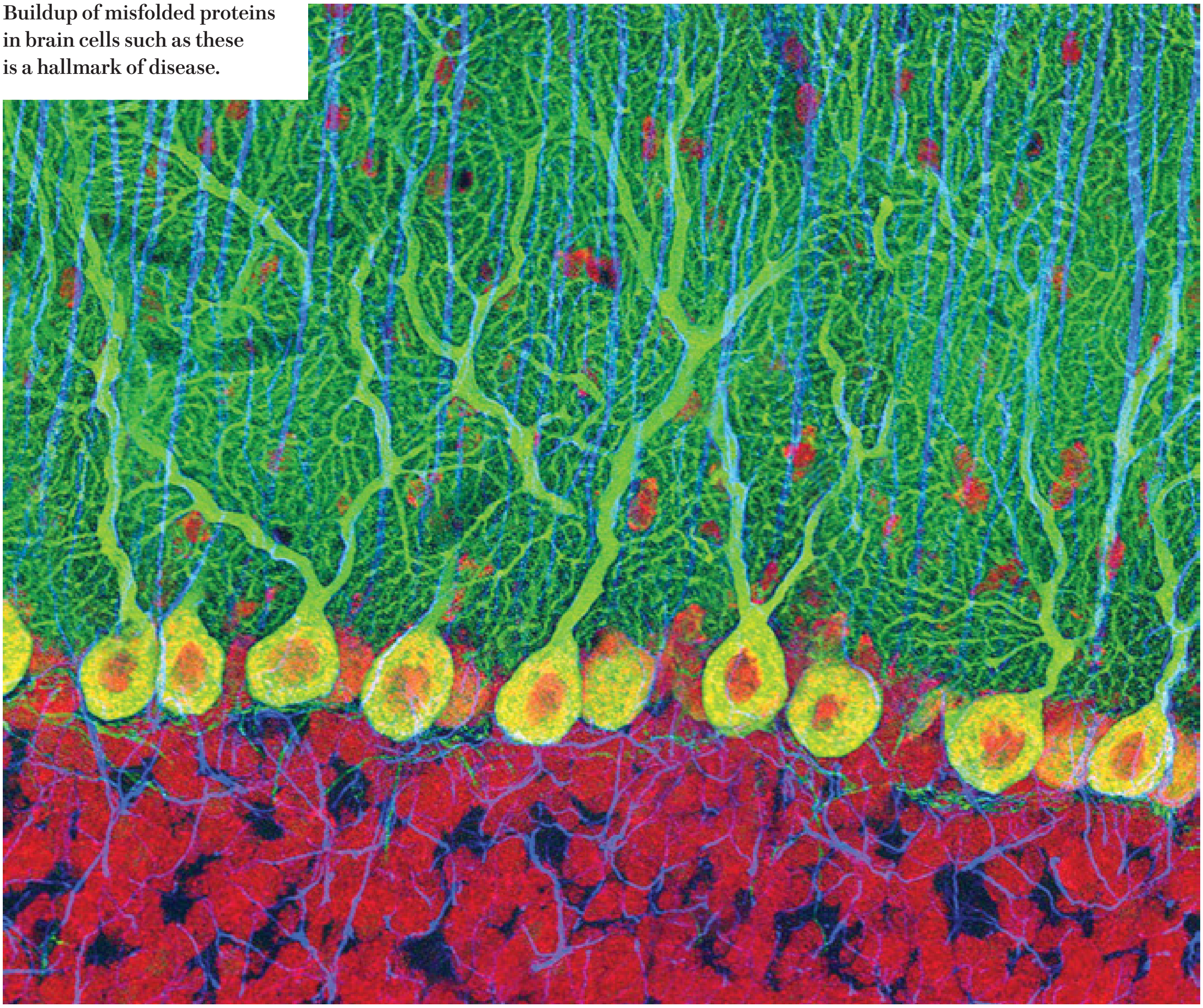
Based on 1289808A0 / 1289807A0 / 1298500A0 / 1295958A0
March 2014
432US14BR00770-04-01

Buildup of misfolded proteins in brain cells such as these is a hallmark of disease.



THOMAS DEERINCK *Science Source*

NEUROSCIENCE

When Good Proteins Go Bad

As baby boomers acquire the neurodegenerative diseases that come with age, researchers focus on a potential avenue to new treatments: targeting cell-to-cell transfer of misfolded proteins

The first step to treating or preventing a disease is often finding out what drives it. In the case of neurodegenerative disorders, the discovery two decades ago of what drives them changed the field: all of them—including Alzheimer's, Parkinson's, Huntington's and amyotrophic lateral sclerosis (ALS or Lou Gehrig's disease)—involve the accumulation of misfolded proteins in brain cells.

Typically when a protein misfolds, the cell destroys it, but as a person ages, this quality-control mechanism starts to fail and the rogue proteins build up. In Huntington's, for example, huntingtin protein—used for many cell functions—misfolds and accumulates. Symptoms such as muscular difficulties, irritability, declining memory, poor impulse control and cognitive deterioration accompany the buildup.

Mounting evidence suggests that not only does the accumulation of misfolded proteins mark neurodegenerative disease but that the spread of the proteins from one cell to another causes the disease to progress. Researchers have seen misfolded proteins travel between cells in Alzheimer's and Parkinson's. A series of experiments reported in *Nature Neuroscience* in August suggests the same is true in Huntington's. (*Scientific American* is part of Nature Publishing Group.)

In their tests, researchers in Switzerland showed that mutated huntingtin protein in diseased brain tissue could invade healthy brain tissue when the two were placed together. And when the team injected the mutated protein into a live mouse's brain, it spread through the neurons within a month—similar to the way prions spread, says Francesco Paolo Di Giorgio of the Novartis Institutes for BioMedical Research in Basel, who led the research. Prions are misfolded proteins that travel through the body and confer their disease-causing characteristics onto other proteins, as seen in mad cow disease. But it is not known if misfolded proteins involved in Huntington's convert other proteins as true prions do, according to Di Giorgio.

Scientists have yet to establish that the movement of bad proteins is critical for the progression of the disease, notes Albert La Spada, a geneticist at the University of California, San Diego, who was not involved in the study. But if it turns out that traveling is essential, then therapies may be able to target the pathway. "If we can find out how it's occurring," La Spada says, "then we might be able to come up with treatments to prevent it." And those treatments could potentially apply to the other neurodegenerative diseases.

The next step is crucial. Researchers will try to block the spread of misfolded proteins and see if that improves symptoms or slows progression. Finding therapies for these diseases is paramount. Approximately 50,000 new cases of Parkinson's alone are diagnosed every year in the U.S., and experts estimate the prevalence will at least double by 2030 because of an aging population. —*Tara Haelle*

WEARABLE TECH

Safety in a Sock

A teenager wins big for an invention that monitors Alzheimer's patients

According to the Alzheimer's Association, more than **5.2 million** Americans have Alzheimer's

60% of them are prone to wander

Fifteen-year-old Kenneth Shinozuka of New York City won the $50,000 *Scientific American* Science in Action Award in August for his invention of a wearable sensor for Alzheimer's patients. The prize, part of the Google Science Fair, recognizes a teen for an innovation that can make a practical difference by addressing an environmental, health or resources challenge.

COURTESY OF KENNETH SHINOZUKA

Shinozuka's creation—a small pressure sensor that can be attached to a foot or a sock—notifies caregivers via their smartphones if a patient who should be sleeping gets out of bed. His grandfather, who has Alzheimer's disease, served as inspiration. "I don't think I will ever forget my shock at seeing Grandfather in his pajamas, accompanied by a policeman who found him wandering on a nearby freeway in the middle of the night," Shinozuka says. He designed the sensor to keep his grandfather safe and to provide much needed relief to his aunt, the primary caregiver. Shinozuka recently demonstrated the technology at a local chapter of the Alzheimer's Association and a number of care facilities. He has obtained a U.S. patent for his invention. —*Rachel Scheer and Annie Sneed*

COMMENT AT ScientificAmerican.com/oct2014

KNOW THE
JARGON

Human shield effect:

(*n.*) The reduction in vigilance that prey animals exhibit when human observers are present.

One morning in South Africa's mountainous Lajuma Research Center, an adult female samango monkey came down from the trees to search for peanuts in an experimental food dispenser. Every once in a while she scanned her surroundings for predators, but she never bothered to look behind her once she realized that Katarzyna Nowak was there.

Animals that are not at the top of their food chains are adept at avoiding their predators. Samango monkeys, for example, stay up in trees. But to retrieve peanuts from the center's dispensers, they have to be on the ground—and that makes them vulnerable. Only when it is certain that no predators are around will a monkey spend time looking for food. So why did this one stop checking for danger behind her? Nowak, a biological anthropologist at Durham University in England and at South Africa's University of the Free State, suspects that the monkey figured that if a human was around, then a leopard was probably not. "[It was] as if she was thinking that I had that area covered," Nowak says.

Nowak put her suspicion to the test. She and her colleagues watched 100 individuals in all and found that they ate more food available on the ground when humans were present than when humans were absent (and observing them via camera). "Researchers were perceived as shields against terrestrial predators," the team writes in the journal *Behavioral Ecology*.

Although researchers have purported to see many animals change their behavior while being watched by humans—from zebras on the African savanna to moose in North American forests—Nowak's study is one of the first to subject the "observer effect" to scientific scrutiny.

—Jason G. Goldman

Illustrations by Thomas Fuchs

Monarch butterflies migrate over thousands of miles.

CONSERVATION

Saving "Bambi"

As monarch butterflies migrate, a trilateral effort to save their continental journey is under way

The monarch butterfly hits the peak of its winter migration in October, and as it makes its way from Canada and the U.S. to Mexico, all three countries will be watching its numbers closely. In February, President Enrique Peña Nieto of Mexico, flanked by President Barack Obama and Prime Minister Stephen Harper of Canada, announced that they would set up a task force charged with saving the continent's monarchs. Then in late May, the three countries devoted several sessions to the butterfly at an annual wildlife conservation summit. That is because the monarch is declining precipitously. In the past decade the population east of the Rocky Mountains dropped from an estimated one billion to the 33 million that survived their journey last winter; the western population, which winters in California, has also dwindled in recent years.

"We are on the verge of losing one of the most magical animal migrations," says Dan Ashe, director of the U.S. Fish and Wildlife Service. Much of the monarch butterfly's life is spent migrating, a journey that for some individuals can cover more than 3,000 miles.

Once called the "Bambi" of the insect world, the monarch is the most recognized butterfly in North America, but its popularity alone will not save it. Researchers and wildlife officials say it will take a combination of approaches to ensure a healthy population. Task force members are now collaborating on a conservation plan that they hope will reverse the drastic decline. And each country has an important role. —*Roger Drouin*

RICHARD ELLIS *Getty Images*

COMMENT AT ScientificAmerican.com/oct2014

Threats

1. Loss of one billion milkweed stems in the summer breeding range because of converted grasslands and herbicides. Monarch larvae eat milkweed exclusively.
2. Extreme weather, including colder winters in central Mexico and droughts in Texas.
3. Invasive flora on which monarchs lay eggs. The hatched larvae are unable to survive there.
4. Increased use of synthetic insecticides.
5. Increasing scarcity of nectar plants along migration routes.

Solutions

MEXICO

The Mexican government has already combated large-scale illegal deforestation in the Monarch Butterfly Biosphere Reserve, a 140,000-acre forested area in central Mexico, where eastern monarchs arrive starting in November and remain until March. But officials are still working on strengthening sustainable forest practices within groups living on ejidos, or small protected, communal lands. Suggested alternatives include eco-tourism and mushroom cultivation.

U.S.

Creating more milkweed habitat is paramount, according to FWS director Ashe. The most direct option is to build "living roadways" of milkweed beside highways such as Interstate 25 and Interstate 35, which run through the central U.S. Another task force objective is to support the Conservation Reserve Program, which protects private farmlands as native environmentally sensitive lands. Those farmlands could sustain milkweed as well as native nectar plants.

CANADA

Fewer monarch offspring are returning in the spring to Canada, where some lay their eggs. The Canadian government is exploring setting aside funds for breeding habitat creation on farmlands, roadsides and utility corridors. Canada currently protects parts of the monarch's staging habitat, where the butterflies congregate as they prepare to migrate south, but larger areas are needed.

FORENSICS

Amoebas on Deathwatch

Microbes could reveal the story of a corpse

Testate amoebas come in many shapes.

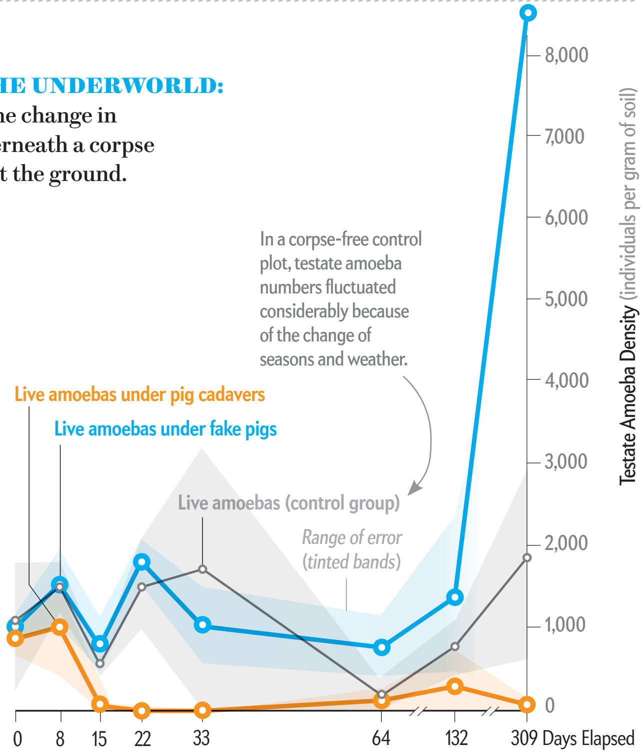
DEE BREGER *Science Source*

One of the most important tasks for a forensic scientist investigating a death is to determine when the person died. Up to 48 hours postmortem, those investigators can use medical methods such as the stiffness or temperature of the body. Longer than that, and they have to turn to the beetles and flies that take up residence in cadavers, using their age and natural succession to estimate the time of death. After about a month, however, there is nothing left to eat and the insects jump ship, leaving investigators without a means of figuring out the age of the corpse.

Forensic biologist Ildikò Szelecz of the University of Neuchatel in Switzerland wondered whether microscopic soil-dwelling organisms could help date older corpses. After all, a body in their midst would presumably affect their ability to thrive. So she and her colleagues placed three dead pigs on the ground and measured their effects on the density of testate amoebas in the soil underneath the cadavers. Testate amoebas are a motley group of single-celled organisms that have shells of many shapes called tests. As it turns out, the 23 species that the team examined abhor corpses—not a single living amoeba could be found under the pig cadavers at 22 and 33 days after placement. "I was expecting a reaction but not that they all died after a certain time," Szelecz says. The study results were published in *Forensic Science International*.

Only by day 64 did the amoebas start to rebound in the soil under the pig. But even after nearly a year, their populations had still not entirely returned to normal compared with controls. Decline and recovery of these microorganisms thus provide a potential way to measure the age of bodies that have languished outside for a considerable period. Just how long remains to be seen: a five-year study involving 13 pig cadavers is under way now. *—Jennifer Frazer*

DEATH AND REVIVAL IN THE UNDERWORLD: **Researchers may be able to use the change in testate amoeba populations underneath a corpse as a way to date when the body hit the ground.**



Graphic by Jen Christiansen

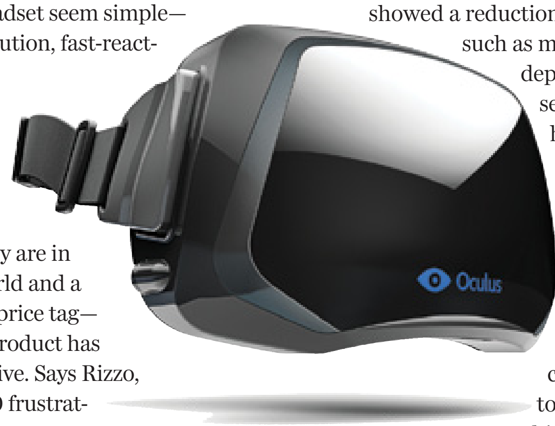
SOURCE: "CAN SOIL TESTATE AMOEBAE BE USED FOR ESTIMATING THE TIME SINCE DEATH? A FIELD EXPERIMENT IN A DECIDUOUS FOREST," BY ILDIKÒ SZELECZ ET AL., IN *FORENSIC SCIENCE INTERNATIONAL*, VOL. 236; MARCH 2014

TECHNOLOGY

Virtually Revolutionary

The Oculus Rift virtual-reality headset is helping researchers reinvent exposure therapy

Albert "Skip" Rizzo of the University of Southern California began studying virtual reality (VR) as psychological treatment in 1993. Since then, dozens of studies, his included, have shown the immersion technique to be effective for everything from post-traumatic stress disorder (PTSD) and anxiety to phobias and addiction. But a lack of practical hardware has kept VR out of reach for clinicians. The requirements for a VR headset seem simple—a high-resolution, fast-reacting screen, a field of vision that is wide enough to convince patients they are in another world and a reasonable price tag—yet such a product has proved elusive. Says Rizzo, "It's been 20 frustrating years."



COURTESY OF OCULUS

In 2013 VR stepped into the consumer spotlight in the form of a prototype head-mounted display called the Oculus Rift. Inventor Palmer Luckey's goal was to create a platform for immersive video games, but developers from many fields—medicine, aviation, tourism—are running wild with possibilities. The Rift's reach is so broad that Oculus, now owned by Facebook, hosted a conference for developers in September.

The Rift, slated for public release in 2015, is built largely from off-the-shelf parts, such as the screens used in smartphones. A multiaxis motion sensor lets the headset refresh imagery in real time as the wearer's head moves. The kicker is the price: $350. (Laboratory systems start at $20,000.)

Rizzo has been among the first in line. His work focuses on combat PTSD. In a 2010 study, he placed patients into controlled traumatic scenarios, including a simulated battlefield, so they could confront and process emotions triggered in those situations. Of his 20 subjects, 16 showed a reduction in symptoms, such as moodiness and depression, after 10 sessions in Rizzo's homegrown VR setup; they maintained those levels through a three-month follow-up. In August, Oculus began delivering close-to-final Rifts to researchers, which will allow Rizzo to move his testing onto the device.

Others are using the Rift in therapy for anxiety and phobias. In an unpublished claustrophobia test, Fernando M. Tarnogol, psychologist and founder of VR company PsyTech, walked subjects into a virtual closet. They reported near-complete immersion, a response he corroborated with physiological data. He aims to release the platform close to the Rift debut. People who own a Rift, however, will not be self-administering therapy. Rather these systems promise clinicians an in-office tool—one that's been stuck in labs for decades.

—Corinne Iozzio

Other researchers applying virtual reality to therapy:

Max Ortiz Catalan
Chalmers University of Technology (phantom limbs)

Hillel Finestone
Elisabeth Bruyere Hospital (stroke rehabilitation)

Page Anderson
Georgia State University (social anxiety)

Patrick Bordnick
University of Houston (heroin addiction)

Giuseppe Riva
Italian Institute for Auxology (eating disorders)

COMMENT AT ScientificAmerican.com/oct2014

BIOLOGY

See-Through Science

New technique turns rodent bodies transparent

One thing is clear: peering inside animals leads to scientific discovery. In the 1960s and 1970s genetic and developmental biology research exploded after laboratories began studying naturally transparent critters, such as the nematode *Caenorhabditis elegans* and the zebra fish *Danio rerio.* With them, scientists could watch young cells develop into a full organism. Now, for the first time, they can see through mammalian bodies, thanks to a technique that can make mice and rats—and perhaps larger animals—clear.

Scientists have been able to render tissues such as the mammal brain transparent, but the procedure can take months. To speed up the process and apply it on a larger scale, Viviana Gradinaru, a neuroscientist at the California Institute of Technology, exploited a rodent's blood vessels. Using a dead rat, the team pumped a series of chemicals through its vessels and into its tissues. The compounds removed cloudy fats and replaced them with clear liquids. In just two weeks the entire rat turned into a see-through, jellylike specimen. The researchers published their results (including photographs, if you're not about to eat) in August in *Cell.*

Postclearing, Gradinaru can look at cells that have been tagged with antibodies or dyes. That ability could help others map nerve fibers or follow cancer cells. "We can see things that we couldn't before," says Guangping Gao, a gene therapist at the University of Massachusetts Medical School, who wants to track viruses in the body. Gradinaru says the technique could be scaled to any organism with vasculature—even humans. —*Julia Calderone*

WHAT IS IT?

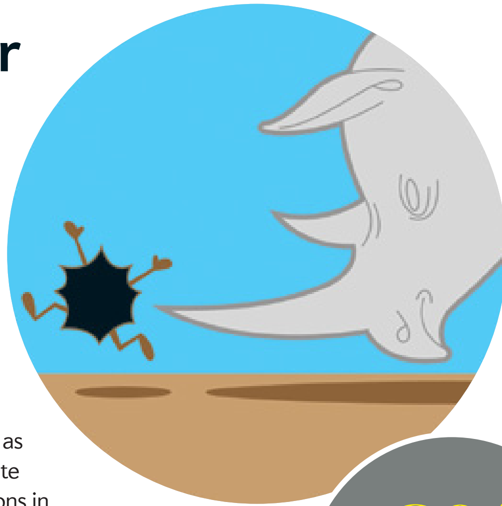
The thick layer of permafrost underneath the Alaska Highway is thawing, and with it goes the highway's integrity. "It is really, really bumpy," says Tanis Davey of the Yukon Research Center, where scientists study the effects of rising annual temperatures on permafrost. Permafrost is a layer of frozen soil or rock that sits under an estimated 20 percent of the world's total land area. That includes stretches of the Alaska Highway—the only land route from Alaska to the continental U.S.—where the layer can be up to 65 feet thick. Geoscientists from the center have collected samples of permafrost (*right*) along the 1,390-mile-long highway for the past three summers to record how global warming is changing the ground and to predict where future damage may appear. Roadways with recurring damage from thawing permafrost cost about 10 times more than average roads to maintain, according to scientist Fabrice Calmels, who submitted this photograph to *Scientific American.* —*Kevin Schultz*

COURTESY OF FABRICE CALMELS

ONCOLOGY

How Big Animals Deter Cancer

Virus suppression could explain why cancer doesn't scale



About 40 years ago Richard Peto surmised that if every living cell has a theoretically equal probability of getting cancer, then large animals should have higher rates of cancer than small animals because they have many more cells and typically live longer. When he went about testing his idea, however, the University of Oxford epidemiologist, now 71 years old, found that this logic does not play out in nature. It turns out that all mammals have relatively similar rates of cancer.

Researchers have come up with multiple theories to explain Peto's Paradox. One explanation holds that the faster metabolisms of small animals generate more cancerous free radicals. Another suggests that evolution has equipped larger animals with extra tumor suppressor genes. Aris Katzourakis, an evolutionary biologist at Oxford, thinks an animal's ability to suppress viruses that jump into and out of its DNA may partially explain the paradox, a hypothesis he and his colleagues put forward in July in *PLOS Pathogens.*

These jumping viruses, known as endogenous retroviruses, can create cancerous mutations at the locations in the genome where they incorporate their own genes. Because the viruses have evolved with mammals for millions of years, their genetic material has come to make up 5 to 10 percent of most vertebrate genomes (including our own), although most of it is now inactive.

8%
or more of the human genome is made up of endogenous retroviruses

To understand how endogenous viruses factor into cancer risk, Katzourakis and his team of researchers studied the relation between body size and the number of endogenous retroviruses that had integrated into the genomes of 38 mammal species over the past 10 million years. The larger the animal, they found, the fewer endogenous retroviruses it acquired. For example, mice picked up 3,331, whereas humans gained 348 and dolphins, 55.

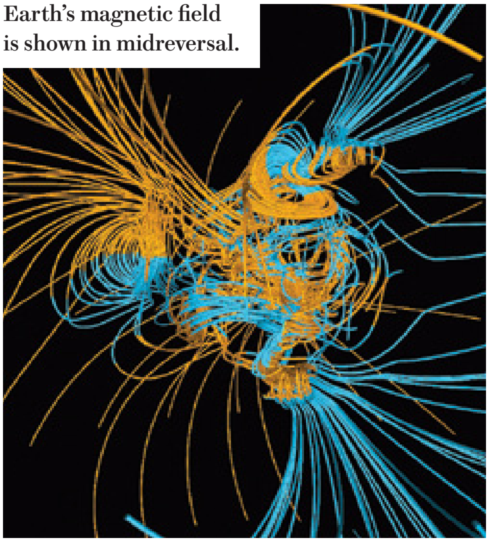
It seems that larger, longer-lived animals have evolved a protective mechanism to limit the number of these viruses. "If an animal evolves a large body size, they've got to make themselves more cancer-proof," says Peto, who was not involved in the study. Katzourakis and his team have yet to identify the mechanism, but Katzourakis predicts that animals such as whales and elephants may have a greater number of antiviral genes that limit viral replication or ones that are more effective. "They've made a striking observation," Peto remarks.

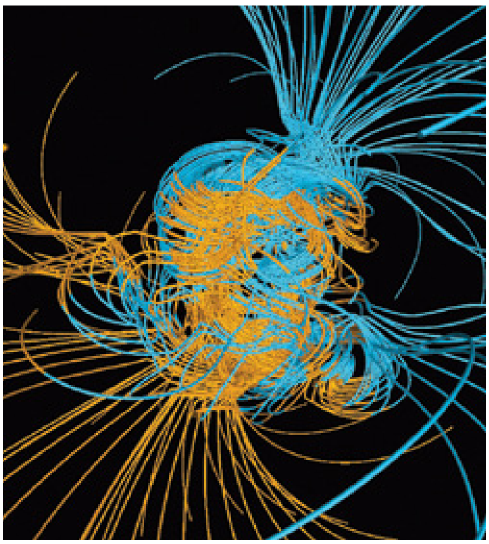
No single mechanism is likely to explain Peto's Paradox. Instead large animals probably evolved a variety of ways to fend off cancer. This is good news, says oncologist Carlo Maley of the University of California, San Francisco: "It would mean there are potentially many different solutions to developing cancer prevention."

—Annie Sneed

COMMENT AT ScientificAmerican.com/oct2014

Earth's magnetic field is shown in midreversal.





COURTESY OF GARY A. GLATZMAIER *University of California, Santa Cruz*, AND PAUL H. ROBERTS *University of California, Los Angeles*

INSTANT EGGHEAD

Earth's Impending Magnetic Flip

The north pole is on a course to Siberia and points south

Earth's magnetic north and south poles have flip-flopped many times in our planet's history—most recently, around 780,000 years ago. Geophysicists who study the magnetic field have long thought that the poles may be getting ready to switch again, and based on new data, it might happen earlier than anyone anticipated.

The European Space Agency's satellite array dubbed "Swarm" revealed that Earth's magnetic field is weakening 10 times faster than previously thought, decreasing in strength about 5 percent a decade rather than 5 percent a century. A weakening magnetic field may indicate an impending reversal, which scientists predict could begin in less than 2,000 years. Magnetic north itself appears to be moving toward Siberia.

Geophysicists do not yet fully understand the process of geomagnetic reversals, but they agree that our planet's field is like a dipole magnet. Earth's center consists of an inner core of solid iron and an outer core of liquid iron, a strong electrical conductor. The liquid iron in the outer core is buoyant, and as it heats near the inner core, it rises, cools off and then sinks. Earth's rotation twists this moving iron liquid and generates a self-perpetuating magnetic field with north and south poles.

Every so often the flow of liquid iron is disturbed locally and twists part of the field in the opposite direction, weakening it. What triggers these disturbances is unknown. It seems they are an inevitable consequence of a naturally chaotic system, and geophysicists observe them frequently in computer simulations. "Similar to a hurricane, you can't predict [exactly] when or where a reversal will start, even though you understand the basic physics," says Gary A. Glatzmaier, a geophysicist at the University of California, Santa Cruz. Typically the local reversal peters out after 1,000 years or so, but sometimes the twisting of the field continues to spread and eventually succeeds in reversing the polarity of the entire field. The flipping takes an average of 5,000 years; it can happen as quickly as 1,000 years or as slowly as 20,000 years.

There is a good chance the weakening magnetic field that the Swarm satellites observed will not lead to a full flip. Indeed, Glatzmaier notes that there have been several false starts over geologic history. The intensity of Earth's magnetic field, though waning, now equals its average strength over millions of years. The field would need to weaken at its current rate for around 2,000 years before the reversal process actually begins.

It is hard to know how a geomagnetic reversal would impact our modern-day civilization, but it is unlikely to spell disaster. Although the field provides essential protection from the sun's powerful radiation, fossil records reveal no mass extinctions or increased radiation damage during past reversals. A flip could possibly interfere with power grids and communications systems—external magnetic field disturbances have burned out transformers and caused blackouts in the past. But Glatzmaier is not worried. "A thousand years from now we probably won't have power lines," he says. "We'll have advanced so much that we'll almost certainly have the technology to cope with a magnetic-field reversal."

—Annie Sneed

Q&A

Life Guard

NASA's Office of Planetary Protection has just one officer, Catharine Conley. Her job is to ensure that NASA and other U.S. organizations that journey into space adhere to the regulations put in place by the international Outer Space Treaty of 1967, which aims to preserve scientists' ability to study other worlds in their natural states, avoid biological contamination of environments we explore and protect Earth's biosphere in case alien life exists. You could say the future of our solar system rests in her hands. *—Edited by Erin Biba*

Planetary protection officer Catharine Conley has been safeguarding Earth from potential alien life since 2005.

COURTESY OF PAUL ALERS NASA

It's evident why we would want to protect Earth from alien life, but why should we care about keeping Earth's organisms off other planets?
If we want to study the potential of biology on other planets, we have to control the level of contamination. When you're doing experiments looking for life, you have to be really careful about which one you believe.

How do you ensure that there's no cross-contamination between Earth and other planets?
On the Viking missions, the landers were packaged and put inside a bioshield and baked in an oven to kill all organisms—a "full-system sterilization," we call it. The landers remained in the bioshield until they got to Mars to prevent recontamination. It was the most stringent implementation of planetary protection that anyone has ever done because we needed to protect the life-detection instruments and protect the Mars environment in case it turned out to be habitable to Earth life.

NASA is planning to redirect an asteroid to an orbit around the moon in the 2020s. Are you worried about what astronauts may encounter there?
Small asteroids have been irradiated, baked by the sun and floating around in space for such a long time that any organisms would have died. We will still evaluate any asteroid that is proposed because we want to keep the system clean, especially if we eventually have regular commercial movement between Earth and the moon.

There are a growing number of commercial space activities. Is NASA able to regulate their level of cleanliness?
We've been spending considerable taxpayer money over the years to protect other planets from contamination. Now we're in the process of figuring out how the U.S. can have an appropriate level of visibility into what our nongovernmental groups are doing. In a situation in which NASA isn't providing support, who's responsible for oversight is currently open.

Will we need a new law to regulate these groups?
We have to consider that. The Federal Aviation Administration already has authority over launches and landings, so we can regulate activities within the atmosphere, and NASA has a framework for providing input into the FAA process. But we're not a regulatory agency.

There are plans for nongovernmental manned missions to Mars in the next few decades. That must create a new set of problems in terms of protecting the Red Planet.
Absolutely. Will the humans be alive by the time they get to Mars? If they die on Mars, are they then contaminating the surface? [Such events could] interfere with future science.

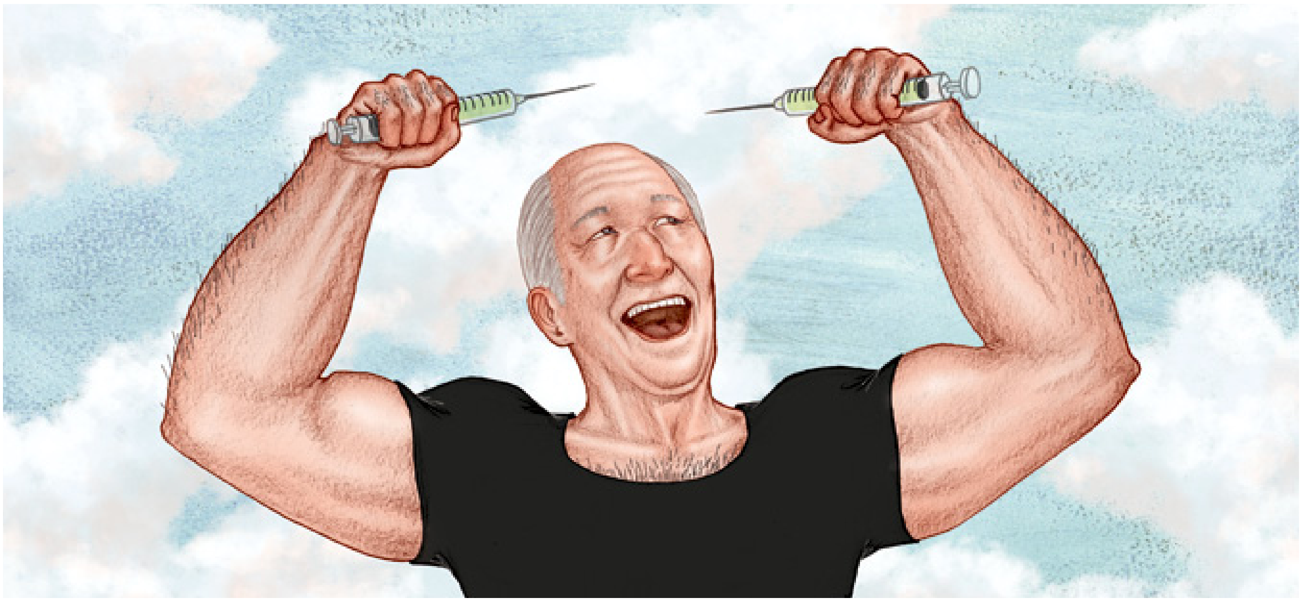
It seems that your office's goals are less about protecting planets from humans and more about protecting planets for humans.
The purpose is explicitly to protect the activities that humans want to do. Initially that would be science, but other things will be done in the future as well. If you wanted to drill into an aquifer on Mars, it would be in the interest of future colonists that you keep the drilling clean because organisms can grow in the aquifer and change the conditions so that it is no longer available. We've seen that happen on Earth. That would be really unfortunate.

COMMENT AT ScientificAmerican.com/oct2014

Carina Storrs is a freelance science and health writer whose work has appeared in *Discover, The Scientist* and Health.com, among other publications.

The Other T Party

Too many men are getting testosterone for the wrong reasons



Doctors around the world have written a surprising number of prescriptions for testosterone treatment in recent years. Nearly 3 percent of American men aged 40 and older are thought to have received such scripts in 2011—three times the percentage in 2001. (If confirmed, the 2011 ratio could mean that perhaps two million older men in the U.S. have been given prescriptions for testosterone.) Originally intended for men who have difficulty producing sex hormones because of damage or disease in their testes or other parts of the endocrine system, testosterone replacement therapy has become increasingly popular with middle-aged and older men who do not have clear deficits but who nonetheless hope to lessen some of the symptoms of aging, including fatigue, muscle wasting and lack of sex drive.

In truth, no one knows whether the hormone can offer any of the health benefits that its proponents claim for aging males. Well-designed, placebo-controlled trials of the drug in men who do not meet the standard criteria for treatment have been scant in number, and their results have been inconsistent.

As testosterone therapy becomes more widespread, a growing number of medical experts worry that it has become too easy for men to get the hormone—whether from their own physicians or stand-alone "low T" clinics—and that many users could be putting themselves at risk for worse conditions than those they are trying to counteract.

EASY ACCESS

TESTOSTERONE, AS PRODUCED by the body, is a versatile hormone. In addition to maintaining sperm production, the molecule helps many tissues to grow: it increases muscle and bone mass, as well as the production of red blood cells—all of which are vital for energy and strength. Disease or injury in the testes or pituitary gland—a part of the brain that instructs the testes to produce testosterone—can hinder the body's ability to make the hormone. When testosterone levels dip too low, men can become depressed and lethargic, lose interest in sex, and lose some of their muscle and body hair.

While the potential risks associated with taking supplemental testosterone—particularly in otherwise healthy men—are not well studied, concern has focused on whether extra amounts of the hormone might damage the prostate, heart or brain. Many prostate tumors depend on testosterone to grow, so increasing the level found in the blood might nudge normal cells to become malignant or push malignant cells to become more aggressive. In addition, two recent studies found an increase in heart attacks and strokes among older men taking testosterone—which the authors speculated might occur if the drug increased clotting risk and drove up blood pressure. Earlier this year the U.S. Food and Drug Administration announced that it is studying the matter to see whether stronger regulations are needed. In the mean-

Illustration by Jason Raish

time, the agency now requires all testosterone products to contain a warning label about the potential for blood clots.

As long as testosterone therapy was available only by injection, its use was largely limited to individuals with testicular injuries or other severe ailments. The treatment markedly improves mood and libido in men with these conditions, and the FDA approved the drug for those situations. But fear of needles no doubt kept some men from seeking treatment.

Individuals were more willing to consider their options once pharmaceutical companies figured out how to deliver the drug more easily. A transdermal patch that delivered the medicine through the skin of the scrotum became available in 1993. (Subsequent patches could be applied to the arms, back and thighs.) But the number of men taking supplemental testosterone really began to soar in 2000, with the introduction of an even easier-to-use gel that could be rubbed on the shoulders, thighs or armpits.

Greater ease of use also led to an expansion in the number of conditions for which doctors considered testosterone therapy to be a plausible treatment in spite of any supportive data. Perhaps an extra dose of testosterone could be helpful for otherwise healthy men whose hormone levels had faded with age or because they were obese or suffered from diabetes? (It is unclear precisely why testosterone levels decline for certain individuals in these situations.) In addition, some men who did not have testicular injuries desired the sex hormone because they thought it would treat erectile dysfunction or boost their mood.

BLIND GUIDES

GIVEN THE CONTINUING UNCERTAINTY about the hormone, the Endocrine Society, an international organization of health care professionals focused on hormone research and endocrinology, advises doctors to perform two blood tests to confirm below-typical levels of testosterone and rule out other potential causes of their patients' symptoms before writing a prescription. Yet the most recent research suggests that between 25 and 40 percent of patients receiving testosterone replacement therapy never had a blood test to measure their testosterone before starting treatment.

Preliminary findings by Jacques Baillargeon, director of the epidemiology division in the department of preventive medicine and community health at the University of Texas Medical Branch at Galveston, and his colleagues offer clues as to why so many men get testosterone prescriptions without the recommended blood work. According to their analyses of insurance claims databases, about 70 percent of men who have tried testosterone therapy did so after seeing a primary care physician, not a urologist or endocrinologist. Although Baillargeon will not speculate about why primary care physicians are more likely to write a prescription without first ordering a blood test, Glenn Cunningham, a professor of medicine and an endocrinologist at the Baylor College of Medicine, suggests that perhaps the generalists are less familiar with the Endocrine Society's guidelines.

Other sources of testosterone include increasingly common low T clinics, many of which require men to pay for prescriptions out of pocket, prompting Baillargeon to suspect "potentially inappropriate prescribing practices."

The clinics say their staff are trained in hormone medicine and do the appropriate blood work, but such claims are hard to verify without a data trail from insurance filings. In addition, the clinics are not reviewed or regulated by medical organizations or government groups.

NEW LIMITS?

THE TROUBLING SPREAD of testosterone therapy in men has parallels to the early use of hormone replacement therapy in postmenopausal women. Starting in the 1990s, a series of studies suggested that many women who took a combination of estrogen and progestin as they grew older would suffer less from heart disease. But by 2004, after researchers had completed two major parts of the Women's Health Initiative—which together formed a massive study of 27,347 women that compared treatment with a placebo in a scientifically rigorous way—doctors realized hormone therapy does more harm than good in most women over the long term.

The study initially prompted a dramatic drop in the number of women taking prescription hormones. Since then, however, a more nuanced view has come into focus: the proved benefit of relieving menopausal symptoms such as hot flashes is worth the risk for some women, provided they limit treatment to the first several years after menopause. "I think we are less naive" than before the Women's Health Initiative, says Bradley Anawalt, a University of Washington professor of medicine and chair of the Endocrine Society's Hormone Health Network. "We are recognizing there is never a simple answer, and we have to discover who benefits and who gets harmed."

For testosterone, some of those answers may soon be forthcoming. Results from a series of scientific studies detailing exactly who might gain from testosterone therapy, and under what circumstances, are expected to be published starting later this year. The series started in 2009, when the U.S. government funded a team of researchers to recruit and study participants for the Testosterone Trial—a group of seven long-term studies of how testosterone therapy affects sexual activity, energy level, memory, heart and bone health, and the ability to walk a certain distance. The trial followed 788 men, aged 65 and older, whose testosterone levels in the blood were much lower than average. Half the men (the experimental group) applied a gel with testosterone to their shoulders, abdomen or upper arms each day for a year, and the other half (the control group) used a gel containing a placebo. Researchers also monitored prostate cancer risk, based on prostate-specific antigen levels and a rectal exam, and stroke risk, based on red blood cell levels during the treatment year and for at least a year afterward.

Studies of the risks of testosterone use would likely follow only if the data on benefits were promising. Health researchers often look first at benefits of a treatment because theses studies call for fewer test subjects than risk studies do. Even though such randomized placebo-controlled trials can take years to conduct, they offer the best hope for separating truth from wishful thinking. SA

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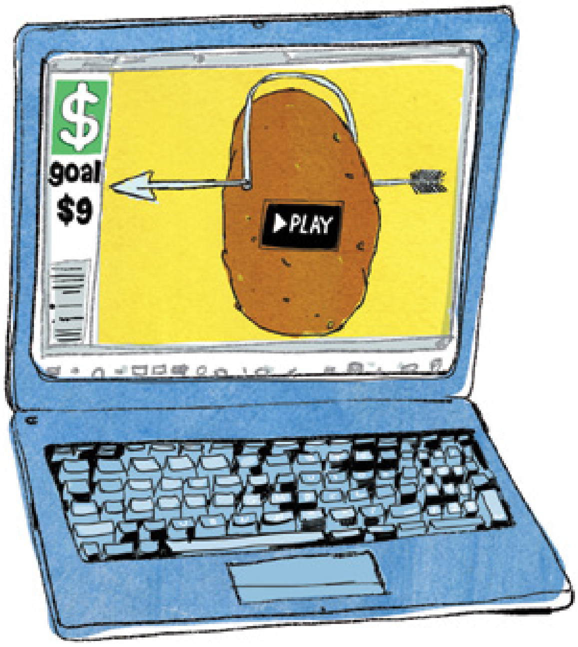
David Pogue is the anchor columnist for Yahoo Tech and host of several *NOVA* miniseries on PBS.

Million-Dollar Stunt

How to get rich with an Internet joke: be a goof



Kickstarter wasn't intended to be a platform for elaborate, participatory jokes. It's a Web site where entrepreneurs seek funding help from the public. You watch a video or read a pitch about a project, and then, if compelled, you donate a few bucks—not because you're investing (you're not) but just to show your support, maybe to feel like a part of someone's quest.

In July, Ohio resident Zack Brown started what may have been the silliest Kickstarter project ever. He set a fundraising goal of $10—to make a potato salad.

He didn't even bother with a video. His entire pitch was: "Basically I'm just making potato salad. I haven't decided what kind yet."

The Internet loves a good joke. Within a couple of days, this one went viral. Thousands of Web surfers thought of the same punch line: contribute to the absurd campaign. The media picked up on the gag, too; next thing anyone knew, Brown's potato salad quest had racked up more than $70,000 in pledges.

Brown isn't a snake oil salesman or a huckster; he was absolutely transparent about what you'd get for your contribution: pretty much nothing. (For $1, he'd say your name aloud while making the salad. For $3, he'd mail you a bite.) The Internet, in other words, makes possible a scheme that has never existed before: get rich quick through sincere goofiness. We, the public, get to be part of the high jinks; they, the gagsters, get the profits.

It had happened before. The Million Dollar Homepage was a 2005 experiment by a British college student. He offered to sell individual pixels of his Web site (a 1,000 × 1,000 pixel grid) to advertisers for $1 each. He sold every last pixel.

Then there was also One Red Paperclip. Canadian Kyle MacDonald asked what someone might trade him for the red paper clip on his desk. Someone offered a fish-shaped pen. MacDonald bartered the pen for a doorknob, which he traded for a camp stove, and so on—until, after 14 trades, he had himself an actual house.

See? Sincere public goofiness. But the reactions to each case suggest that there are some rules to making these farcical schemes successful.

First: you can't repeat the viral success of a nutty Internet stunt. There were, inevitably, other "million-dollar home page" attempts—and at least a dozen copycat potato salad campaigns on Kickstarter. They failed. (One, called "I'm also making potato salad," earned a whopping $10 in contributions.) Only the original idea thinker gets the loot.

Second rule: don't stray from straight goofiness. You'll ruin it. Case in point: Brown appeared on *Good Morning America,* vowing to figure out how to "do the most good" with the money. The goofiness was gone; now he was a do-gooder.

Final rule: stay sincere. Next Brown began promoting other stuff—a local restaurant, a photography studio, a radio station—on his Kickstarter page; now the earnestness was gone, too. "This is outrageous!" said one commenter. "Stop plugging businesses," said another. "It's really lame, and takes away from the tongue in cheek fun of the whole 'potato salad' kick."

Shortly thereafter, the pledges actually dropped by $30,000, leading to rumors of an anticommercialism backlash. (Kickstarter says that, instead, it canceled three large donations that seemed to be phony.) By the time the campaign was finished, Brown had raised more than $55,000.

The Web's short history of silly fundraising campaigns demonstrates that the public loves a good, pure, zany stunt. Yes, there will be some who begrudge any get-rich-quickers—especially those who succeed based on a little online joke. Others will disparage the apparent frivolity. But if your joke is good enough, a lot of the (paying) public will enjoy coming along for the ride.

Just remember the prime directives: Be original. Stay sincere. And stay goofy. SA

SCIENTIFIC AMERICAN ONLINE
The greatest crowdfunding disasters: ScientificAmerican.com/oct2014/pogue

Illustration by Tim Hamilton

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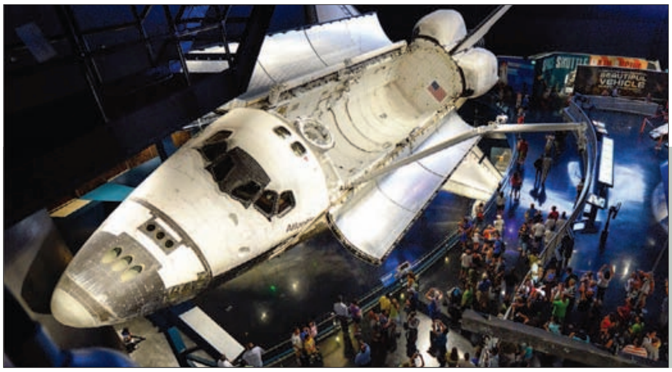

LIGHTNING

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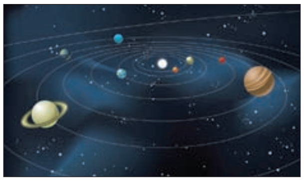

OUR SOLAR SYSTEM

- Cosmic Collision: The Search for the Dinosaur's Killer
- Our Neighborhood in the Solar System
- Exploring our Solar System

NEUROSCIENCE

- Life and its Discontents
- Scratching Sheep, Mad Cows, and Laughing Death
- Why Old Brains Falter
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THE INCLUSION EQUATION

Science and technology are society's main engines of prosperity. Who gets to drive them?

By Fred Guterl

COLLABORATION HAS BEEN A RECURRING THEME in science and technology in recent years. The life of the mind is increasingly transnational in nature. It roams centers of excellence from every continent, linked by communications of great speed and breadth. Twice we have looked at collaboration in our State of the World's Science reports, last year with a focus on innovation, the year before on basic research. Here we address it again, from the standpoint of the individual.

The word "diversity" is shorthand for a vast effort to remake society to include everyone—not just those in privileged positions—in politics, culture and the pursuit of happiness. This ambition goes well beyond the scope of this report; we have stayed within the realm of science and its activities. Because we prefer to look at evidence, we take the opportunity to focus on the empirical grounding of diversity, which often gets lost in the larger conversation.

Illustration by Edel Rodriguez

Diversity, it turns out, goes to the heart of how to do research and innovation effectively. In the scientific literature, it is clear that diversity speaks directly to the quality and effectiveness of teams. As Katherine W. Phillips tells us, starting on page 42, when we have to work with people who are not like ourselves, we tend to prepare more thoroughly and work harder to marshal our arguments, and we do better work as a result. Diversity is beneficial for teams precisely because we react differently to people who are different from us. If the end goal is excellence, diversity is an essential ingredient.

For diversity to be effective, the working environment must be right. For an individual, it takes conscious effort to be on the watch for unconscious biases and to overcome them. For an organization, it takes processes, procedures and an ethos of acceptance. Victoria Plaut points out, beginning on page 52, that groups who abandon color-blind policies and embrace the differences among their members in ways that do not stereotype or pigeonhole tend to be successful in taking advantage of what diversity has to offer.

We do not treat diversity exclusively as a utilitarian matter in this special section, of course. Science imposes the discipline of having to find the best ideas among varied teams of people, which gives scientists and engineers the opportunity to be pioneers in cultural change. So we have sprinkled this package with essays from some extraordinary people who are embracing that challenge.

We would like to have included a Diversity Index—a measure of how nations fare when it comes to inclusiveness in the science and technology workforce. At the moment that is too tall an order, however. In a welcome development from two of the world's most visible technology companies, Google and Apple recently released data on the diversity, or lack of it, of their respective workforces. It is a drop in the information bucket, however. Data overall are scarce, for several reasons.

Racial and ethnic identity, for one, are hard to define consistently. A United Nations census found that two thirds of nations categorized their populations along these lines but used a kaleidoscope of terms—*race, ethnic origin, nationality, ancestry, tribal, Aboriginal,* and so on. Many countries track the poor and underprivileged, but these categories mean different things in different places. Disability is even more difficult to pin down. Gender is easier to define (although ambiguities exist there as well), but little information is gathered that is specific to the science-related workforce. "Comprehensive, internationally comparable data on the worldwide science and engineering workforce do not exist," says the National Science Foundation in its *Science and Engineering Indicators 2014* report. From what we do know, however, it's clear that we can do better.

To that end, we believe that data should be a high priority. Scientists pride themselves on their objectivity, but personal experience and point of view have a lot to do with what questions get asked in the first place and how researchers go about answering them. The people in science and engineering are driving the world's most vital engine of prosperity and new ideas. Who are they? SA

Fred Guterl is executive editor of Scientific American.

WHERE ARE THE DATA?

Global figures on diversity in the science and engineering workforce are hard to come by, but what we know is not flattering

THE NUMBER OF PEOPLE engaged in scientific research has been rising strongly. China reports a tripling of researchers between 1995 and 2008, with substantial growth currently; South Korea doubled the number of researchers between 1995 and 2006 and continues its upward swing. Even the U.S. and Europe have posted gains. The research workforce grew by 36 percent in the U.S. between 1995 and 2007 and by 65 percent in Europe between 1995 and 2010. Exceptions are Japan, which is flat, and Russia, which is down. When it comes to diversity, however, all we have are snapshots. Here are the best ones. *—F.G.*

MORE TO EXPLORE

Science and Engineering Indicators 2014. National Science Board. National Science Foundation, 2014. www.nsf.gov/statistics/seind14/index.cfm/home

A Picture of the UK Scientific Workforce: Diversity Data Analysis for the Royal Society. The Royal Society, 2014. https://royalsociety.org/policy/projects/leading-way-diversity/uk-scientific-workforce-report

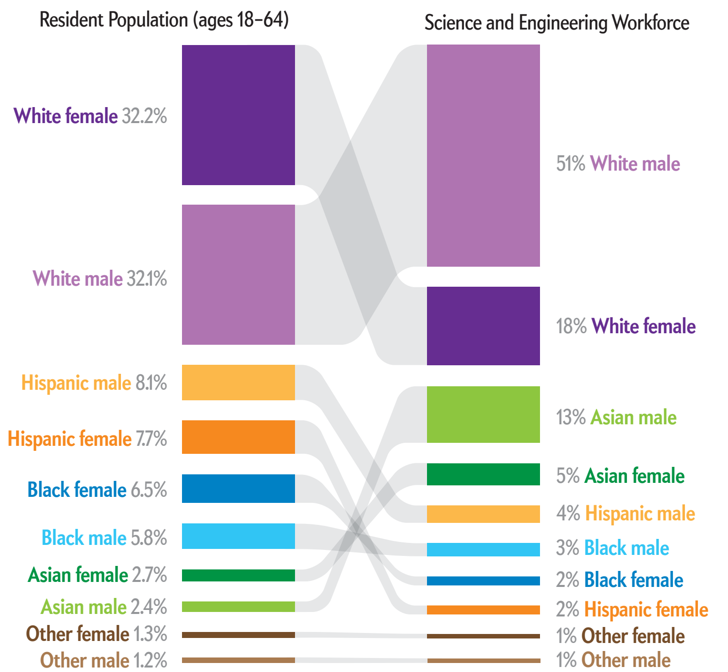
National Science Foundation's Women, Minorities, and Persons with Disabilities in Science and Engineering: http://nsf.gov/statistics/wmpd/2013

UNESCO Institute for Statistics's Women in Science report: www.uis.unesco.org/ScienceTechnology/Pages/women-in-science-leaky-pipeline-data-viz.aspx

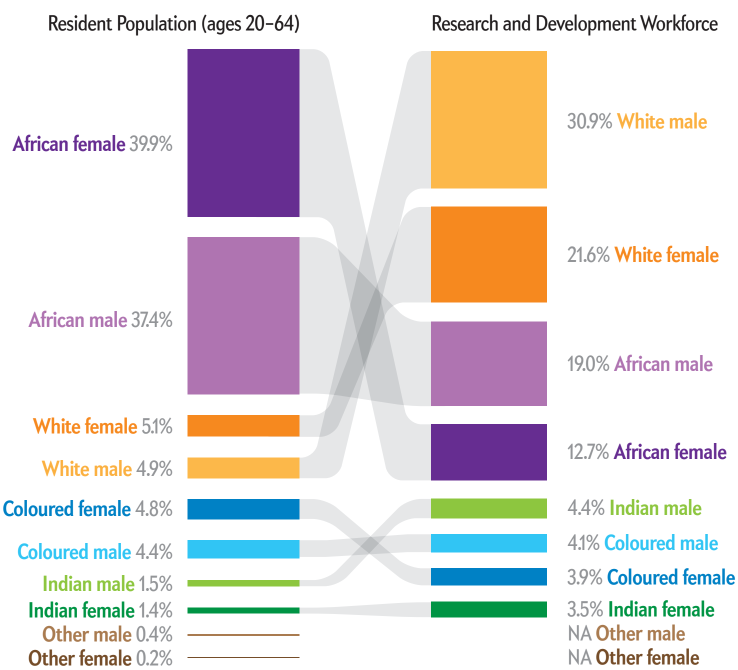
SOURCES: *WOMEN, MINORITIES, AND PERSONS WITH DISABILITIES IN SCIENCE AND ENGINEERING: 2013,* BY NATIONAL CENTER FOR SCIENCE AND ENGINEERING STATISTICS. NATIONAL SCIENCE FOUNDATION, 2013 (*U.S. demographics, workforce and disability status*); *CENSUS 2011: CENSUS IN BRIEF.* STATISTICS SOUTH AFRICA, 2012 (*South Africa demographics*); *SOUTH AFRICAN NATIONAL SURVEY OF RESEARCH AND EXPERIMENTAL DEVELOPMENT: STATISTICAL REPORT 2011/12.* CENTER FOR SCIENCE, TECHNOLOGY AND INNOVATION INDICATORS AND HUMAN SCIENCES RESEARCH COUNCIL, MARCH 2014 (*South Africa workforce*); WOMEN IN SCIENCE, UNESCO INSTITUTE FOR STATISTICS (*gender*); *LEADING THE WAY: INCREASING THE DIVERSITY OF THE SCIENCE WORKFORCE: PROJECT TWO: EXPLORING THE IMPACT OF SOCIO-ECONOMIC BACKGROUND ON CAREERS IN SCIENCE,* BY TBR. THE ROYAL SOCIETY, 2013 (*socioeconomics*)

Race and Ethnicity: Most census questionnaires sort their populations by national or ethnic group. Yet definitions vary widely from one country to the next. (South Africa, for instance, has used the mixed-race category "coloured.") When information is available, it is generally part of broader demographic surveys, not ones focused on science and engineering education or employment. A few countries track minority participation in science-related fields.

U.S. (2010)



South Africa (2011)



Research Workforce, by Region (2010, or latest data)

Female	Male	
20%	80%	East Asia, Pacific
20%	80%	South and West Asia
29%	71%	Sub-Saharan Africa
32%	68%	North America/Western Europe
38%	62%	Arab States
40%	60%	Central and Eastern Europe
44%	56%	Latin America, Caribbean
46%	54%	Central Asia

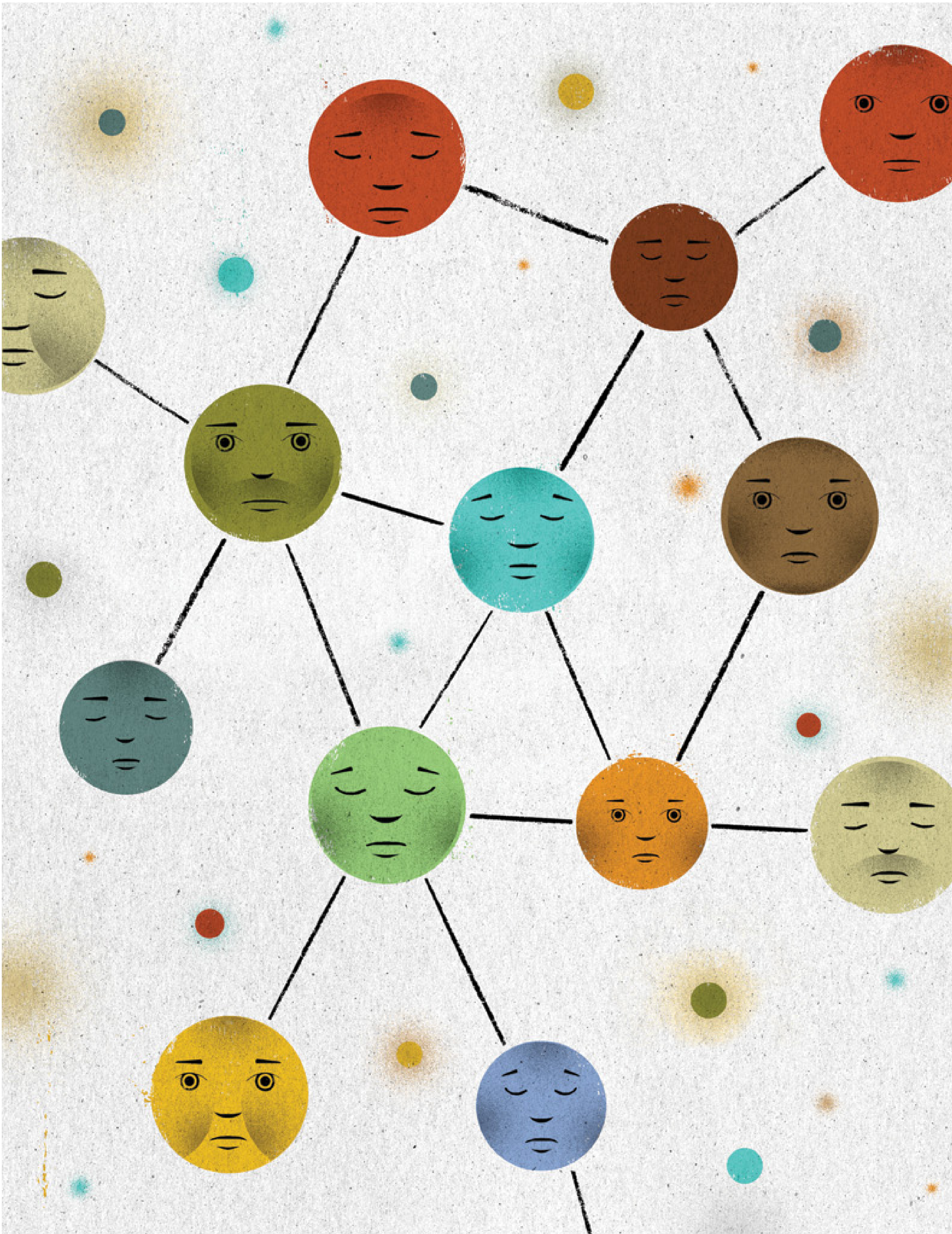
Gender: This is the most commonly cited diversity category in relation to science and engineering education and employment, for the simple reason that most nations count men and women (though not transgender individuals). On average, women remain underrepresented in STEM fields. For more on that, see the graphics on Ph.D.s awarded for men versus women on pages 50 and 51.

Socioeconomic Background: A report made for the British Royal Society recently analyzed data on the U.K.'s science and engineering workforce and found a strong correlation between socioeconomic background and pursuit of a science-related field. "The higher an individual's socioeconomic background, measured in terms of parental social class or parental education, the more likely they are to work in science." The link was "so strong that it could be described as a gradient, just as the relationship between socioeconomic background and a child's educational achievement is often described in the literature as a gradient."

With disability	Without disability	
10%	90%	Civilian Noninstitutionalized Population (ages 18–64, 2010)
8%	92%	Nonscience and Engineering Occupations (2010)
6%	94%	Science and Engineering Occupations (2010)

Disabilities: Comparative data on the representation of people with disabilities are hard to define and thus difficult to measure and compare at a global level. To complicate matters, disabilities can be present at birth or acquired at any point during a person's lifetime. Regardless of when disabilities were acquired, persons with disabilities are underrepresented in the science and engineering workforce as compared with the population as a whole.

Graphics by Jen Christiansen, Research by Amanda Hobbs



Katherine W. Phillips is Paul Calello Professor of Leadership and Ethics and senior vice dean at Columbia Business School.

HOW DIVERSITY WORKS

Being around people who are different from us makes us more creative, more diligent and harder-working

Katherine W. Phillips

THE FIRST THING to acknowledge about diversity is that it can be difficult. In the U.S., where the dialogue of inclusion is relatively advanced, even the mention of the word "diversity" can lead to anxiety and conflict. Supreme Court justices disagree on the virtues of diversity and the means for achieving it. Corporations spend billions of dollars to attract and manage diversity both internally and externally, yet they still face discrimination lawsuits, and the leadership ranks of the business world remain predominantly white and male.

It is reasonable to ask what good diversity does us. Diversity of *expertise* confers benefits that are obvious—you would not think of building a new car without engineers, designers and quality-control experts—but what about social diversity? What good comes from diversity of race, ethnicity, gender and sexual orientation? Research has shown that social diversity in a group can cause discomfort, rougher interactions, a lack of trust, greater perceived interpersonal conflict, lower communication, less cohesion, more concern

IN BRIEF

Decades of research by organizational scientists, psychologists, sociologists, economists and demographers show that socially diverse groups (that is, those with a diversity of race, ethnicity, gender and sexual orientation) are more innovative than homogeneous groups.

It seems obvious that a group of people with diverse individual expertise would be better than a homogeneous group at solving complex, nonroutine problems. It is less obvious that social diversity should work in the same way—yet the science shows that it does.

This is not only because people with different backgrounds bring new information. Simply interacting with individuals who are different forces group members to prepare better, to anticipate alternative viewpoints and to expect that reaching consensus will take effort.

Illustrations by Edel Rodriguez

about disrespect, and other problems. So what is the upside?

The fact is that if you want to build teams or organizations capable of innovating, you need diversity. Diversity enhances creativity. It encourages the search for novel information and perspectives, leading to better decision making and problem solving. Diversity can improve the bottom line of companies and lead to unfettered discoveries and breakthrough innovations. Even simply being exposed to diversity can change the way you think. This is not just wishful thinking: it is the conclusion I draw from decades of research from organizational scientists, psychologists, sociologists, economists and demographers.

INFORMATION AND INNOVATION

THE KEY TO UNDERSTANDING the positive influence of diversity is the concept of informational diversity. When people are brought together to solve problems in groups, they bring different information, opinions and perspectives. This makes obvious sense when we talk about diversity of disciplinary backgrounds—think again of the interdisciplinary team building a car. The same logic applies to social diversity. People who are different from one another in race, gender and other dimensions bring unique information and experiences to bear on the task at hand. A male and a female engineer might have perspectives as different from one another as an engineer and a physicist—and that is a good thing.

Research on large, innovative organizations has shown repeatedly that this is the case. For example, business professors Cristian Deszö of the University of Maryland and David Ross of Columbia University studied the effect of gender diversity on the top firms in Standard & Poor's Composite 1500 list, a group designed to reflect the overall U.S. equity market. First, they examined the size and gender composition of firms' top management teams from 1992 through 2006. Then they looked at the financial performance of the firms. In their words, they found that, on average, "female representation in top management leads to an increase of $42 million in firm value." They also measured the firms' "innovation intensity" through the ratio of research and development expenses to assets. They found that companies that prioritized innovation saw greater financial gains when women were part of the top leadership ranks.

Racial diversity can deliver the same kinds of benefits. In a study conducted in 2003, Orlando Richard, a professor of management at the University of Texas at Dallas, and his colleagues surveyed executives at 177 national banks in the U.S., then put together a database comparing financial performance, racial diversity and the emphasis the bank presidents put on innovation. For innovation-focused banks, increases in racial diversity were clearly related to enhanced financial performance.

Evidence for the benefits of diversity can be found well beyond the U.S. In August 2012 a team of researchers at the Credit Suisse Research Institute issued a report in which they examined 2,360 companies globally from 2005 to 2011, looking for a relationship between gender diversity on corporate management boards and financial performance. Sure enough, the researchers found that companies with one or more women on the board delivered higher average returns on equity, lower gearing (that is, net debt to equity) and better average growth.

PARTICULAR POINTS OF VIEW

By Douglas Medin, Carol D. Lee and Megan Bang

Productivity and equity are probably the most often cited reasons to attend to diversity in science. Gender and culture also affect the science itself, however. They influence what we choose to study, our perspectives when we approach scientific phenomena and our strategies for studying them. When we enter the world of science, we do not shed our cultural practices at the door.

Evolutionary biology is one example. Despite popular images of Jane Goodall observing chimpanzees, almost all early studies of primate behavior were conducted by men. Male primatologists generally adopted Charles Darwin's view of evolutionary biology and focused on competition among males for access to females. In this view, female primates are passive, and either the winning male has access to all the females or females simply choose the most powerful male.

The idea that females may play a more active role and might even have sex with many males did not receive attention until female biologists began to do field observations. Why did they see what men missed? "When, say, a female lemur or bonobo dominated a male, or a female langur left her group to solicit strange males, a woman fieldworker might be more likely to follow, watch, and wonder than to dismiss such behavior as a fluke," wrote anthropologist Sarah Hrdy. Her interest in maternal reproductive strategies grew from her empathy with her study subjects.

Culture also made a difference in approach. In the 1930s and 1940s U.S. primatologists, adopting the stance of being "minimally intrusive," tended to focus on male dominance and the associated mating access and paid little attention to individuals except to trace dominance hierarchies; rarely were individuals or groups tracked for many years. Japanese researchers, in contrast, gave much more attention to status and social relationships, values that hold a higher relative importance in Japanese society.

This difference in orientation led to striking differences in insight. Japanese primatologists discovered that male rank was only one factor determining social relationships and group composition. They found that females had a rank order, too, and that the stable core of the group was made up of lineages of related females, not males. The longer-term studies of Japanese researchers also allowed them to notice that maintaining one's rank as the alpha male was not solely dependent on strength.

Diversity has had an effect on studies of education and social science. Lawrence Kohlberg's highly influential work on stages of moral development in children in the early 1970s was later called into question by psychologist Carol Gilligan on the grounds that it ignored the perspective of women, who tended to emphasize the ethic of caring. Nor did Kohlberg's model account for moral principles associated with Eastern religious traditions, in part because his scheme did not include principles of cooperation and nonviolence.

Validity in the sciences involves much more than attending to canons about the need for proper controls, replicability, and the like. It involves choices about what problems and populations to study and what procedures and measures to use. Diverse perspec-

HOW DIVERSITY PROVOKES THOUGHT

Large data-set studies have an obvious limitation: they only show that diversity is correlated with better performance, not that it causes better performance. Research on racial diversity in small groups, however, makes it possible to draw some causal conclusions. Again, the findings are clear: for groups that value innovation and new ideas, diversity helps.

In 2006 Margaret Neale of Stanford University, Gregory Northcraft of the University of Illinois at Urbana-Champaign and I set out to examine the impact of racial diversity on small decision-making groups in an experiment where sharing information was a requirement for success. Our subjects were undergraduate students taking business courses at the University of Illinois. We put together three-person groups—some consisting of all white members, others with two whites and one nonwhite member—and had them perform a murder mystery exercise. We made sure that all group members shared a common set of information, but we also gave each member important clues that only he or she knew. To find out who committed the murder, the group members would have to share all the information they collectively possessed during discussion. The groups with racial diversity significantly outperformed the groups with no racial diversity. Being with similar others leads us to think we all hold the same information and share the same perspective. This perspective, which stopped the all-white groups from effectively processing the information, is what hinders creativity and innovation.

Other researchers have found similar results. In 2004 Anthony Lising Antonio, a professor at the Stanford Graduate School of Education, collaborated with five colleagues from the University of California, Los Angeles, and other institutions to examine the influence of racial and opinion composition in small group discussions. More than 350 students from three universities participated in the study. Group members were asked to discuss a prevailing social issue (either child labor practices or the death penalty) for 15 minutes. The researchers wrote dissenting opinions and had both black and white members deliver them to their groups. When a black person presented a dissenting perspective to a group of whites, the perspective was perceived as more novel and led to broader thinking and consideration of alternatives than when a white person introduced *that same dissenting perspective*. The lesson: when we hear dissent from someone who is different from us, it provokes more thought than when it comes from someone who looks like us.

This effect is not limited to race. For example, last year professors of management Denise Lewin Loyd of the University of Illinois, Cynthia Wang of Oklahoma State University, Robert B. Lount, Jr., of Ohio State University and I asked 186 people whether they identified as a Democrat or a Republican, then had them read a murder mystery and decide who they thought committed the crime. Next, we asked the subjects to prepare for a meeting with another group member by writing an essay communicating their perspective. More important, in all cases, we told the participants that their partner disagreed with their opinion but that they would need to come to an agreement with the other person. Everyone was told to prepare to convince their meeting partner to come around to their side; half of the subjects, however, were told to prepare to make their case

tives and values are important in these choices. For instance, predominantly white, middle-class social scientists focus their research programs primarily on white, middle-class populations, which may lead to conclusions that are not generalizable.

If participation in cultural practices is central to our development as humans, then these practices will influence *how* we learn and practice science. In psychology, scholars who have intentionally focused on cultural orientations have expanded previously accepted conceptions of identity development, motivation and resilience. Research on the effect of teaching children to appreciate their racial heritage has pushed boundaries of accepted conceptions of identity development. Minority scholars have pointed out that studies tend to focus on the effects of diversity rather than the effects of homogeneity and other gaps in scientific practices.

A diversity of scientists is important for reducing bias and for providing different ways of looking at the world. Two of us (Bang and Medin) and our colleagues have documented consistent cultural influences on the perceived relationship between humans and nature: rural European-Americans tend to see themselves as apart from nature, whereas Native Americans see themselves as a part of nature (although it is more complicated than we have space to explain). This may influence how we think about environmental issues. It may also be why the mainstream view excludes urban settings as part of any ecosystem and sees ideal ecosystems as free of human influence, and so on.

It is commonly said that scientists should have a professional distance from what they study. But the metaphor of distance is misleading. Science, like a painting, necessarily has a perspective. To the extent that we can remove our biases and learn from multiple perspectives, we will understand our world better.

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to a member of the opposing political party, and half were told to make their case to a member of their own party.

The result: Democrats who were told that a fellow Democrat disagreed with them prepared less well for the discussion than Democrats who were told that a Republican disagreed with them. Republicans showed the same pattern. When disagreement comes from a socially different person, we are prompted to work harder. Diversity jolts us into cognitive action in ways that homogeneity simply does not.

For this reason, diversity appears to lead to higher-quality scientific research. This year Richard Freeman, an economics professor at Harvard University and director of the Science and Engineering Workforce Project at the National Bureau of Economic Research, along with Wei Huang, a Harvard economics Ph.D. candidate, examined the ethnic identity of the authors of 1.5 million scientific papers written between 1985 and 2008 using Thomson Reuters's Web of Science, a comprehensive database of published research. They found that papers written by diverse groups receive more citations and have higher impact factors than papers written by people from the same ethnic group. Moreover, they found that stronger papers were associated with a greater number of author addresses; geographical diversity, and a larger number of references, is a reflection of more intellectual diversity.

THE POWER OF ANTICIPATION

DIVERSITY IS NOT ONLY about bringing different perspectives to the table. Simply adding social diversity to a group makes people *believe* that differences of perspective might exist among them and that belief makes people change their behavior.

Members of a homogeneous group rest somewhat assured that they will agree with one another; that they will understand one another's perspectives and beliefs; that they will be able to easily come to a consensus. But when members of a group notice that they are socially different from one another, they change their expectations. They anticipate differences of opinion and perspective. They assume they will need to work harder to come to a consensus. This logic helps to explain both the upside and the downside of social diversity: people work harder in diverse environments both cognitively and socially. They might not like it, but the hard work can lead to better outcomes.

In a 2006 study of jury decision making, social psychologist Samuel Sommers of Tufts University found that racially diverse groups exchanged a wider range of information during deliberation about a sexual assault case than all-white groups did. In collaboration with judges and jury administrators in a Michigan courtroom, Sommers conducted mock jury trials with a group of real selected jurors. Although the participants knew

SCIENCE EXPOSED

By Steven Bishop

Opening science to public participation, the "citizen science" mode of research, has stimulated a diversity of projects that have led to real innovation and changes in behavior. It has done more than simply enhance existing research. It has also engaged a range of viewpoints that otherwise would have remained below the radar, allowing new people to provide new ideas to solve new problems.

Citizen science is driven mainly by the Internet, cloud computing, smartphones and social media, which enable thousands of scientists—or nonqualified individuals who are often globally dispersed—to participate in the gathering of information and knowledge on a range of scales: Galaxy Zoo (galaxyzoo.org) classifies galaxies, Qcumber (q-cumber.org) allows international users to upload sites of environmental hazards, Project FeederWatch (feederwatch.org) counts birds in North America, and the California Roadkill Observation System (wildlifecrossing.net/California) reports animals killed by vehicles. These programs enable data sampling on a scale finer than could be achieved by any other means.

Ubiquitous mobile devices means that projects need not be restricted to the affluent, literate and educated public. In his work with the ethnic Baka groups in Cameroon, Jerome Lewis of University College London uses simple images to document valuable trees. Methods of citizen science are being opened up to projects in social science to study discrimination and human-rights abuses and to support local peoples in better representing themselves to outsiders.

Besides data gathering, many citizen science projects change our perceptions. The Annual Audubon Christmas Bird Count (birds.audubon.org/christmas-bird-count) gives information about population trends. It engages with society and in doing so provides education that can help lead to cultural change. The project was started to replace the tradition of shooting birds on Christmas day.

Ideas can also be readily scaled up. A project started in a classroom can soon become a global initiative. Projects such as Leafsnap (leafsnap.com), which identifies plants, feed information back to individuals, who become part of a two-way process. This collective knowledge may spark other ideas, leading to new ways of doing science, as seen, for instance, in solutions to the protein-folding puzzles put forward by the Foldit project (fold.it/portal). Platforms such as Zooniverse (zooniverse.org) give millions of people access to all manner of collaborations. At CERN near Geneva and other large-scale scientific projects, people with a range of skills have come together to work toward specified goals; through citizen science, this idea can be broadened, be it by classifying newly discovered galaxies or identifying plants. This adds a novel dimension to citizen science, letting the crowd propose new solutions to unsolved problems.

In Iceland, after the 2008 financial crash, city councilors had hard choices to make about how to spend their limited budgets. Better Reykjavik was set up to enable citizens to debate innovative ideas to improve their communities. They crowdsourced potential projects, prioritized them and decided what budgets to allocate. Such successes have opened our eyes to new ways of funding science, such as the Experiment crowdfunding platform (experiment.com). How long will it be before such approaches become de rigueur in scientific funding?

When coupled with big data, citizen science projects will expand yet further. Open platforms will give individuals access to data, models and analyses, so they can pose their own questions and find solutions. This will change the way we teach science in schools and perform research.

Steven Bishop is a professor of mathematics at University College London.

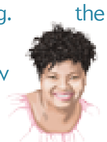
TAKING IT PERSONALLY

By D. N. Lee

Creating safer communities. Ensuring access to clean water. Tackling such problems requires science. Yet for much of its history, science has been shaped by European values. White European and American men have largely controlled who asks the questions, how they are studied and what is significant. Many important discoveries and innovations have been made, but many questions have been overlooked or unacknowledged because the experiences of investigators were limited.

Pursuing personally relevant research broadens science and makes it more meaningful for us all. Robin Nelson, an assistant professor of anthropology at Skidmore College, acknowledges that opinions on research design in biological anthropology are shifting because more people recognize the role of personal experience in shaping science. She recalls the moment in her work on caretaking strategies in Caribbean families when she decided to heed advice from her female subjects and expand a study to include male family members who also contribute to familial well-being.

"To fully comprehend female caregiving dynamics, I had to understand how these women construct their universe," Nelson says. "They live in a patriarchal social system. That meant interviewing male family members such as brothers and fathers, too." She discovered that female caretaking strategies were often, in part, a response to financial and emotional provisions of male family members.



D. N. Lee is a biologist who studies animal behavior and ecology. She writes The Urban Scientist blog for *SA's* blog network.

When individuals from underrepresented groups become scientists, they often come with a mission. Carl Hart, an associate professor of psychology and psychiatry at Columbia University, grew up in inner-city Miami during the 1980s war on drugs. After witnessing friends and neighbors suffer from drug-related crime and a short stint selling and trying drugs, he remapped his trajectory. He graduated from college and went on to study physiological effects of drugs on the human brain because he wanted to understand how drugs affected people. "You just have these different perspectives that are not from our typical pool of scientists, and so you look at problems differently," he told the Huffington Post in 2013. "You are certainly more courageous in some areas because you see the impact on people you care about."

Margaret Hiza Redsteer, a research scientist at the U.S. Geological Survey, studies climate change impacts on the Navajo Nation's land and water. While raising her family on the reservation, she grew frustrated about water supplies that were intermittent and sometimes contaminated. When she began her college studies at 28, she was interested in geology and hydrology because she wanted to better understand the relations among the land, how it was used and the water her community needed. "One of the most important things I learned over the course of my education is that who you are helps define how you look at the world and how you approach a problem," says her profile for the Society for Advancement of Hispanics/Chicanos and Native Americans in Science. "Using traditional Native American knowledge is not just important from a scientific point of view but also from a cultural point of view.... We need people who approach problems from this perspective in the sciences so that we can learn—and hopefully teach others—how to be better stewards of the land."

Ecologists have recently begun to pay attention to urban environmental issues. But these issues were not new to people of color and those living in low-income communities, who saw through the lens of environmental justice. As a native Chicagoan, Kellen A. Marshall-Gillespie, a doctoral student in urban ecology at the University of Illinois at Chicago, noticed how pollution from cars and businesses affected the respiratory health of her neighbors. She hypothesized that these pollutants would negatively affect the growth and physiological development of plants, including vegetables in nearby gardens. "Environmental inequities and racism [have] tremendous implications for the sustainability of natural systems and ecosystem services," she wrote for the Ecological Society of America. "I felt a deep charge to connect the social benefits of studying ecosystem services, [environmental justice], and segregation."

When science is inclusive, everyone wins. Long underserved communities are finally heard, and scientists who listen are rewarded with fresh insights.

the mock jury was a court-sponsored experiment, they did not know that the true purpose of the research was to study the impact of racial diversity on jury decision making.

Sommers composed the six-person juries with either all white jurors or four white and two black jurors. As you might expect, the diverse juries were better at considering case facts, made fewer errors recalling relevant information and displayed a greater openness to discussing the role of race in the case. These improvements did not necessarily happen because the black jurors brought new information to the group—they happened because white jurors changed their behavior in the presence of the black jurors. In the presence of diversity, they were more diligent and open-minded.

GROUP EXERCISE

CONSIDER THE FOLLOWING SCENARIO: You are writing up a section of a paper for presentation at an upcoming conference. You are anticipating some disagreement and potential difficulty communicating because your collaborator is American and you are Chinese. Because of one social distinction, you may focus on other differences between yourself and that person, such as her or his culture, upbringing and experiences—differences that you would not expect from another Chinese collaborator. How do you prepare for the meeting? In all likelihood, you will work harder on explaining your rationale and anticipating alternatives than you would have otherwise.

This is how diversity works: by promoting hard work and creativity; by encouraging the consideration of alternatives even before any interpersonal interaction takes place. The pain associated with diversity can be thought of as the pain of exercise. You have to push yourself to grow your muscles. The pain, as the old saw goes, produces the gain. In just the same way, we need diversity—in teams, organizations and society as a whole—if we are to change, grow and innovate. SA

Stephanie C. Hill is vice president and general manager of Lockheed Martin Information Systems & Global Solutions Civil.

IN PURSUIT OF THE BEST IDEAS

How I learned the value of diversity

By Stephanie C. Hill

I WAS A young African-American woman in 1996, determined to do my best at Lockheed Martin, one of the world's foremost technology companies, when I was named to lead an integrated-product team for a mission-critical U.S. Navy program.

I was confident in my abilities as a software engineer, and I had been intimately involved in writing the program requirements. But the scope of the program was much broader than software development. We were tasked with creating an advanced launch control unit peripheral for a navy vertical-launch system.

Our challenge was to take a legacy system, based on a 16-bit computer with a rudimentary keypad input and tape cartridge device, and design a new unit that incorporated off-the-shelf technology—a 166-megahertz PowerPC VME processor and a touch-screen graphical user interface. This was before the iPad, when touch screens were a big deal. It was one of the navy's first ventures into forward-compatible, off-the-shelf technology. The system also had to be ruggedized to withstand a near-miss explosion. And we had to deliver it quickly and affordably.

Given the complexity, deadline and the amount of innovation required for the program, we needed every ounce of original thinking from people of many differ-

dismissed without consideration. I also established an environment where people felt safe in asking questions that often go unasked because everybody is afraid of being the only one who doesn't already know the answer. Asking those questions early in a discussion gets us past them (because, in truth, many other people have them, too) and allows us to use our time more efficiently.

Among my biggest concerns as a leader is that I will allow the best idea in the room to go unexpressed because someone did not feel comfortable enough to express it.

Once I found myself sitting next to a young engineer in a roomful of more experienced colleagues. I noticed he had something he wanted to say, but he was always a split second late in gaining the floor. After this had gone on for a while, I stopped the discussion, turned to him and asked for his opinion. He proceeded to make a suggestion that nobody else had considered. It was risky, and the group was skeptical. Eventually we adopted his idea, and it resulted in completely winning over a customer.

Perhaps the most important outcome of my experience as team leader was that it helped me evolve my understanding of diversity into a broader concept of inclusion. Diversity of age, gender, skin color, ethnicity, and more—the attributes of a diverse workplace that are the first to come to mind—is often visible and easy to identify and requires focus to engage and develop. The presence of diversity that you can see is often an indicator of an inclusive environment that embraces diversity of thought. A team dynamic that opens the door to inclusion will elicit ideas that spring from varied professional, educational and social experiences.

ent backgrounds, both professional and personal. Our team of about 30 individuals had several people of color and several women, which was significant for my industry at the time, and a healthy mix of experience and youth. I had to establish an atmosphere of inclusion across race, gender and age diversity.

It was the diversity of professional expertise on the team that proved to me that an inclusive, sharing environment is imperative to success. We had systems, software, and electrical and human factors engineers. We had experts in shock attenuation, electromagnetic pulses and testing simulation systems. And we needed to engage all of them in a give-and-take dialogue in which ideas were stood up, picked apart and modified to become stronger with each iteration.

It was the kind of environment that not only benefits from diversity, it *demands* it. And because we were successful in establishing and managing it, we were also successful in delivering the capability that the customer required.

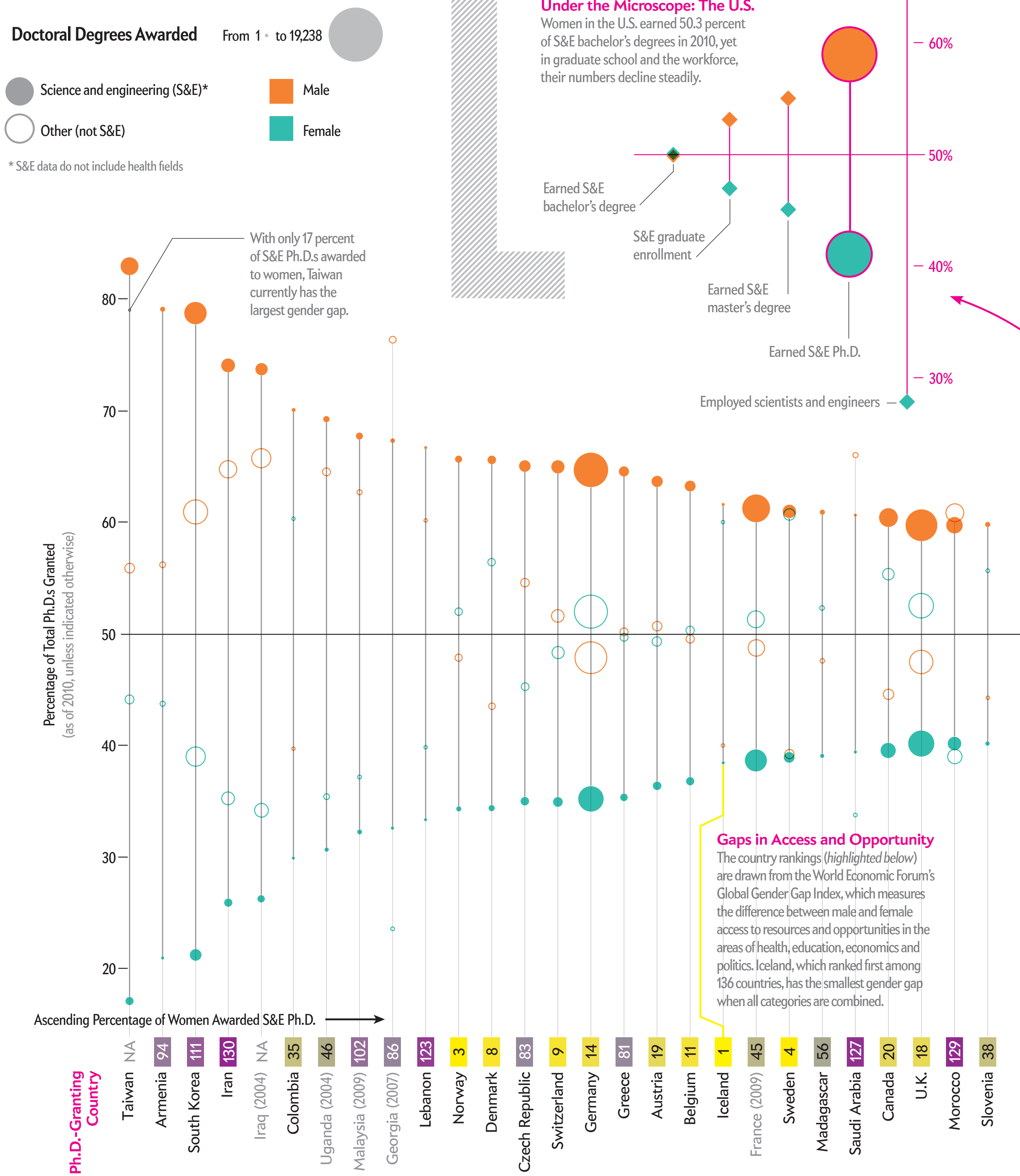
As a leader, I had to set the tone for people to express their ideas, even if they differed from those of their colleagues. I would not allow someone's ideas to be

It's a truism that the best teams are greater than the sum of their parts. I believe that is *only* true when those parts are diverse. When everyone looks the same, acts the same and *thinks* the same, is it any wonder that they often fail to embrace—or even produce—innovative and unconventional ideas?

I am fortunate to work for an organization that not only understands that concept but makes a conscious choice to live by it. To choose otherwise would be to resign ourselves to comfortable mediocrity—and that will never be a viable option in the pursuit of excellence. SA

Illustration by Edel Rodriguez

Global Ph.D.s by Gender



Graphic by Periscopic and Jen Christiansen, Research by Amanda Hobbs

GENDER GAP

How women and men fare in doctoral studies around the world

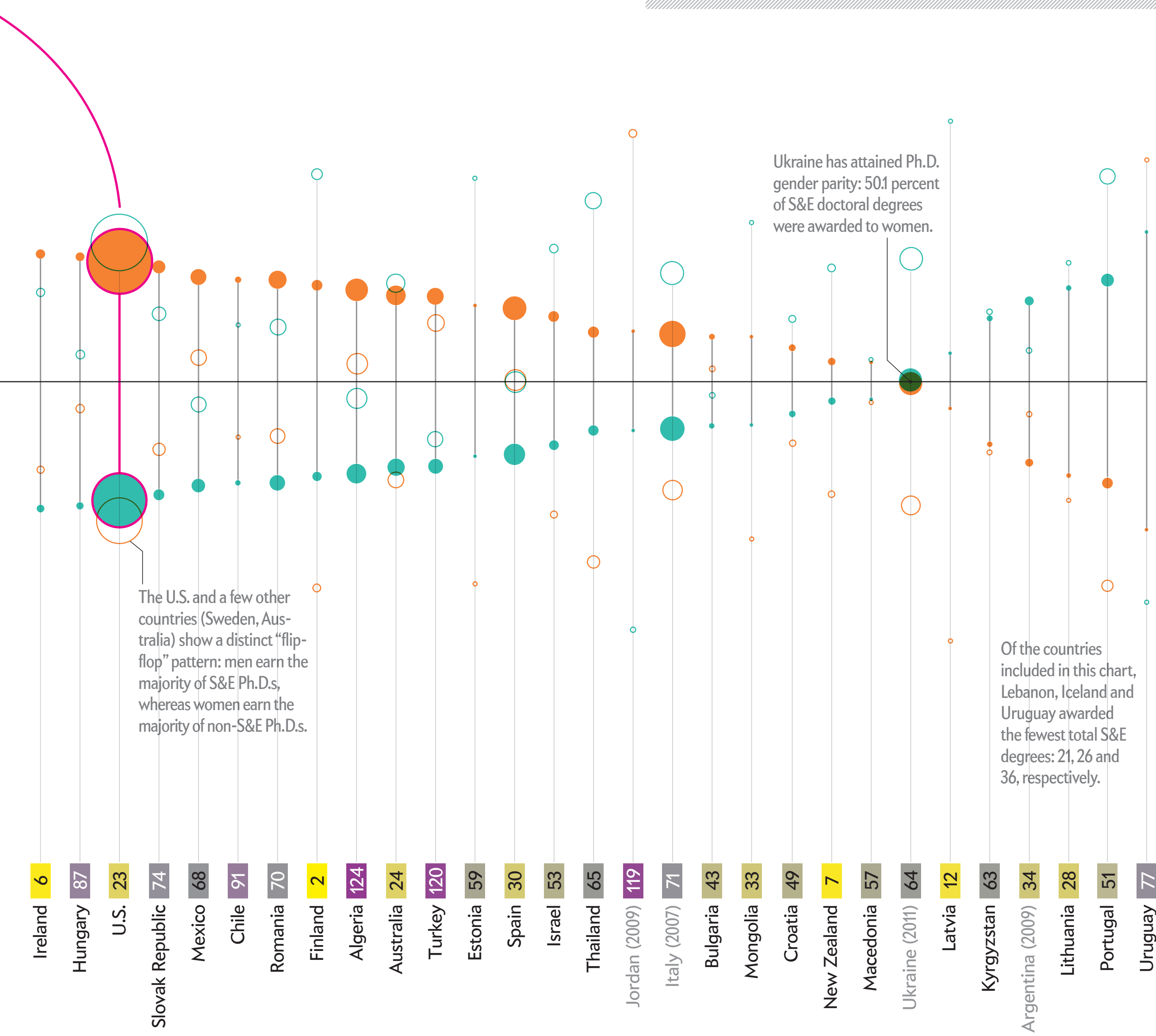
IN THE U.S., women are going to college and majoring in science and engineering fields in increasing numbers, yet here and around the world they remain underrepresented in the workforce. Comparative figures are hard to come by, but a disparity shows up in the number of Ph.D.s awarded to women and men. The chart here, assembled from data collected by the National Science Foundation, traces the gender gap at the doctoral level for 56 nations. The situation in individual countries varies widely, but as the numbers make clear, there are interesting exceptions to the global trend. SA

MORE TO EXPLORE

Science and Engineering Indicators 2014. National Science Board. National Science Foundation, 2014. www.nsf.gov/statistics/seind14/index.cfm/home

The Global Gender Gap Report 2013. World Economic Forum, 2013. www.weforum.org/reports/global-gender-gap-report-2013

Nature Index of scientific research (to launch in Fall 2014): www.natureindex.com



SOURCES: *SCIENCE AND ENGINEERING INDICATORS 2014*, BY NATIONAL SCIENCE BOARD. NATIONAL SCIENCE FOUNDATION, 2014 (*education data*); *THE GLOBAL GENDER GAP REPORT 2013*. WORLD ECONOMIC FORUM. 2013 (*WEF index*)

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INVITING EVERYONE IN

There is no formula for bringing diversity to the workplace or classroom, but new research that deepens our understanding of how diversity operates suggests some modestly successful strategies

By Victoria Plaut

EVERY TIME I SPEAK with an audience about diversity, I get the same question: How do we do it? All of my audiences—schools, academic departments, businesses, health care organizations and law firms—seem mystified. They want the secret recipe or a foolproof checklist. They hope I will say, "Follow these simple steps, and you will have diversity and inclusion." So let me begin with this disclaimer: a simple, foolproof method for ensuring that a group is well represented across racial, ethnic, socioeconomic or gender lines does not exist.

IN BRIEF

Not surprisingly, good intentions alone cannot guarantee success in creating a diverse working or academic environment. Fortunately, a growing body of social science research shows which approaches are likely to prove more successful than others.

Three common misconceptions often get in the way, however, of creating work or academic settings in which individuals from underrepresented groups feel comfortable enough to engage productively and to remain committed to the enterprise.

At a minimum, fostering a more diverse workforce in science, technology and health care requires attending to difference, nurturing a sense of belonging for a wide range of individuals and giving someone the responsibility for achieving diversity goals.

Illustrations by Edel Rodriguez

A few common misperceptions, in my experience, interfere with many people's and organizations' sincere desire to create a more inclusive environment in the office or classroom. First, many of us assume that we do not need to think about what makes us different to promote diversity. Second, we think that everyone experiences school or work settings in basically the same way. And third, if problems arise, we assume that we personally cannot do much about them, because they are too systemic or, alternatively, are mostly caused by a few biased people (who could be changed through specialized training).

Research shows that these assumptions, though widely held, are mistaken. Their continued persistence fuels the misguided impression that all it takes to pursue a career in STEM (science, technology, engineering and mathematics) is to be competent and motivated, with access to the right tools. These falsehoods in turn lead to a false conclusion: if people are not signing up for or staying in science, it must be because they cannot or do not want to.

Fortunately, those who are open to trying can change their assumptions. And a growing body of evidence from experimental social psychology and organizational sociology suggests some approaches to producing more inclusive environments are more likely to prove successful than others. New understanding and growing confidence in the latest research findings are producing more inclusive environments at a number of organizations.

FORGET COLOR BLINDNESS

PERHAPS AN IDEAL WORLD EXISTS in which race or gender is beside the point in the office or classroom. In our world, however, most people find it easier to thrive in an actively supportive environment in which it is safe to be different.

Several years ago my colleagues and I conducted a study in a health care organization consisting of scientists, doctors, nurses and other health care workers. We asked people whether they thought racial and ethnic differences should be actively ignored or positively acknowledged as part of the organization's efforts to promote diversity. We then examined how employees of color felt about their work and the organization. In departments in which white employees believed that differences should be ignored, we found that the sense of engagement felt by nonwhite workers was lower than in departments in which

BECOMING VISIBLE

By Brian Welle and Megan Smith

Gloria Steinem said, "Women have always been an equal part of the past. We just haven't been an equal part of history." Along these lines, over the past few years, we discovered some pretty ugly news about our beloved Google Doodles. We had been making these embellishments to the corporate logo on our home page, often in honor of specific people on their birthdays, ever since the company was founded in 1998. For the first seven years, we celebrated exactly zero women. Between 2010 and 2013 we did a little better: women accounted for about 17 percent, men of color 18 percent, women of color an appallingly low 4 percent; 62 percent of the honorees were white men.

We had not noticed the imbalance.

The Web did, however. Gender equality champions did the math and called us out, quite publicly. The Doodle findings held up a mirror to the unconscious biases we had inherited. The problem is far bigger than Google. Women and minorities are not as clearly visible in the science and technology workplace and indeed in our culture in general.

Women make up half of the labor pool and hold roughly 30 percent of the jobs in science, technology, engineering and mathematics (STEM) in the U.S., but fewer than 21 percent of female characters in family films, prime-time programs or children's shows are depicted as working in these fields. For computer science jobs in family films, the ratios are worse: 15 men are depicted for every woman. (These figures come from the Geena Davis Institute on Gender in Media, which has done an important job of cataloguing the representation of girls and women, with a focus on family and children's media; Google awarded the institute a Global Impact grant in 2013.)

Visibility matters. An abundance of research shows that seeing very few people like oneself represented in a profession leads people—especially girls and students of color—to feel less welcome and makes them more anxious than they would feel in gender- or race-balanced professions. It can create debilitating performance pressure. Ultimately fewer women and minorities will pursue computer science as a profession or persist with the career once they are there.

The Doodle analysis turned out to be a learning opportunity. It helped to shock us awake.

Google recently commissioned a project to identify what makes girls pursue education in computer science. The findings reinforced what we already knew. Encouragement from a parent or teacher is essential for them to appreciate their own abilities. They need to understand the work itself and see its impact and importance. They need exposure to the field by having a chance to give it a shot. And, most important, they need to understand that opportunities await them in the technical industry.

The rapidly growing field of computer science careers is in overwhelming need of a reputational and role-model overhaul. To that end, in June, Google launched Made with Code, a $50-million program over three years that supports marketing campaigns and other initiatives (including the Girls Scouts, Girls Inc., and Girls Who Code) to bring computer science education and access to girls. In 2012 we launched a professional developer organization, Women Techmakers, in part to increase the visibility of technical women and minorities who are already working in teams and, in some cases, leading them. Some are among the most important and influential founders of our industry, which reinforces the notion that invisibility is a serious problem.

The cycle that keeps women and people from underrepresented groups out of tech fields can start much earlier than educational programs can reach. It begins with the biases that children learn at a very young age and are reinforced—often unknowingly by their friends, parents, peers and the media. These biases can find their way into the behavior and decision making white workers publicly espoused support for diversity—regardless of how many persons of color actually worked in the department. Moreover, in the "color-blind" departments, individuals from underrepresented groups perceived more bias. In the acknowledging departments, they perceived less.

Several studies indicate that unconscious bias, subject to suggestion, may be at play here. For example, in 2004 Jennifer A. Richeson, then at Dartmouth College, and her colleagues measured the reaction times on certain psychological tests of about 50 white college students after half of them had been given material that argued for color-blind policies to achieve interracial harmony and the other half received material favoring the deliberate promotion of racial diversity. Richeson then measured how quickly participants linked certain pairs of words with ethnically suggestive names (for example, "Jamal" and "good" or "Josh" and "good" versus "Jamal" and "bad" or "Josh" and "bad"). Participants who were perfectly unbiased should have been able to pick the equivalent word pairs equally quickly, regardless of racial overtones. Faster reactions times whenever the white-pleasant and black-unpleasant associations were called for indicated an implicit bias in favor of whites.

Whereas both groups completed their tests more quickly when pairing "white" and "pleasant" words, study participants who had been exposed to the multicultural approach showed less of a difference than those who had been given the color-blind material. Richeson, who is now at Northwestern University, thus concluded that color-blind policies might backfire, generating more racial tension by stoking rather than lessening implicit bias. More recent studies have found that the prescription to ignore racial differences tends to increase prejudicial behavior in both verbal and nonverbal ways by white students and, perhaps because of this, to cognitively exhaust students of color.

Similarly, other studies show that our biases leak out in subtle ways. In 2002 researchers measured a group of white students' explicit and implicit racial attitudes, using a questionnaire and a reaction time task. They then arranged for the students to have a conversation with a black student on a topic not ostensibly about race (dating). Afterward, other students listened to an audiotape of the participants and rated their verbal friendliness. They also watched silent videos that showed only the white participants and rated their nonverbal mannerisms for signs of friendliness. The result: students whose speech was rated as less friendly also scored worse on the explicit bias test, whereas those who appeared to be less friendly on the video did worse on the reaction time test, providing evidence that even supposedly hidden bias is often clearly noticeable.

Such cues are not lost on those individuals from underrepresented groups, who may become discouraged and decide to leave a particular field or firm. Indeed, surveys on college campuses suggest that perceptions of the diversity climate and experiences with prejudice and discrimination play a role in underrepresented students' decisions to avoid or leave STEM majors. Likewise, in the working world, perceptions about an organization's acceptance of diversity predict how likely individuals from underrepresented groups are to leave. Adopting a color-blind approach, therefore, leaves organizations blind to the processes that help to shape people's desire to engage productively or to seek greener pastures.

Groups that abandon color-blind policies are not necessarily home-free. But embracing difference in a way that does not stereotype or pigeonhole people appears to hold promise for achieving diversity. In a recent intervention at Northwestern by Nicole M. Stephens and her

of even the most well-intentioned of people. They can affect the educational path that boys and girls choose and the workplace cultures that encourage or repel them.

To fight these biases, in May 2013 Google created an Unconscious Bias work stream. Its goals are to educate Google employees about bias—their own and others'—to give them the tools and insight to change their behaviors, and to change the company's culture to be more inclusive of diverse perspectives. In the past two years more than 20,000 Googlers have participated in a training program to learn the science of identifying and eradicating biased decision making at work and with our families.

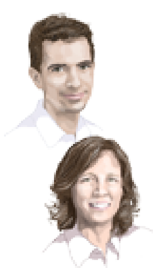
Just projecting the idea that tech fields are improving for women and minorities will have a positive effect, studies suggest. Emily Shaffer of Tulane University and her colleagues recently found that the simple act of reading an article on how representation of women in STEM is increasing improved the performance of girls on math tests and other tasks, erasing any performance difference between girls and boys.

Armed with this research and a recognition that things need to shift, we have started outreach work to media partners—Hollywood influencers who might help change perceptions from our television screens, writers, directors, producers, actors, agents, studio leaders and other potential collaborators. We hosted the writing room team for the hit HBO show *Silicon Valley* at Google to talk with amazing technical women about innovation, providing (we hope) inspiration for future characters.

Gloria Steinem also said, "Don't think about making women fit the world—think about making the world fit women." Our industry is just starting to appreciate what insight means for how we might change and adapt our tech culture to better accommodate the neglected innovators among us. It is important not only for including the best talent but also for making better products.

For more than a year now, Googlers on the Doodle team have been on a mission to correct the gender and minority imbalance in the representation of heroes on our home page. By summer women accounted for 49 percent of the 51 Doodles we had hosted in 2014. People of color accounted for roughly 33 percent, which puts us on track to top 2013, but still there is room for improvement.

As the tech industry wakes up to the reality of its unconscious biases, our innovation culture gives us the potential to lead the change. It is up to us to see the reality and collaborate to improve. Awareness will help us discover, debug, innovate, pilot and scale solutions to our cultural deficits.



Brian Welle is director of people analytics at Google. **Megan Smith** is an entrepreneur and a vice president at Google[x].

colleagues, some first-year students attended a panel in which other students discussed their experiences by *drawing attention to* difference (the experimental group)—in this case, their status as first-generation college students. Others (the control group) attended a panel that ignored difference. Both panels provided advice, but those in the "difference" group did so by explicitly connecting social class to their discussion of obstacles and strategies. More important, the latter panel emphasized difference in a constructive and supportive way—not in a way that signaled a deficiency. The result of this one-hour intervention: a 63 percent reduction in the academic gap between first-generation and continuing-generation students at the end of the first semester.

BOLSTER BELONGING

IT IS EASY TO THINK that science is science and that so long as people have the necessary preparation and motivation, they can join the club, but the truth is more complicated. Research in social psychology suggests that for underrepresented students, a sense of belonging is a key driver of participation and performance.

Gregory M. Walton and Geoffrey L. Cohen, both at Stanford University, recently decided to test this observation with a group of nearly 100 college freshmen at an "elite college" (they did not say which one in their 2011 report). Half the students (the experimental group) read testimonials from more senior students about how they, too, had experienced social difficulties in their first year and had worried that these experiences meant that they did not belong at the school but had eventually grown confident that they belonged. The other half (the control group) were given unrelated information about changing social and political attitudes. Three years after the intervention occurred, the researchers checked the students' progress. Being in either group made little difference to the white students. Black students in the experimental group, in contrast, did significantly better academically than their peers in the control group—cutting in half the average achievement gap between racial groups seen at the start of the study. Of course, as Walton and Cohen point out, such an intervention may not work in an openly hostile environment.

The critical importance of developing a sense of belonging may explain why historically black colleges and universities are traditionally much stronger producers of black STEM graduates. Predominantly white schools—and workplaces—face significant challenges in creating inclusive and welcoming environments, but various methods are available to do so.

In the domain of computer science, for example, nonprofits have sprung up across the U.S. to teach coding to underrepresented youth. These organizations include Code2040, the Hidden Genius Project, Black Girls Code, CodeNow and Girls Who Code. Notably, what ties these types of programs together is not only that they teach valuable skills and promote educational and career opportunities but also that they reinforce belonging, encourage collaboration and emphasize applications that relate to students' lives and communities.

Such efforts extend even to the choice of decor. In 2009 my colleagues and I determined that the act of changing the types of objects found in a computer science classroom from the stereotypically geeky (*Star Trek* posters, junk food and soda cans) to more neutral objects (nature posters, coffee mugs and water bottles) was enough to raise female students' level of interest in the subject matter to that of the males. Similarly, a separate study showed that emphasizing the ways in which the pursuit of science is a collaborative effort instead of a solitary one boosted women's inclination to pursue a scientific career.

TAKE ACTION

SO IS THAT IT, THEN? Just acknowledge people's differences and make them feel included, and they will participate and stay in science? Research in organizational sociology suggests a third vital component: the ways we structure diversity efforts within organizations.

Frank Dobbin of Harvard University, Alexandra Kalev, now at Tel Aviv University, and their colleagues have analyzed diversity initiatives in hundreds of U.S. companies over three decades. They have found that organizations that put someone in charge of diversity have stronger records of employing managers from underrepresented groups. A full-time diversity staffer results in, on average, a 15 percent increase in the proportions of black women and men in management in about five to seven years. Similarly, companies that establish a diversity task force of employees who are held accountable for increasing diversity experience significant increases in black, Latino, and Asian-American men and women and white women in management.

Research shows that hiring diversity managers and launching diversity task forces also increase the effectiveness of other programs, such as employee network groups that help people from underrepresented groups to feel less isolated and diversity councils that address specific issues, such as the retention and development of employees from underrepresented groups. In addition, multiple studies, including Dobbin and Kalev's, show that active, targeted recruitment programs also boost workforce diversity.

EMBRACING DIFFERENCE IN A WAY THAT DOES NOT STEREOTYPE OR PIGEONHOLE PEOPLE APPEARS TO HOLD PROMISE FOR ACHIEVING DIVERSITY.

Lest anyone think, however, that only systemic initiatives make a difference—a common belief related to the final blind spot I would like to address—Dobbin, Kalev and others have shown that mentoring programs are the most effective in increasing the numbers of white and black women and Latino and Asian women and men in management. Gains in proportions of managers for some of these groups reached almost 40 percent after such programs were launched.

Similarly, the importance of good mentoring cannot be understated in science education, where opportunities to get involved in a laboratory and learn about postcollege possibilities often come through mentors, who may also help bolster the belonging processes described here. In his book *Whistling Vivaldi,* social psychologist and University of California, Berkeley, provost Claude Steele, who is black, recounts how, as a Ph.D. student at Ohio State University, his white adviser treated him in a way that made him feel like he belonged there—as a scientist—in the midst of an environment that otherwise felt pretty alienating: "He had faith in me as a worthy partner. Somehow his assumptions about what he was doing as a scientist included me as, at least potentially, a capable colleague. My race and class identities didn't get in his way."

Notably, research shows that diversity leadership, targeted recruitment and mentoring appear to be more effective than common initiatives such as diversity training and diversity performance evaluations. Dobbin, Kalev and their colleagues suggest the following reason: the less common techniques engage managers in the task of identifying problems and solutions related to diversity rather than placing blame on them.

These programs alone will not create sweeping change, but they improve the chances for increasing diversity, provided they are not reduced to merely symbolic initiatives. Employees must be given the responsibility and institutional authority for "getting" diversity. A good example of a comprehensive intervention program that recruits and trains underrepresented undergraduate students in STEM is the Meyerhoff Scholars Program at the University of Maryland, Baltimore County. It combines *14* different components and has been particularly successful at increasing the number of African-American science degree holders. Another is the recently formed California Alliance for Graduate Education and the Professoriate (a partnership between U.C. Berkeley, U.C.L.A., Stanford and the California Institute of Technology), which targets underrepresentation in academia. What is more, it was built on principles from social science research and plans to analyze the effectiveness of different initiatives. (Such "real world" data are in short supply. Nor is there a central repository of research or a system for different groups—particularly from industry and academia—to communicate and partner with one another about what works best.)

For scientific and nonscientific organizations alike to get results, a deeper understanding of how diversity operates is required. No matter how sincere the goal setting, merely caring about diversity is not enough. Although there is no simple or perfect recipe to translate these sentiments into action and results, organizations are more likely to attract and retain diverse talent when they are smart and persistent in their outreach, nourish a sense of belonging, and put in place people who are accountable for—and monitor—diversity. SA

MORE TO EXPLORE: DIVERSITY

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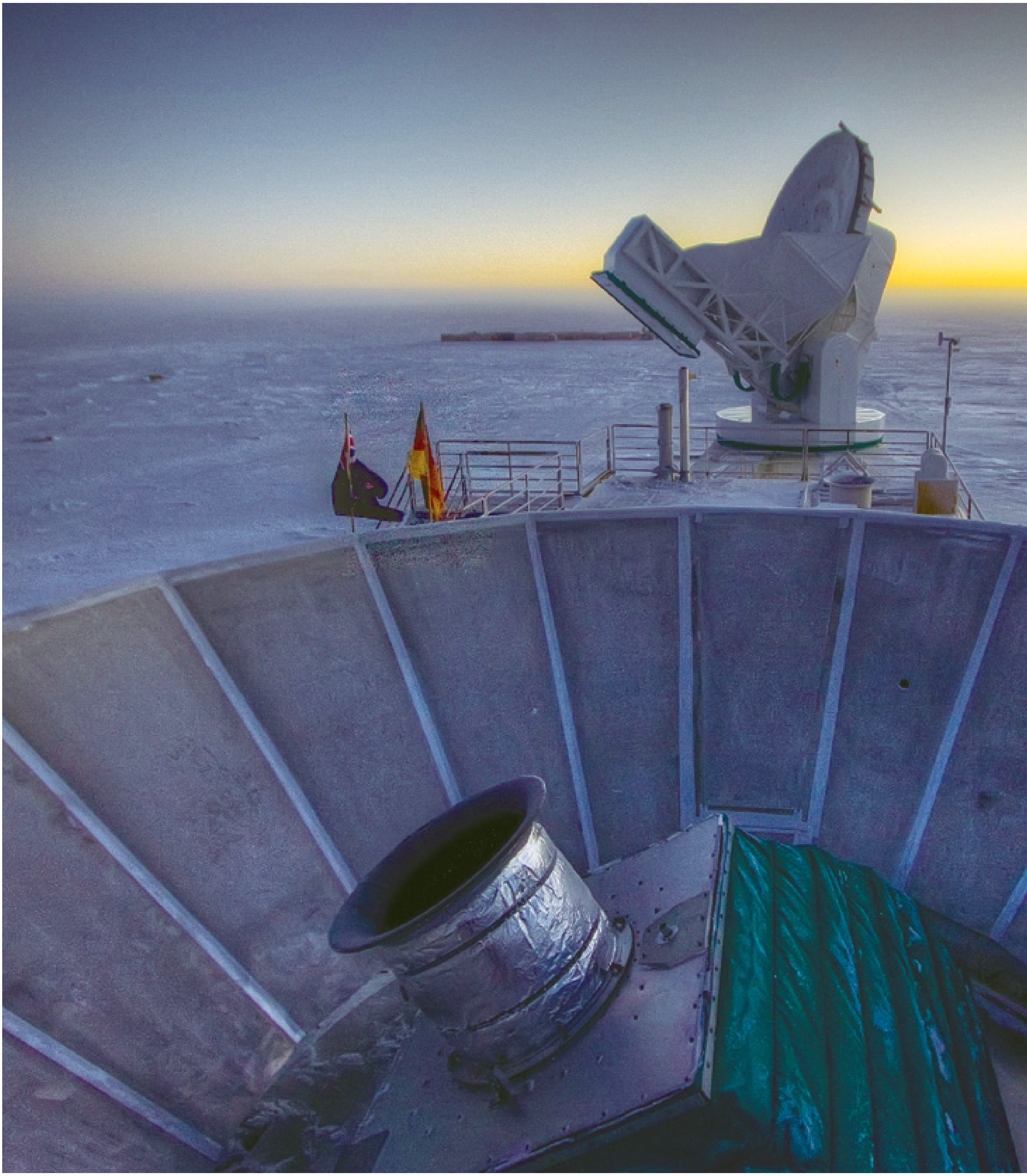


POLAR EYES: The BICEP2 telescope at the Amundsen-Scott South Pole Station observed the same small patch of sky from January 2010 through December 2012, searching for signatures of primordial gravitational waves in ancient light.

COSMOLOGY

A Beacon from the Big Bang

If the recent discovery of gravitational waves emanating from the early universe holds up under scrutiny, it will illuminate a connection between gravity and quantum mechanics and perhaps, in the process, verify the existence of other universes

By Lawrence M. Krauss

Lawrence M. Krauss, a theoretical physicist and cosmologist, is Foundation Professor and director of the Origins Project at Arizona State University.

In March a collaboration of scientists operating a microwave telescope at the South Pole made an announcement that stunned the scientific world. They claimed to have observed a signal emanating from almost the beginning of time. The putative signal came embedded in radiation left over from the action of gravitational waves that originated in the very early universe—just a billionth of a billionth of a billionth of a billionth of a second after the big bang.

The observation, if confirmed, would be one of the most important in decades. It would allow us to test ideas about how the universe came to be that hitherto scientists have only been able to speculate about. It would help us connect our best theories of the subatomic (quantum) world with our best theories of the massive cosmos—those based on Einstein's general theory of relativity. And it might even provide compelling (though indirect) evidence of the existence of other universes.

Since that announcement was made, other scientists have questioned whether the signal is real. Their skepticism has injected a new urgency to ongoing observations from other experiments that will definitively confirm or refute the claim, most likely in the next year. Although the jury is out on whether we have indeed seen a beacon from the infant universe, we will not have to wait long to know. The present moment in our exploration of the cosmos is one of heightened anticipation.

THE ROAD TO INFLATION

HOW DID WE GET to this dramatic moment? It started with two apparent paradoxes of the early universe, which this beacon (if it is one) may help resolve.

The first paradox has to do with the large-scale geometry of

IN BRIEF

Earlier this year scientists announced that they had found gravitational waves that emanated from the first moments after the big bang.

If confirmed, the discovery would allow researchers to study the first instants of time—potentially providing a way to unify quantum mechanics and gravity.

It could also provide indirect evidence for the existence of the multiverse—an infinite bubbling of physically separate universes.

PRECEDING PAGES: COURTESY OF STEFFEN RICHTER *Harvard University;* THIS PAGE: COURTESY OF NASA, ESA, G. ILLINGWORTH, D. MAGEE AND P. OESCH *University of California, Santa Cruz,* R. BOUWENS *Leiden University* AND HUDF09 TEAM

UNIFORM UNIVERSE: **On a grand scale, the universe appears largely the same in every direction we look. We find a similar density of galaxies, on average, in any given patch of sky, such as this image of a patch called the eXtreme Deep Field. Within an area smaller than the full moon, many hours of Hubble Space Telescope observations have revealed thousands of galaxies. The universe's sameness could be explained if space inflated rapidly just after the big bang.**

the universe. In the 13.8 billion years since the universe formed in the big bang, it has been expanding. Even after such a long period of expansion, it has remained almost perfectly flat. A flat, three-dimensional universe is the universe most of us might have imagined we live in—in it, light travels, on average, in straight lines.

The trouble is, general relativity implies that a flat universe is far from guaranteed—in fact, it is a special, perhaps unlikely, outcome. When matter or radiation is the dominant form of energy in the universe, as certainly has been the case for most of its history, then a slightly nonflat universe will quickly deviate from the characteristics of a flat universe as it expands. If it were ever off by just a little bit, the universe today would look open—where space is curved like a saddle—or closed—where space is curved like the surface of a sphere. For the universe to still appear flat today, its early characteristics would have had to have been absurdly fine-tuned.

The second paradox has to do with the fact that the universe appears to be the same in all directions—it is isotropic. This is odd. Light from one side of the vast observable universe has only recently been able to reach the other side. This distance means that far-off regions of the universe could not have previously communicated with one another (physicists say they have not been in "causal contact"). How, then, could they have evolved to be so similar?

In 1980 a young postdoctoral physicist named Alan Guth was pondering these paradoxes when he hit on a solution: the universe, he conjectured based on ideas from particle physics, could have ballooned rapidly shortly after it was born. Guth arrived at the idea, which he called inflation, by thinking about a central part of the Standard Model of particle physics called spontaneous symmetry breaking, which describes what happens when forces that were once unified become separate.

There is good evidence that spontaneous symmetry breaking has already occurred at least once in the universe. According to the electroweak theory, two of the universe's fundamental forces—the electromagnetic force (the force of magnetism and electricity) and the weak force (which is responsible for the radioactive decay of atomic nuclei)—appear dissimilar today only because of an accident of the universe's history. At one time, they were a single, unified force.

But as the universe cooled, when it was about a millionth of a millionth of a second old, it underwent a phase transition (similar to water transitioning from liquid to ice) that changed the nature of empty space. Instead of being empty, it was filled with a background field (something like an electric field but, in this case, a type of field that is not as easily detectable). This background field, known as the Higgs field, developed throughout the universe.

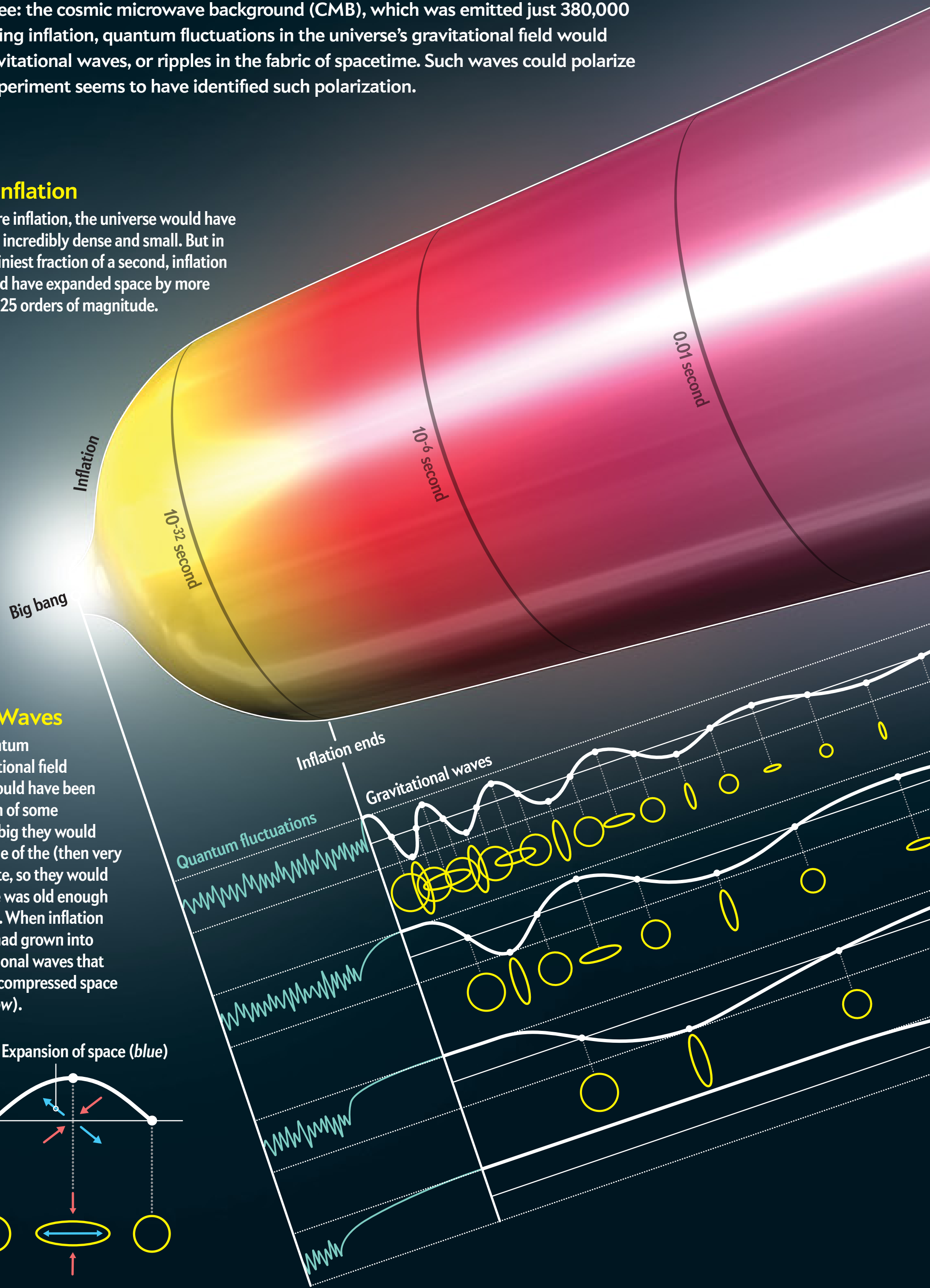
The Higgs field affects the way particles propagate through

From Inflation to Gravitational Waves to Polarized Light

If a period of inflation rapidly stretched the universe just after it was born, we might be able to find proof in some of the oldest light we see: the cosmic microwave background (CMB), which was emitted just 380,000 years after the big bang. During inflation, quantum fluctuations in the universe's gravitational field would have been amplified into gravitational waves, or ripples in the fabric of spacetime. Such waves could polarize the CMB, and the BICEP2 experiment seems to have identified such polarization.

1 Inflation

Before inflation, the universe would have been incredibly dense and small. But in the tiniest fraction of a second, inflation would have expanded space by more than 25 orders of magnitude.



2 Gravitational Waves

During inflation, tiny quantum fluctuations in the gravitational field pervading the universe would have been stretched. The wavelength of some fluctuations would get so big they would require longer than the age of the (then very young) universe to oscillate, so they would "freeze" until the universe was old enough for them to again oscillate. When inflation ended, these oscillations had grown into long-wavelength gravitational waves that alternately stretched and compressed space around them (*ellipses below*).

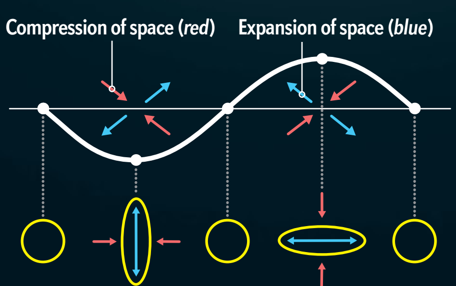
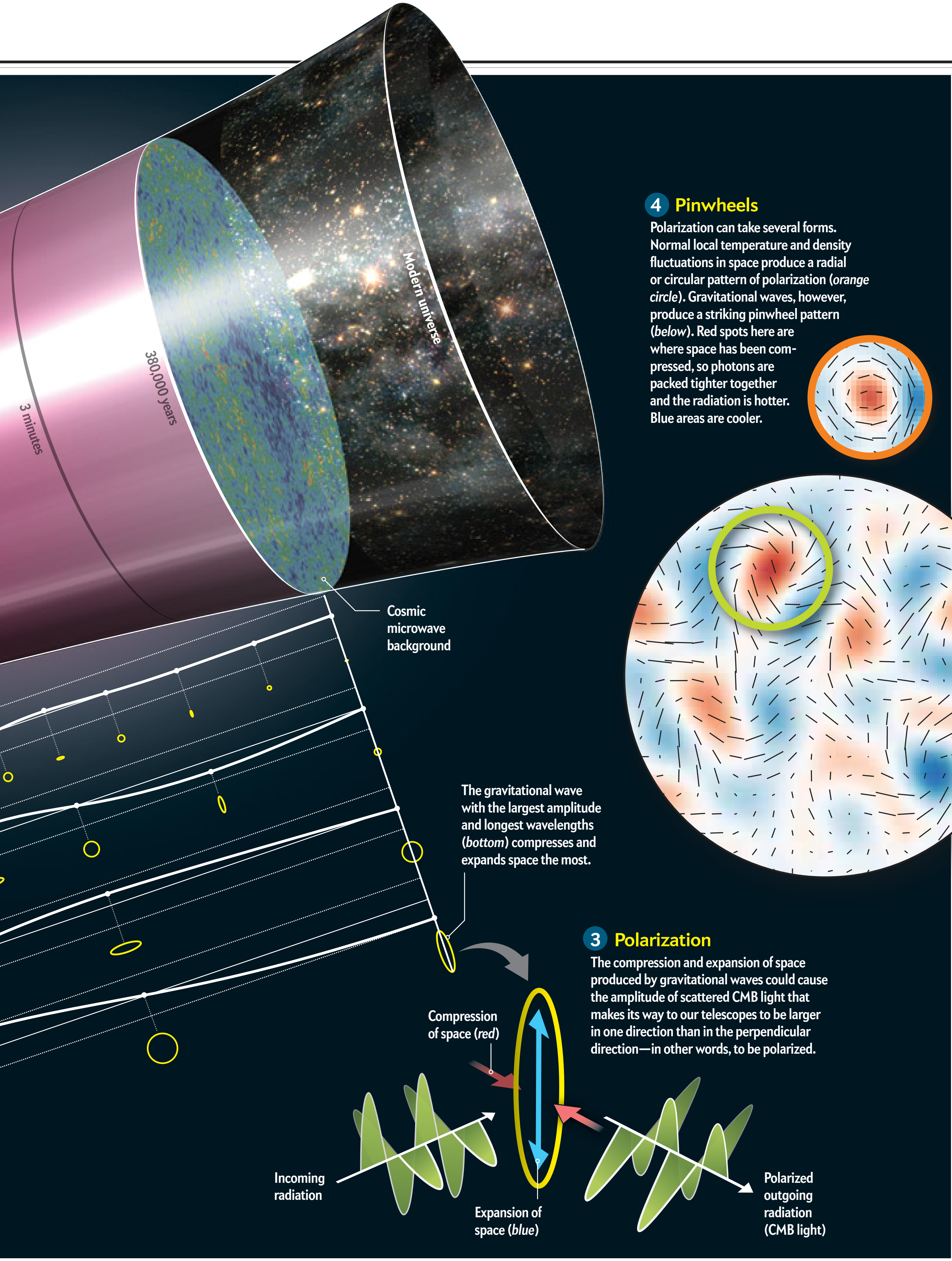


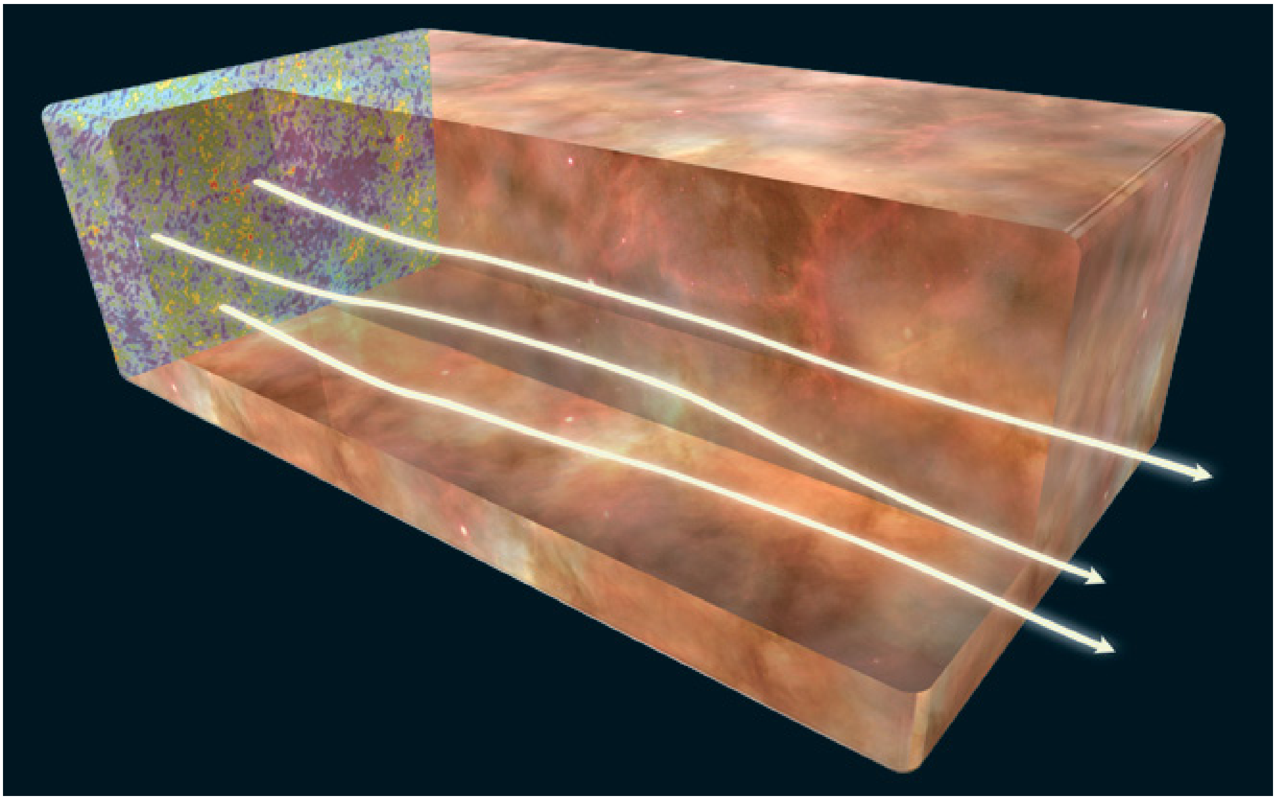
Illustration by Don Foley (universe) and Jen Christiansen (schematics)



BICEP2 COLLABORATION (*polarization insets*)

Contaminating Effects

The discovery of polarization in the cosmic microwave background (*mottled blue surface*) is not yet definitive evidence of gravitational waves, because other processes may account for the finding. The paths of CMB photons (*curved lines*), for example, have bent around massive galaxy clusters whose gravity warps the spacetime around them in a process called gravitational lensing, which introduces polarization. Dust grains in our Milky Way galaxy also emit polarized light that is hard to distinguish from CMB radiation. Recently the Planck satellite revealed that such dust could be more prevalent than previously thought.



space. Those particles that interact with this field—the ones that convey the weak force, for example—experience a resistance that causes them to behave as massive particles. Those that do not interact with the field—for example, the photon, carrier of the electromagnetic force—remain massless. As a result, the weak force and the electromagnetic force began to behave in different ways, breaking the symmetry that otherwise unified them. This fantastical picture was validated at the Large Hadron Collider (LHC) at CERN near Geneva in 2012, with the discovery of the Higgs boson.

Perhaps, Guth reasoned, a similar symmetry-breaking event occurred even earlier in the universe's past. Before this event, three of the universe's four fundamental forces—the electromagnetic and weak forces, as well as the strong force (responsible for holding protons and neutrons together), but excluding gravity—might have been connected. Indeed, a great deal of indirect evidence suggests that such a phenomenon happened back when the universe was approximately 10^{-36} second old. As the universe cooled, it might have undergone a phase transition that also changed the nature of space involving a background field that caused the electroweak force to begin to behave differently from the strong force—spontaneously breaking their symmetries, or connectedness.

As in the case of the Higgs field, this symmetry-breaking field would lead to exotic and very massive particles, but the masses involved would be much higher than the mass of the Higgs particle. In fact, one would need to build an accelerator 10 trillion times more powerful than the LHC to directly explore the theories behind this phenomenon. We call them grand unified theories, or GUTs, because they unify the three nongravitational forces of the universe into a single force.

Guth realized that such spontaneous symmetry breaking in the early universe could solve all the problems of the standard big bang if, for a short period at least, the field responsible for this symmetry breaking got stuck in a "metastable state."

Water goes into a metastable state when, say, the ambient temperature drops quickly below freezing, but water on the street does not freeze immediately; when it eventually does freeze—when the phase transition is completed—the water releases energy, called latent heat.

Illustration by Don Foley

In a similar fashion, the field that caused the GUT phase transition might have briefly stored tremendous latent energy throughout space. During the short period of inflation, this energy would have produced a gravitational repulsion that could have caused the universe to expand exponentially fast. What is now the observable universe could have increased in size by more than 25 orders of magnitude in less than 10^{-36} second. Like blowing up a balloon, such extreme expansion would also tend to make the universe we observe today flat and isotropic, thus naturally addressing the two apparent paradoxes of the large-scale structure of the universe.

As compelling as the idea of inflation may be, however, as of yet we do not have a fundamental theory of exactly how inflation would have played out, largely because we do not know the details associated with grand unification, such as the precise energy level at which the forces would have been unified. While the simplest inflation theories explain much of what we observe in the cosmos today, different versions of inflation could have produced radically different universes.

What we really need is a way to directly probe the universe for evidence that it actually underwent inflation and, if so, to explore the detailed physics associated with it. Gravitational waves, it turns out, provide just such an opportunity.

GRAVITATIONAL-WAVE SIGNATURES

WHEN ALBERT EINSTEIN published his general theory of relativity in 1915, he recognized that it implied the existence of an exciting new physical phenomenon. In general relativity, a gravitational field is just a distortion in the underlying global fabric of spacetime. A time-varying source of energy—for example, the motion of a planet around its sun or of one star around another—would produce a time-varying distortion that would propagate away from the source at the speed of light. As gravitational waves pass by, the distance between nearby objects changes very slightly.

Because gravity is so weak compared with electromagnetism, gravitational waves are extremely difficult to detect. Einstein doubted whether they would ever be found. Nearly 100 years after he first predicted them, we have not been able to directly measure such gravitational waves emanating from catastrophic astrophysical phenomena such as colliding black holes (although researchers think they are getting close). Fortunately, however, the universe can provide us with a much more powerful source of gravitational waves: the fluctuating quantum fields in the moments after the big bang.

When the universe was very young, before the time of inflation, it was compressed into a volume much, much smaller than the size of an atom. At such tiny scales, the rules of quantum mechanics reign. And yet because the amount of energy packed into each bit of that tiny space was extremely high, this large energy requires us to use the theory of relativity to describe it. To understand the properties of the early universe, we need to use, as Guth did, the ideas of quantum field theory, which incorporates both quantum mechanics and special relativity—the theory that relates space and time together. Quantum field theory tells us that at very small scales, all quantum-mechanical fields are wildly fluctuating. If all other quantum fields behave similarly during the period when the inflationary energy density dominated the expansion of the universe, then the gravitational fields may have fluctuated as well.

During the exponential expansion of inflation, any initial quantum fluctuation with a small wavelength will be stretched along with the expansion. If the wavelength becomes large enough, the time the fluctuation takes to oscillate will grow larger than the age of the (extremely young) universe. The quantum fluctuation will essentially become “frozen” until the universe becomes old enough for it to start oscillating again. During inflation, the frozen oscillation will grow, a process that amplifies these initial quantum oscillations into classical gravitational waves.

Around the time when Guth was proposing inflation, two sets of Russian physicists, Aleksei A. Starobinsky and Valery A. Rubakov and his colleagues, independently pointed out that inflation always produces such a background of gravitational waves and that the intensity of the background simply depends on the energy stored in the field that is driving inflation. In other words, if we can find the gravitational waves from inflation, we get not only a smoking-gun confirmation that inflation once took place but also a direct view into the quantum processes that drove inflation.

SMOKE FROM THE GUN

A POTENTIALLY UNAMBIGUOUS signature for inflation is only useful, however, if it is detectable. And whereas the scale of inflation is expected to be close to the scale at which quantum-gravitational wiggles could be large, the weakness of gravity itself would seem to make the likelihood of actually probing gravitational waves from inflation difficult at best.

Difficult but not impossible. The cosmic microwave background, or CMB, might help. The CMB is radiation that emerged from a time when the young universe first cooled sufficiently so that protons could capture electrons to form neutral atoms, making the universe transparent to light, which could then propagate to us. In this sense, it is the oldest visible light in the universe. If gravitational waves existed on large scales at the time the CMB was created, when the universe was 380,000 years old, then we might be able to see signs of it in the CMB. Back then, free electrons would have been immersed in a radiation bath that was slightly more intense in one direction than another because large-scale gravitational waves would have been compressing space in one direction and stretching it in another. If the effect were large enough, it could have produced a small distortion in the CMB that might be detectable. But gravitational waves can also have another, more subtle effect. The spatial distortion produced by gravitational waves could cause the electron-scattered CMB radiation to have a greater amplitude along one axis than along the perpendicular one. In other words, the CMB can be polarized.

Measuring polarization in the CMB is not by itself evidence of the existence of gravitational waves. There are many other possible causes of polarization—they could be created by underlying temperature fluctuations in the CMB or emission by possible foreground sources such as polarized dust in our galaxy. One can, however, try to separate the possible effects of gravitational waves from other sources by exploring the spatial pattern of polarization in the sky.

In particular, a twisting pattern would be characteristic of gravitational waves. Other polarization sources would tend to produce patterns without such twisting. The two possible spatial polarization modes are called E and B modes. B modes, the twisty kind, are associated with gravitational waves, and E modes tend to be produced by other sources.

This insight, which came in 1997, energized the CMB community because it meant that even if the direct temperature variations that might be induced by primordial gravitational waves were too small to be directly detected amid other temperature distortions in the CMB, a measurement of the polarization of the CMB could identify a much smaller gravitational-wave signal. Over the intervening decade or so, a host of experiments, both terrestrial and space-based, have been designed to seek out this possible holy grail of inflation.

Because experimentalists have already measured temperature fluctuations in the cosmic microwave background, researchers present their results in terms of a ratio: the ratio of a possible gravitational-wave polarization signal to the magnitude of the measured temperature fluctuation signal. This ratio is denoted by r in the literature.

THE NEW RESULTS

UNTIL THIS YEAR, only upper limits on the polarization of the CMB have been reported—that is, we knew they could not be larger than these limits, or we would have seen them. The European Space Agency's Planck satellite reported that, according to its measurements, r could be anywhere from zero, implying no gravitational waves, all the way to an upper bound of about 0.13. Thus, the physics world was stunned in March, when the Background Imaging of Cosmic Extragalactic Polarization 2 (BICEP2) experiment at the South Pole announced that it had found an r of about 0.2—larger than the limit indicated by Planck—suggesting that gravitational waves exist. It also declared, at the time, that the chance that a spurious background produced the observed signal was less than one in a million. Everything about the signal reflects the character of a signal expected from inflation.

Alas, as of this writing, the situation remains unsettled. Polarization observations are very difficult, and although statistically, the signal is clear, other possible astrophysical processes could produce effects that might mimic a gravitational-wave signal from inflation.

While the BICEP2 team examined a number of possible contaminants, the hardest to discount is radiation emitted by polarized dust in our galaxy. The BICEP2 collaboration studied what it envisaged were likely dust concentrations in our galaxy and concluded that these sources did not strongly contaminate its signal. But in the intervening months, the Planck satellite has reported new measurements that indicate the Milky Way may contain more dust than assumed by the BICEP2 team. Several groups have tried to reanalyze the BICEP2 signal in light of these new data, as well as incorporating more sophisticated models of dust backgrounds from other experiments, and have concluded that it is possible that dust could reproduce all (or most of) the claimed BICEP2 polarization signal.

Although these developments have dampened the exuberance of many in the physics community regarding the BICEP2 result, the BICEP2 team stands by its estimates—but it now admits that it cannot rule out a dust explanation. The scientists point out, however, that the shape of the observed spectrum fits the inflationary prediction remarkably well—somewhat better than dust predictions do.

More important, a host of new experiments are coming online that can shed light on dust emission and explore for a polarization signal on different scales and in different directions. In the best tradition of science, empirical confirmation or refutation of BICEP2 should be possible within a year or so after this article appears.

WHAT GRAVITATIONAL WAVES REVEAL

IF THE BICEP2 SIGNAL is confirmed, our empirical window on the universe will have increased by a greater amount than at essentially any other time in human history. Gravitational waves interact so weakly with matter that they can travel basically unimpeded from the beginning of time. Not only would the BICEP2 findings represent the first detection of gravitational waves themselves—a fundamental prediction of general relativity—these waves would give us a direct signal of the physics operating when the universe may have been only 10^{-36} second old, 49 orders of magnitude earlier than when the CMB light was created.

If the BICEP2 signal is indeed the smoking gun from inflation, we will have much more to learn about the universe. In the first place, the inferred strength of the gravitational-wave signal would imply that inflation occurred at an energy scale that is very close to the energy scale at which the three nongravitational forces in nature would come together in a grand unified theory—but only if a new symmetry of nature, called supersymmetry, exists. The existence of supersymmetry, in turn, could imply the existence of a plethora of new particles with masses in the range that can be probed by the LHC when it turns on again in 2015. Thus, if BICEP2 is correct, 2015 may be another banner year for particle physics, unraveling new phenomena that might explain the nature of fundamental forces.

If BICEP2 is correct and if it is measuring gravitational waves from inflation, gravity must be described by a quantum theory.

There is another, less speculative implication of the discovery of gravitational waves from inflation. As I described earlier, such waves should be generated when primordial quantum fluctuations in the gravitational field are amplified during inflation. But if this is the case, then it suggests that gravity must be described by a quantum theory.

This issue is particularly important because we have, as of yet, no well-defined quantum theory of gravity—that is, a theory that describes gravity using the rules governing the behavior of matter and energy at the tiniest scales. String theory is perhaps the best attempt so far, but there is no evidence that it is correct or that it can consistently resolve all the problems that a complete quantum theory of gravity must address. Moreover, as Freeman Dyson of the Institute for Advanced Study in Princeton, N.J., has pointed out, there is no terrestrial device capable of detecting individual gravitons, the presumed quantum particles that carry the force of gravity, because any such detector would need to be so large and dense that it would collapse to form a black hole before it could complete an observation. Thus, as he has speculated, we can never claim to be sure that gravity is described by a quantum theory after all.

If gravitational waves from inflation do show up, however, it would seem that they could obviate Dyson's argument. But one loophole remains. If we find gravitational waves from inflation, which are classical (nonquantum) objects, we can calculate the origin of these waves using quantum mechanics. Yet every classical physics result, including the motion of a baseball, can be calculated quantum-mechanically. Just seeing a baseball in flight does not prove that quantum mechanics is behind it—indeed, its motion would be identical even if quantum mechanics did not exist. What we need to prove is that the generation of gravitational waves from inflation, unlike the motion of a baseball, derives from quantum processes.

Recently my colleague Frank Wilczek of the Massachusetts Institute of Technology and I closed this remaining loophole. Using the most basic technique in physics, so-called dimensional analysis, which explores physical phenomena in terms of their representation in units describing mass, space and time, we were able to demonstrate, on very general grounds, that a gravitational-wave background caused solely by inflation would vanish if Planck's constant, the quantity that governs the magnitude of quantum-mechanical effects in the world, were to vanish. Thus, if BICEP2 is correct and if it is measuring gravitational waves from inflation, gravity *must* be described by a quantum theory.

IMPLICATIONS FOR THE MULTIVERSE

FROM THE PERSPECTIVE of understanding the very origins of our universe and the vexing question of why it exists at all, probing inflation by the observation of gravitational waves has the potential of turning what many consider to be one of the grandest metaphysical speculations of all into hard physics.

Recall that inflation is driven by a field that stores and releases tremendous amounts of energy during a phase transition. It turns out that the necessary characteristics of this field imply that once the process starts, the field driving inflation will tend to continue to inflate the universe ad infinitum. Inflation will go on without end, preventing the creation of the universe as we know it because any preexisting matter and radiation would have been diluted away by the expansion, leaving nothing but rapidly expanding empty space.

Yet Andrei Linde, a physicist at Stanford University, found a way to escape this problem. He showed that as long as some small region of space completed its phase transition after sufficient expansion, this region could encompass our entire observed universe today. In the rest of space, inflation could continue forever, with small "seeds" forming in different locations where the phase transition might be completed. In each such seed, an isolated universe undergoing a hot big bang expansion would emerge.

In such a picture of "eternal inflation," our universe is then a part of a much bigger structure that could be infinitely big and might ultimately contain an arbitrarily large number of disconnected universes that may have formed, may be forming or will form. Moreover, because of the way the phase transition ending inflation in each seed can occur, the physics governing each resulting universe can be different.

This possibility has become known as the multiverse hypothesis, suggesting our universe may be one of a possibly uncountably large number of separate, physically different universes. In this case, it is possible that the underlying physical constants in our universe are what they are simply by accident. If they were any different, beings like us could not evolve to measure them.

This suggestion, often somewhat pompously labeled the anthropic principle, is abhorrent to many and leads to a number of possible problems that physicists have yet to resolve. And for many people, multiverses and the anthropic principle are indications of how far fundamental physics may appear to be diverging from what is otherwise considered to be sound empirical science.

But if BICEP2 (along with the LHC and other experiments) enables us to probe the phenomena of inflation and grand unification, we may be able to uniquely determine the fundamental physics governing the universe at these scales of energy and time. One of the results may be that the inflationary transition producing our observed universe requires Linde's eternal inflation. In this case, while we may never be able to directly observe other universes, we will be as confident of their existence as our predecessors in the early 20th century were of the existence of atoms, even though they, too, could not have been observed directly at the time.

Will BICEP2 provide as revolutionary a guidepost to understanding the physics of the future as the early experiments that led to a quantum theory of atoms did? We do not yet know. But the possibility is very real that it, or perhaps a subsequent CMB polarization probe, could open a new window on the universe that will take us back to the beginning of time and out to distances and phenomena that may make the wild ride that physics provided in the 20th century pale by comparison. SA

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Saving Coffee

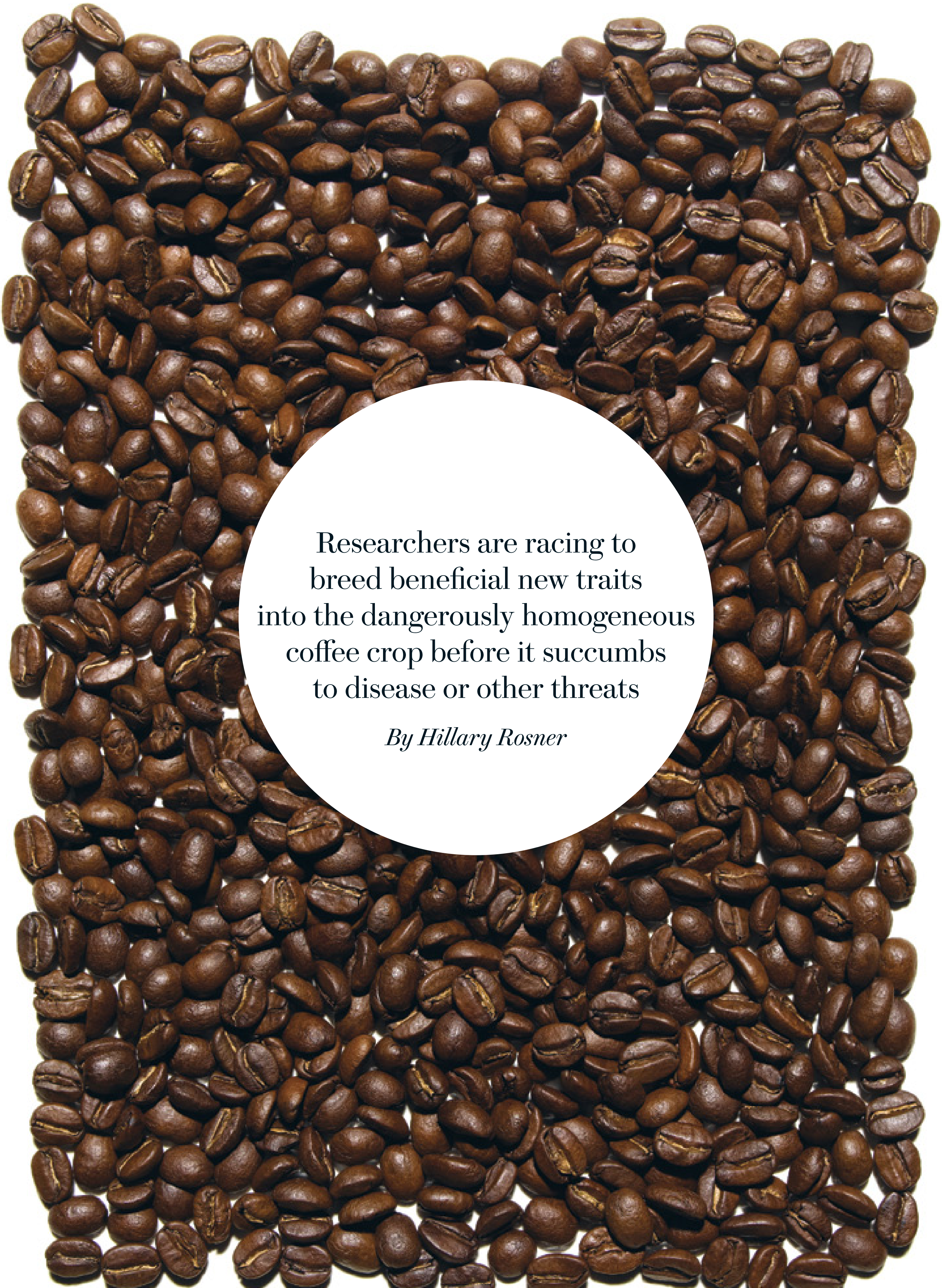
IN BRIEF

Cultivated coffee trees are under serious threat from climate change, disease and insect pests.

The homogeneity of the crop makes it particularly vulnerable: nearly all of the world's cultivated coffee originated with a handful of plants grown in Ethiopia.

Little scientific research has gone into cultivating coffee, but that situation is beginning to change. Scientists are now hurrying to introduce helpful new genes into the crop through crossbreeding methods.

They are mining gene banks and wild plants for as wide a variety of genes as they can find to fortify the crop against looming trouble.



Researchers are racing to breed beneficial new traits into the dangerously homogeneous coffee crop before it succumbs to disease or other threats

By Hillary Rosner

Hillary Rosner is a freelance writer based in Colorado. She has written for the *New York Times, Wired, Popular Science* and *Mother Jones,* among other publications.

THE COFFEE THAT THE CATERER had set down alongside some guava-filled pastries was tepid and bitter, with top notes of chlorine. Several of the guests would not touch it, no matter how much they craved caffeine. Standing on a narrow balcony, facing the scrubby hills of Turrialba, Costa Rica, they sipped water or pineapple juice instead. They were entitled to a little coffee snobbery. The roughly 20 people gathered this past March at CATIE, an agricultural university, to discuss the uncertain future of Central American coffee included leading experts on humanity's most beloved beverage.

They had convened to discuss a serious threat: coffee rust, or *roya,* as it is known in Spanish. The rust is a fungus that infects the plants' leaves, making them unable to absorb the sunlight they need to survive. It has ravaged the region's crop over the past few years, afflicting approximately half of the one million acres planted across Central America and slashing production by about 20 percent in 2012 compared with 2011.

The outbreak, which is still spreading, is just one crisis looming over coffee in our era of global warming. "Most coffee varieties today aren't likely to be able to tolerate disease and insect pressures, as well as increased heat and other environmental threats from climate change," Benoît Bertrand, a geneticist and coffee breeder at CIRAD, a French center focused on agriculture and development, told the group in Costa Rica after the coffee break. If crops fail, coffee farmers lose their livelihoods. They may tear out the trees and plant other crops or sell their land to developers—leaving a trail of unemployed laborers and environmental destruction.

Bertrand, who wore a blue sweater tossed over his shoulders and has the debonair look of a French filmmaker rather than someone who spends his days hunched over a petri dish, is justifiably concerned. Coffee, it turns out, cannot adapt to heat or fend off disease, because it lacks crucial genetic diversity. Although the selection of coffees on tap in your local café may read like a guidebook to exotic travel destinations—an acidic brew from Aceh, Indonesia, a velvety roast from Vietnam, a mellow cup from Madagascar—all that variety hides a surprising fact: cultivated coffee is incredibly homogeneous. In fact, 70 percent of it comes from a single species, *Coffea arabica*. The strain, growing region and roasting method make for a remarkable range of tastes, but they also mask the plant's genetic history. Nearly all of the coffee that has been cultivated over the past few centuries originated with just a handful of wild plants from Ethiopia, and today the coffee growing on plantations around the world contains less than 1 percent of the diversity contained in the wild in Ethiopia alone.

Despite coffee's importance on a global scale—for economic, political and environmental stability, not to mention its roles as a centerpiece of cultural life and an essential caffeine-delivery system—it is an "orphan crop," largely abandoned by modern research. There is no Monsanto of coffee, no agribusiness behemoth that stands to make a fortune selling patented seeds. That orphan status allows small farmers in poor countries to make a decent living growing coffee for export. But it also means there has been little investment in science, leaving the crop highly vulnerable to whatever nature throws its way. Now, faced with mounting threats against cultivated coffee, researchers are racing to advance the science and save our joe—before it is too late.

HARNESSING DIVERSITY

TIM SCHILLING, A GENETICIST who resides in the French Alps and is best known for helping to revamp Rwanda's coffee industry in the early 2000s, has made it his mission to bring some much

PAGE 68: LEVI BROWN *Trunk Archive*; PRECEDING PAGE: TOM SCHIERLITZ *Trunk Archive*

Coffee in Crisis

Coffee crops around the world are incredibly alike genetically. This homogeneity leaves cultivated coffee particularly susceptible to threats from diseases, pests, and shifts in temperature and rainfall. And as global climate changes, these threats are worsening: extreme weather events are becoming more common, and fungi and insects are spreading into areas where they have never been seen before. Wild coffee populations, with their greater stores of genetic diversity, are better equipped to handle these menaces. Yet they face trouble of their own: deforestation. Representative examples of recently affected regions are shown below.

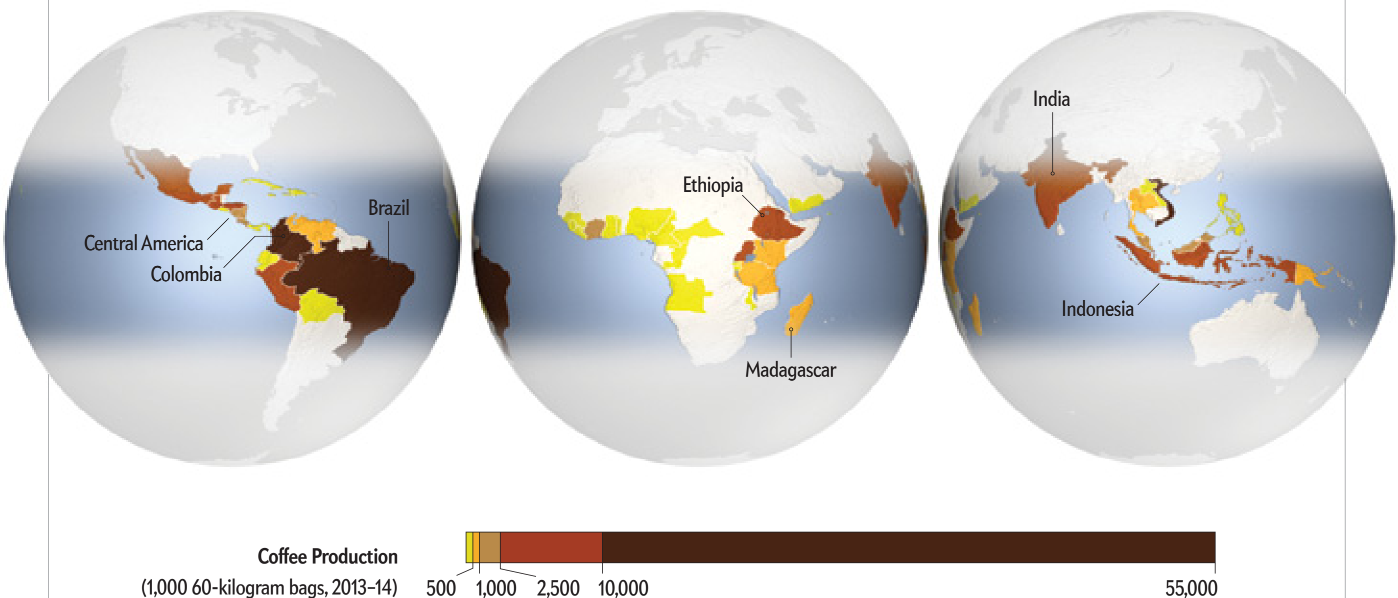
Threats

Disease: Fungi such as *Hemileia vastatrix* (coffee rust) and *Colletotrichum kahawae* have devastated crops in Central America and Ethiopia, respectively.

Insects: A tiny beetle known as the coffee cherry borer has reduced yields in Colombia, among other places. The insect's range is increasing with climate change.

Deforestation: Loss of habitat for wild coffee plants in places such as Ethiopia and Madagascar means losing genetic diversity that could help fortify cultivated coffee plants.

Climate change: Excessive rainfall has significantly reduced yields in India and Indonesia. Drought and high temperatures have taken their toll in Brazil.



needed science to the business of making java. Today he oversees World Coffee Research, a new nonprofit funded by the coffee industry—30 companies big and small, including Peet's, Allegro and Counter Culture. He has been called the Indiana Jones of coffee, but presiding over the meeting in Turrialba, in jeans and a long-sleeved white shirt, with black owl-frame glasses and thick locks, Schilling bore a closer resemblance to Andy Warhol. He asked the group how much research was currently available on climate change and coffee rust. A coffee breeder in the room held up his thumb and index finger about half an inch apart, the international sign for "peanuts."

Experts worry the impact could be huge. The coffee rust fungus thrives in warm weather, and as temperatures rise, the fungus could spread to higher altitudes. Changes in rainfall—too much rain or even too little—might also give the fungus a boost. Fungicide sprays can combat *roya,* but the chemicals are expensive and may not work against emerging strains of the disease.

To Schilling, the only real long-term solution is harnessing genetics. As a first step, he wants to exploit the adaptations that already exist in the gene pools of *C. arabica* and the other cultivated coffee species, *Coffea canephora*. Known in the industry as robusta, *C. canephora* is easier to grow and higher-yielding, but it tastes bitter and is used mainly as a filler in lower-quality coffees—like the kind on tap at the CATIE meeting. Although cultivated coffee is homogeneous in that it belongs to just these two species, the many strains of each do offer some regional genetic variation, just as human populations differ despite all belonging to *Homo sapiens*. Schilling's grand plan includes a relatively simple project, currently under way, to swap coffee strains between regions and countries—sending plants from Congo to Brazil, say, or from Colombia to Honduras, to see if they will grow better than the strains local farmers are already growing. In three to four years, farmers will be able to say, "Hey, this coffee from India produces way more beans," and they can then opt to plant more

SOURCE: FOREIGN AGRICULTURE SERVICE, U.S. DEPARTMENT OF AGRICULTURE

Maps by George Retseck

of the Indian seeds. Scientists identified 30 of the highest-yielding coffee strains from 10 countries for the study.

Taking advantage of the genetic variation within cultivated coffee may help in the short term. But it almost certainly will not be enough to save the crop. Commercially grown strains contain only a tiny portion of the total genetic diversity in *C. arabica* and *C. canephora*. Their wild counterparts, however, are incredibly varied. Recent advances in coffee genome sequencing have revealed what Bertrand calls "a vast catalogue of genes" in these untamed cousins of the farmed beans, many of which reside in gene banks around the world. He hopes to exploit that rich genetic soup to make coffee crops more resilient, productive and delicious.

Evidence of that genetic diversity abounds at CATIE. Across campus from the meeting and down a dirt road, a wooden sign with painted yellow letters reads "Café Coleccion de Etiopia (FAO)." Here nearly 10,000 *arabica* coffee trees grow, row after row of them stretching across roughly 21 acres. Established in the 1940s, the assortment includes coffee plants collected during several different expeditions to Ethiopia, first by the British during World War II and more recently, in the 1960s, by the United Nations Food and Agriculture Organization and a French research team. The repository also includes coffee plants from Madagascar and elsewhere in Africa, as well as from Yemen. Unlike the seeds of many other crop plants, such as corn, coffee seeds cannot survive in jars stored in refrigerated vaults. Instead they must be continually grown in the field or else cryopreserved. So at CATIE, one of the world's most important gene banks for coffee DNA is "stored" as one big, scruffy coffee garden.

Bertrand is building new hybrid strains of coffee using promising plants from living coffee gene banks akin to the one at CATIE. A variety he created more than a decade ago by crossing *C. arabica* with some of its wild cousins boosted yields by more than 40 percent. Now he and Schilling have selected 800 plants from CATIE, as well as another 200 from coffee gene banks around the world, and sent them to a laboratory in Ithaca, N.Y., to have their DNA sequenced. That information will help him evaluate what traits each plant could offer up.

The researchers are looking for genes that might make a plant strong in all kinds of ways: resistant to rust, less thirsty, able to thrive in heat. To find them, Bertrand and Schilling are screening for plants that are "pumped up with incredible amounts of genetic diversity," as Schilling puts it. They want the biggest possible range of traits in the smallest number of plants. "Then we'll be crossing that material with stuff that we all love—great-tasting, high-yielding, disease-resistant material we know of already."

There are roughly 125 known species of coffee on the earth, plus others that remain to be discovered—assuming we can find them before they vanish.

INTO THE WILD

SCHILLING IS CERTAIN that those breeding efforts will yield far better varieties for coffee farmers to grow—and for roasters to sell and consumers to drink. But he and his collaborators have another ambition, too: to one-up Mother Nature by producing a new, synthetic version of *C. arabica*. In essence, they want to develop a plant that has the flavor of *C. arabica* and the temperament and yield of *C. canephora*. The plan is to redo the original cross that created *C. arabica* (that of *C. canephora* and another species, *Coffea eugenioides*), only with a far more diverse group of parents this time. To manage this feat, they need to look beyond what exists in gene banks. They need to go back to the wild.

There are roughly 125 known species of coffee on the earth, each of which contains much more genetic variation than can possibly be represented in a gene bank's small sample. And other species surely remain to be discovered—assuming researchers can find them before they vanish.

When Aaron Davis began hunting for wild coffee plants in 1997, he did not expect to find anything new. The then recent Ph.D. graduate was having tea one day at the Royal Botanic Gardens in Kew, England, when a renowned coffee taxonomist happened to sit nearby. Davis asked her how many species of coffee there were, where coffee grew and what its natural range was. The answer to all his questions, she replied, was that "nobody knows." In short order, she sent him off to find out. Davis spent the next 15 years traipsing around Madagascar—a country known for coffee diversity—where he found a vast range of species, some already catalogued but a lot completely unknown to anybody apart from some local villagers.

In Madagascar, he found the plant with the world's largest coffee cherry, or fruit—about three times the standard size—and the world's smallest, about half the diameter of a pushpin. He found two species whose seeds are dispersed via water, rather than animals, and bear winged fruits that look like folded ribbons. He discovered a species called *Coffea ambongensis,* whose beans resemble brains. Davis's expeditions showed that wild coffee grows across a wide swath of the tropics, from Africa to Asia and even as far as Australia. In Ethiopia, *C. arabica*'s main territory today, some forests are packed with arabica plants, as many as 8,000 per acre. Those plants, Davis believes, have huge potential for breeding.

But these wild plants, like their cultivated counterparts, are in trouble. Up to 70 percent of them are in danger of extinction. And 10 percent could be gone within a decade. Land conversion poses the biggest threat. By the late 1990s more than 80 percent of Ethiopia's forests had already been cleared. In 2007 in Madagascar, where people continue to clear forests at an alarming rate, Davis's team came across a new species growing in a patch of forest no bigger than a baseball diamond. Where wild coffee plants are concerned, he says, in many cases, "climate change is not going to have a chance to have an impact." The plants will simply disappear, along with their habitat.

SCIENTIFIC AMERICAN ONLINE View a slide show of coffee species at ScientificAmerican.com/oct2014/coffee

COFFEE RUST, a fungus, has damaged the beans of this coffee plant from Guatemala.

MOISES CASTILLO *AP Photo*

Davis worries that researchers are placing too much emphasis on what is already in gene banks while potentially vital genetic material is languishing in the wild—or being bulldozed. "There's this feeling, 'Yeah, we've got everything, we're fine,'" he says. "But that's your storehouse of genetic resources, those wild populations."

Ethiopia itself poses another problem. The country where coffee originated curates a large collection of coffee plants that exist nowhere else in the world. But the government keeps them under lock and key and will not allow foreign researchers access. "There's been a lot of bad blood between Ethiopia and the coffee industry," Davis explains. "It's no wonder they're guarded about their genetic resources." A few years ago, for instance, Ethiopia got into a heated dispute with Starbucks over whether the country had the right to trademark the names of Ethiopian coffee cultivars.

Access to the Ethiopian germplasm—the organic material stored in gene banks—could give Schilling's coffee-breeding projects a huge boost. Perhaps it contains crucial genes for adapting to higher temperatures or for growing more beans on less land. Schilling hopes the country will relent. In the meantime, scientists are working with what they have.

Digging in the archives at Kew, Davis discovered records showing that local people in Uganda and elsewhere have long made coffee from wild varieties growing nearby. Some of it may taste awful, but all of it produces a recognizable coffee-like aroma if you roast the beans. And, Davis says, "some that were used 100 years ago are reputed to be excellent. We're going back and reinvestigating some of those early cultivated species that could have potential in their own right or in breeding programs."

RACING THE CLOCK

SHORTLY AFTER SCHILLING formed World Coffee Research—with the help of an industry group that represents high-quality and boutique coffee companies (the Specialty Coffee Association of America) and with initial funding from Green Mountain Coffee and Coffee Bean International—the rust outbreak hit Central America. So Schilling convened a small meeting in Guatemala to discuss what the organization could do. Almost immediately, he started getting requests from people who had heard about the meeting and wanted to attend it. "It turned into about 200 people," recalls Ric Rhinehart, executive director of the Specialty Coffee Association of America and one of Schilling's chief collaborators. "We couldn't hold them all."

Among the interested players was the U.S. Agency for International Development, which invited Schilling to apply for a grant for coffee rust research. If Central America's coffee industry were to collapse, it could spark a wave of migration to the U.S.—so the government has an interest in it. World Coffee Research estimates that the 2012 rust outbreak cost coffee farmers $548 million and cut workers' pay by 15 to 20 percent. Roughly 441,000 jobs disappeared. If nothing is done, Central America's coffee industry could be wiped out by 2050.

Although short-term, "emergency" responses to the rust crisis were under way in 2012—supplying farmers with fungicides and credit, for instance—Schilling believed a much more coordinated, long-term effort was needed. USAID ultimately funded Schilling's plan, which will help build a high-tech breeding program to provide new climate- and pest-resistant coffee varieties to farmers.

The rust epidemic is, in many ways, a preview of what might befall coffee worldwide, as new diseases hit defenseless plants that are weakened by heat or extreme weather. At the CATIE meeting, Carlos Mario Rodriguez, director of global agronomy for Starbucks, mentioned that Chinese farmers were reporting as many as five new strains of rust on their plants. "At high elevations, farmers didn't know about rust—and now they do," Rodriguez said.

For coffee to survive, it must become far more resilient. Brett Smith, president of North Carolina–based Counter Culture Coffee, likens the DNA problem to "a stock portfolio with very few stocks." He is confident, though, that Schilling and his band of collaborators are up to the task of safeguarding coffee.

The only question is whether they can do it in time. "If we'd done this research 10 years ago, we wouldn't be facing these problems now," Rhinehart says. "If we don't start today, every day that we wait is more time. And we could be facing an existential threat." SA

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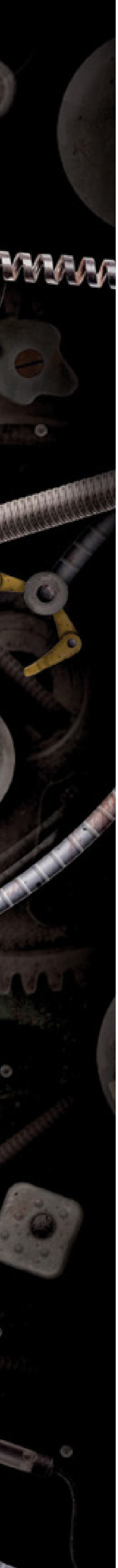


TWISTS OF FATE

CELL BIOLOGY

Physical pushes and pulls on a cell, not just genes, determine whether it will become part of a bone, a brain—or a deadly tumor

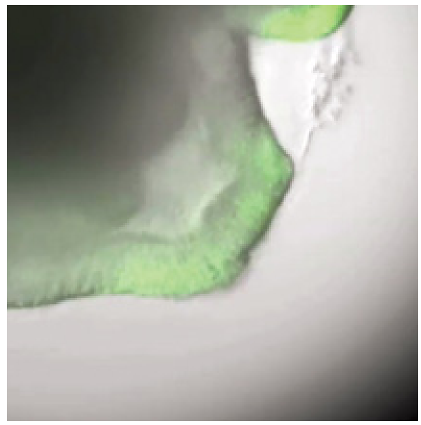
By Stefano Piccolo

Illustration by John Ueland

Stefano Piccolo is a professor of molecular biology at the University of Padua in Italy. His laboratory studies how cells sense their environment and use this information to build tissues.

THE HUMAN CELLS

in our laboratory looked mild-mannered. They were normal cells, not cancer cells, which are able to proliferate rampantly, invade nearby tissues, and ultimately can kill.



But something disturbingly malignant occurred when we forced these cells to change their shape, stretching them by pulling on their edges. This maneuver, flattening out their rounded mounds, increased the activity of two proteins within the cells, YAP and TAZ. As the proteins peaked, our benign cells began acting cancerous, replicating uncontrollably. It was stunning to see how these changes were triggered not by gene modifications but by a physical force.

Modern biologists tend to explain the lives of cells in terms of genes and proteins: gene A gives rise to a protein that controls gene B, which in turn produces protein X, and so forth, and these molecules determine cell behavior. Ultimately genes do tell cells how to act. Yet it is becoming increasingly clear that some of the most important processes in a cell are sparked by mechanical yanks and pushes that originate in their surroundings, such as nearby cells or fluids.

Over the past several decades scientists who study the way cells interpret such pushes and pulls, the province of a field called mechanobiology, have learned just how powerful these forces can be. For instance, cells with room around them keep dividing, whereas cells clustered together with thousands of others grow much more slowly or stop. Tissue stiffness matters, too: a class of stem cells, which have the potential to morph into a variety of types, will become neurons in surroundings that mimic brain stiffness but will become muscle cells if they encounter muscle-type stiffness. These mechanics guide the self-assembly of stem cells in a lab dish into complex organs, such as parts of eyes or structures normally found in the brain.

IN BRIEF

Physical forces affect the human body on a microscopic level, acting on each of its cells. Those forces can have impacts that are as profound as the effects of genes, and they are generated by a cell's surroundings.

Cells with room around them keep dividing, while cells clustered together with others grow much more slowly or stop. This space-driven behavior may determine the regenerative properties of stem cells.

A protein switch connects these physical and biological works, and flipping it can determine a cell's destiny and whether it is normal or becomes a dangerous tumor.

Until recently, no one knew exactly how cells translated physical pressures into directives to change activities. But my lab's experiments, carried out during the past several years, point to one elusive link. Our work shows that YAP and TAZ constitute a molecular switch that connects forces in the outer regions of a cell to genes in the cell's nucleus that ultimately carry them out. When cells get pulled in certain ways, YAP and TAZ react to the force and activate genes that determine how the cell behaves. Along with exciting research by other scientists around the world, the discovery is providing new insights into the workings of an array of biological processes, from embryonic development to tissue maintenance and wound healing. It also suggests new avenues for attacking cancer and for advancing efforts to grow new organs in the lab.

SELF-CONTROL: **Floating in an uncrowded lab dish, human embryonic stem cells self-assemble into a nascent eye during several days (*left to right*).**

COURTESY OF YOSHIKI SASAI *RIKEN Center for Developmental Biology*

FORCES OF NATURE

A MYRIAD OF MECHANICAL FORCES operate in a living body, although most people know of only the most obvious ones, such as heart pumping, muscle flexing and blood flow. Biologists have long appreciated the large-scale effects of these repeated contractions and stretches. For instance, mechanical loading from physical exercise fosters bone mineralization and prevents osteoporosis, and rhythmic expansion of blood vessels protects them from arteriosclerosis.

Yet physical forces also profoundly affect the human body on a microscopic level, acting on each of its estimated 40 trillion cells. The forces arise because of the way cells connect to one another. Every cell has an inner framework, the cytoskeleton, consisting of specialized sets of proteins that serve as cables, struts and tie rods. These proteins buttress and shape the nucleus, various other structures known as organelles and the cell membrane. Outside the membrane, adhesive proteins on the cell surface connect that inner cytoskeleton to the outside world. They anchor themselves to a lattice of external filamentary proteins called the extracellular matrix, which in turn is linked to other cells.

The cell's cytoskeleton and the surrounding extracellular matrix are in a constant tug-of-war. For example, a nearby deformation of the matrix pulls the adhesion sites outward. If unopposed, this action would stretch the cell. The cell, however, responds to such pulls with an equal inward contraction and a restructuring of its cytoskeleton. This back-and-forth stabilizes cell shape. But it is clearly dynamic: it can rapidly reset if the cell encounters a different pattern of mechanical stresses, eventually changing the overall cell shape.

Starting in the late 1970s, scientists began to appreciate that mechanical signals affecting these structures were essential for the control of cell reproduction, also known as cell growth. Donald Ingber of the Wyss Institute for Biologically Inspired Engineering at Harvard University and Fiona Watt of King's College London developed methods to engineer cell shape by attaching the cells to different sticky dots of extracellular matrix proteins that were printed onto glass slides. Remarkably, the cells reproduced only when they were anchored to a large area, which allowed them to stretch and flatten out. If the exact same cells were rooted to a small area, they rounded up, stopped dividing and switched on genetic programs that led them to differentiate (mature into specialized cell types) or to die.

These findings garnered a lot of attention. But something was missing from this picture. To regulate cell reproduction or differentiation, mechanical forces had to affect the core of the cell, its genome, and turn on a number of genes responsible for growth or death. What linked the physical and biological worlds? How was cell mechanics translated into perfectly orchestrated changes of gene activity?

These questions attracted me and my colleagues at the University of Padua in Italy. About five years ago Sirio Dupont, a member of my research team, followed a trail of clues in the best tradition of scientific detectives. He began by searching a computer database for genes activated by mechanical stress. (If you pull on a cell, these are the genes that swing into action.) He then searched for proteins associated with the control of those genes. He found two: YAP and TAZ.

We then confirmed through lab experiments that YAP and TAZ indeed form a switch that turns a cell's response to physical forces on and off. We could take command of cell behavior, overriding any changes in cell shape, by experimentally increasing or reducing the amount of YAP and TAZ produced by cells. For example, if we raised YAP and TAZ levels in small rounded cells that had stopped growing and dividing, we could restore proliferation.

The switch appears to work like this: Generally, YAP and TAZ sit in the cytoplasm of the cell. When the cytoskeleton gets stretched out, they move to the nucleus, park themselves on selected spots of DNA and activate particular growth-inducing genes. If levels of YAP and TAZ increase, more of the proteins can make this move and become active. Conversely, in rounded cells confined to small areas, YAP and TAZ remain in the cytoplasm—deteriorating while they are there—and stay out of the nucleus.

These two proteins are close siblings, although they have different names. Their molecular structures are very similar, and they perform overlapping functions. Consequently, they are usually referred to as one: YAP/TAZ.

KEEPING ORGANS IN SHAPE

THE IMPORTANCE OF THIS YAP/TAZ switch for the body's proper functioning becomes clear when it is studied in tissues and organs. Consider what happens if tissues are wounded, such as skin getting a cut. When cells are lost because of this kind of injury, reduced pressure on the remaining cells tells them that they have more free room. So they spread out, stretching their cytoskeleton. This stretching seems to activate YAP/TAZ, fostering cell proliferation. The process stops when the wounded area fills with new cells, re-creating a more tightly packed, growth-suppressing environment.

Some experiments on mice show how this sequence operates in real organs. Duojia (D. J.) Pan of Johns Hopkins University demonstrated that YAP is instrumental for regenerating the cellular lining of intestines in mice after inflammatory damage (colitis). And Eric Olson of the University of Texas Southwestern Medical Center demonstrated that YAP/TAZ was able to promote partial cardiac muscle regeneration after a heart attack. When researchers genetically engineered mice to produce extra YAP in their skin—work done by both Elaine Fuchs of the Rockefeller University and Fernando Camargo of Boston Children's Hospital—the outer skin layer thickened and stratified in abnormal ways. So it appears that levels of YAP/TAZ have to be "just right" for proper tissue regeneration. Too little translates into a failure to heal, and too much means that cells might pile up in aberrant tissues, which carries a risk of tumor development.

Damage repair is not the only reason why a properly functioning YAP/TAZ switch is crucial to health. Many of our organs need to replenish cells constantly even without wounds or disease. The need arises because organs live for many decades, but the life span of each cell within them is typically much shorter. New cells have to compensate for the death of old ones, or else the organ will wither and die.

The balance in cell numbers is only one aspect of organ maintenance, however. A second aspect is controlling where in the organ those new cells grow. Organs are like tightly packed apartment buildings—they are a collection of various cell types, each lodged within a sophisticated three-dimensional architecture. And this spatial organization is also replenished one cell generation after another. Where is the information about "what goes where" coming from? New findings suggest that, once again, the answer involves YAP/TAZ and the way it responds to the organ's three-dimensional shape.

Organ architecture is complicated. It is a collection of various structures, such as pits, borders, convex or concave curves, and flat layers, all defined by the way cells fit together in their associated extracellular matrix scaffold. Because that scaffold actually lives longer than the cells attached to it, it can work as the spatial memory for new incoming cells, answering that vital "what goes where" question.

The puzzle, though, has been how the scaffold does this. Celeste Nelson, now at Princeton University, and Christopher Chen, now at Boston University, as well as Mariaceleste Aragona, working in my group, provided evidence that the answer lies in the scaffold's varied shape. Such variations produce different mechanical forces that affect cellular behavior. For example, when we engineered a device that allowed us to curve a multicellular layer at particular points—think of speed bumps rising up from a flat road—only cells that stretched around curved areas activated YAP/TAZ and proliferated. This finding has led us to propose that local tissue anatomy controls the behavior of constituent cells by influencing activation of YAP/TAZ. The amount of YAP/TAZ that gets activated and moves to the nucleus peaks in areas where tissues stretch or curve and drops within flat, densely packed cell layers. In this way, tissue architecture can form a template that perpetuates organ shapes through many cell generations, embodying memories for body components that have none of their own.

Levels of YAP/TAZ have to be "just right" for proper tissue regeneration. Too little translates into a failure to heal, and too much means that cells might pile up, which carries a risk of tumor development.

YAP/TAZ's response to cellular surroundings could explain another mystery: how organs know when to stop growing. At the time my lab discovered the duo's role in conveying mechanical signals to the nucleus, YAP/TAZ was already a focus of intense interest because scientists had observed that animals whose cells have higher than normal activity levels of these factors develop giant organs. Because tissue architecture can affect the pair's activity and because mechanical forces change as an organ grows, we suspect that when organs reach their correct size, the resulting balance of forces shuts off YAP/TAZ activity and stops further growth.

Topography is just one feature in an organ that can influence

Changing Cell Behavior

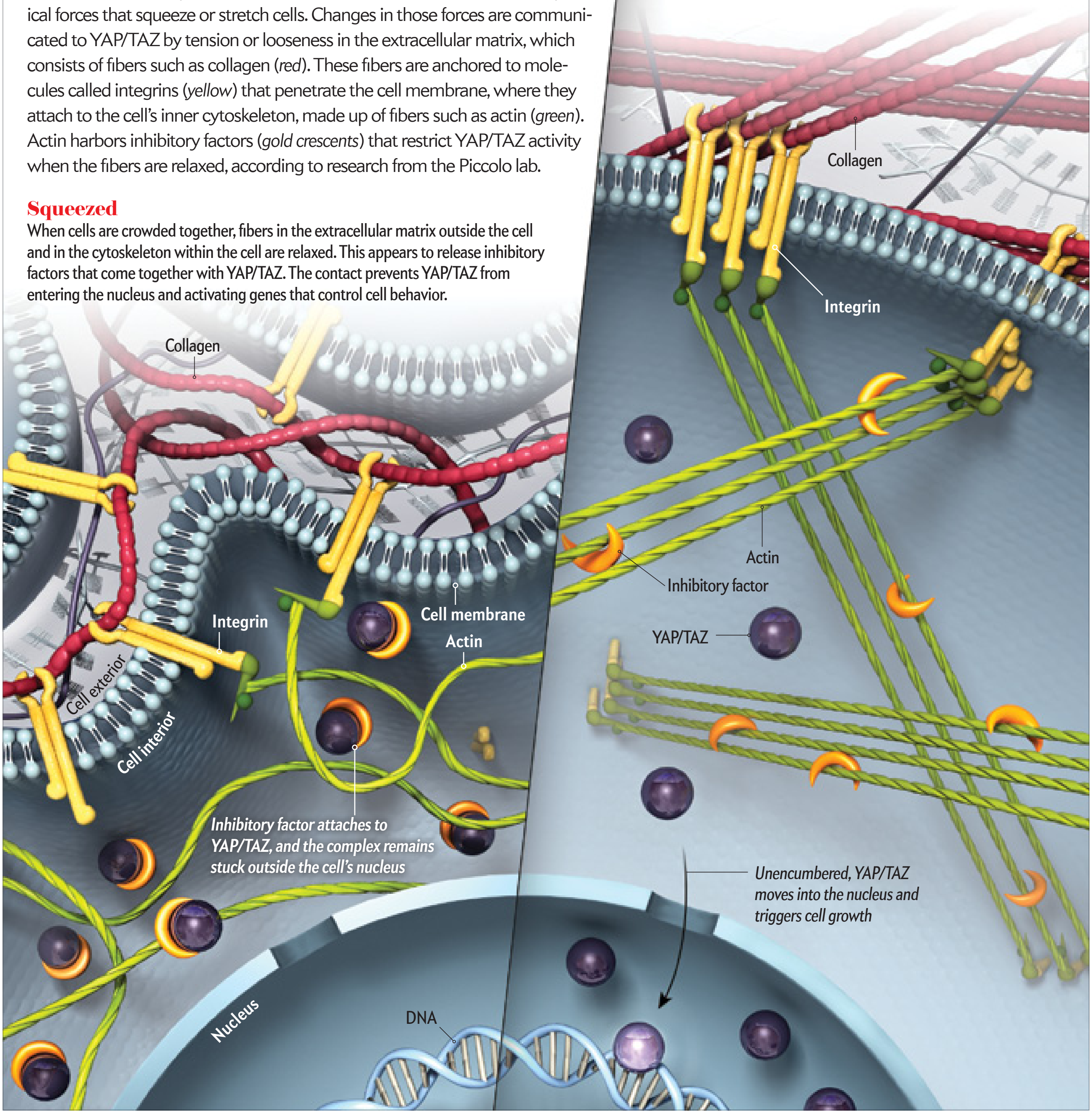
In a cell, the location of a key protein duo called YAP/TAZ (*purple*) can control whether the cell will proliferate. The duo's movements are influenced by physical forces that squeeze or stretch cells. Changes in those forces are communicated to YAP/TAZ by tension or looseness in the extracellular matrix, which consists of fibers such as collagen (*red*). These fibers are anchored to molecules called integrins (*yellow*) that penetrate the cell membrane, where they attach to the cell's inner cytoskeleton, made up of fibers such as actin (*green*). Actin harbors inhibitory factors (*gold crescents*) that restrict YAP/TAZ activity when the fibers are relaxed, according to research from the Piccolo lab.

Squeezed

When cells are crowded together, fibers in the extracellular matrix outside the cell and in the cytoskeleton within the cell are relaxed. This appears to release inhibitory factors that come together with YAP/TAZ. The contact prevents YAP/TAZ from entering the nucleus and activating genes that control cell behavior.

Stretched

When a cell has room to stretch, inhibitory factors are restrained by tense actin fibers of the cytoskeleton. This restraint frees YAP/TAZ to enter the nucleus and, in combination with other molecules, activate genes involved in cell proliferation and regeneration.



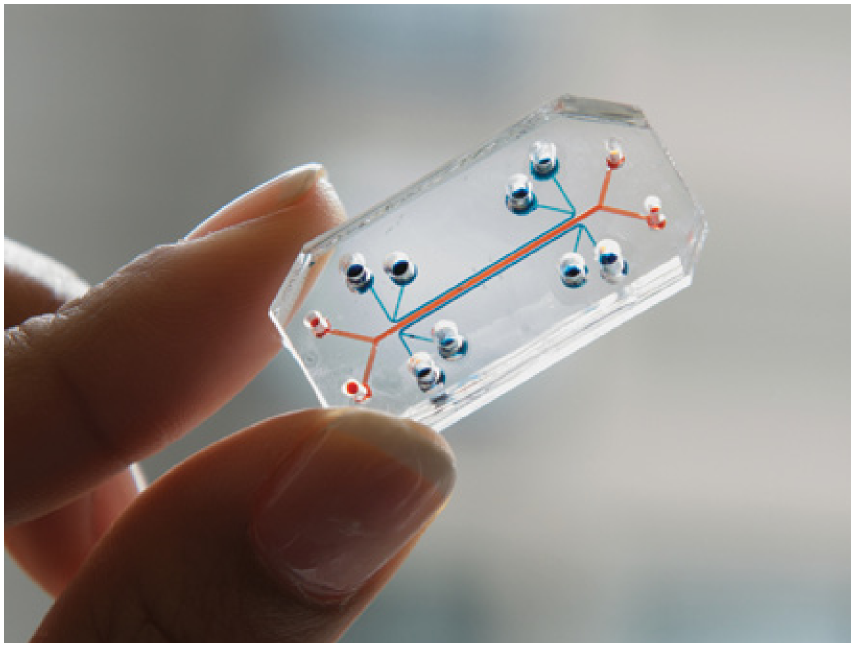
mechanical forces and affect a cell's fate. A second is the different types of ground that a cell can encounter. The extracellular matrix to which cells are secured is indeed not monotonous but has different textures. Some tissues, such as bone, create a stiff, dense matrix, like solid rock. Other tissues, such as brain tissue or fat, develop a much softer version. In other words, each organ's matrix has its own signature.

These signatures appear crucial in organ development and regeneration. Notably, their differing mechanical properties guide the efforts of a very important cell type: mesenchymal stem cells. These cells are found in many adult organs and contribute to repair after an injury. They differentiate into a strikingly diverse array of cell types, including bone, fat, nerve and muscle cells. For years biologists assumed that the cocktail of

Illustration by Emily Cooper

chemical factors that mesenchymal stem cells find at their destination determines their fate. But Adam Engler and Dennis Discher, both then at the University of Pennsylvania, punched a hole in that idea in a 2006 *Cell* paper. They engineered synthetic matrices with a range of rigidities matching those typical of different tissues. Astoundingly, mesenchymal stem cells displayed chameleonlike behavior when they were placed in these different matrices. They morphed into neurons on substrates tuned to brain stiffness and turned into muscles on substrates with muscle stiffness.

When Dupont repeated these experiments in Padua, he found that the degree of YAP/TAZ activation in mesenchymal stem cells changed along with the rigidity of different matrices. On very stiff substrates, for instance, YAP/TAZ was more active in cells and guided those cells on a journey toward becoming bone. Yet on the softest environment, high overall levels and activity of YAP/TAZ dropped, and these stem cells turned into fat cells. By experimentally playing with YAP/TAZ levels and activity, we could actually trick these cells: adding a modified version of YAP/TAZ to soft mesenchymal stem cells—the ones that were becoming fat—made them act as if they were on a much harder substrate and turned them into bone instead.



BUILDING A LUNG: **When this chip created forces that mimic breathing, blood vessel and lung cells on it formed complex lung structures.**

COURTESY OF WYSS INSTITUTE FOR BIOLOGICALLY INSPIRED ENGINEERING, HARVARD UNIVERSITY

CELL SWITCH THERAPY

THE BIOMEDICAL WORLD has come to focus on stem cells precisely because of this ability to morph into many specialized cell types. The hope is that with the proper guidance, the cells could restore and replenish damaged tissue and even be grown into replacement organs. But to take advantage of stem cells, investigators need to understand how they react to physical forces.

For example, stem cells that give rise to muscle could be used to bolster weakened tissue in patients with muscular dystrophy. But the stem cells need to be grown outside the body into populations large enough to have a therapeutic effect. Helen Blau of Stanford University showed that such production happens only when muscle stem cells are grown on materials matching the exact elasticity of the normal muscle environment.

Constructing new organs outside the body—a science-fiction-like prospect now approaching scientific reality—also depends on understanding how mechanical signals end up altering cellular activities. In the classic sci-fi movie *Blade Runner,* researchers grew functioning eyes in vats. Now the late Yoshiki Sasai of the RIKEN Center for Developmental Biology in Kobe, Japan, and his colleagues have established that it is possible to make embryonic eyes in a petri dish, starting from a ball of initially identical embryonic stem cells floating in a soft extracellular matrix. When the ball reaches the proper size, the cell layer starts to autonomously fold, twist and sink, mechanically self-assembling into eyelike structures as if it were living origami. This phenomenon occurs only when the scientists detach cells from the mechanical constraint imposed by flat walls in plastic dishes and let them follow an inner developmental script driven by a series of mechanical operations: folding, stretching, bending, and softening here and becoming more rigid there.

So-called organs on a chip recently reported by Ingber and his colleagues also obey these physical signals. Rather than growing cells on plastic dishes, Ingber's team grew them in tiny containers that exert pressure on the cells through minuscule amounts of fluids. These devices can change that pressure with finely honed accuracy. In this way, the cells experience the mechanical strains typical of real tissues. For example, lung cells were exposed to cycles of pressure and release that mimicked physiological breathing movements, and intestinal cells were stretched and compressed by motions like those of the digestive tract. Re-creating the normal rhythms and pressures of our bodies awakened some unexpected behaviors in otherwise dull, undifferentiated cell clumps. Some of them underwent a spontaneous change into differentiated organlike structures.

If tissues use mechanical regulation of YAP/TAZ to increase or decrease the number of their stem cells, the protein switch may let us produce more of these cells on demand. Stem cells occur only in secluded locations within tissues—at borders, bulges or the bottom of hollow tubes—that is, in special mechanical niches. These confined areas may be able to instill "stemness" in cells, the ability to regenerate themselves and, at the same time, to generate a progeny of multiple cell types. In several of these locations, stem cells display high levels of YAP/TAZ in their nucleus, which increases their capacity to reproduce, and the locations appear to influence these protein levels. By engineering niches that mimic those in the body, investigators may be able to expand rare stem cell populations in the lab. In a not too distant future, we might be able to manipulate stem cells within living tissues by delivering drugs that stimulate YAP/TAZ activity in the cells. Or drugs could turn it off,

SCIENTIFIC AMERICAN ONLINE Watch Donald Ingber explain why physical forces on a cell can be as important as genes at **ScientificAmerican.com/oct2014/cell-forces**

which should stop expansion and induce the cells to morph into a particular cell type needed by a given tissue.

Stem cell therapies do have a dark side: these cells may be ineffective or even dangerous if, instead of differentiating into a desired kind of tissue, they keep growing. Cancer stem cells, the most dangerous type of cancer cell, behave this way. That risk is one reason why many of us who work in mechanobiology believe that any future attempt to inject patients with stem cells for therapy needs to ensure that those cells will end up in the proper physical surroundings. The wrong surrounding forces could nudge these cells down an undesirable path, toward an inappropriate cell type or a cancerous growth.

PULLING THE STRINGS OF CANCER

INDEED, WHILE RESEARCHERS working on stem cells and the field of regenerative medicine are looking to boost the expansion of these cells and regrow damaged tissue, cancer researchers are struggling to do just the opposite: to restrict growth. Here, too, the physical forces tugging at cells may play a decisive role. For 40 years the war on cancer has largely been ruled by the view that genetic mutations drive tumor growth. Although some therapies that block the activity of such mutants have been effective, it is uncertain whether this approach will translate into a wide range of new treatments. Simply put, there are too many mutations, even in a single tumor, to chase and block all of them.

While researchers working on stem cells are looking to regrow damaged tissue, cancer researchers are struggling to do just the opposite: to restrict growth. Here, too, the physical forces tugging at cells may play a decisive role.

Cancer, however, is as much a disease of a disturbed microenvironment as it is a result of disturbed genes. Alterations of cell shape and of the cell's surroundings actually precede the onset of tumors and may even initiate disease. For example, work at Valerie Weaver's lab at the University of California, San Francisco, has shown that increasing the rigidity of the surrounding extracellular matrix prompted nonmalignant cells to switch to a tumorlike program of aggressive growth.

In our experiments, we demonstrated that forced shape changes translated into activation of YAP/TAZ and into more malignant behavior. Michelangelo Cordenonsi, a member of my lab, found that when he artificially raised TAZ in benign cells, these became indistinguishable from cancer stem cells. Indeed, YAP/TAZ is active in breast cancer stem cells, where they increase malignancy. Tumor cells do not invent anything new. Instead they co-opt a key mechanism by which tissues control the number and differentiation of their stem cells.

Because of this work, researchers in my group are pursuing an unorthodox idea about cancer. We think the initial acquisition of malignant properties may not necessarily involve accumulation of genetic lesions. Rather cancer may result from a rift in the body's normal microscopic architecture. Now it appears particularly apt that tumors have long been called "wounds that never heal" for their tendency to endlessly produce cells as if they were needed to repair a gash.

Restoring the environment, then, may be a balm as much as disturbing it is a bane. When Weaver took cancer cells and blunted their unusual pulling capacity by cutting their attachment strings to the extracellular matrix, their growth signals slowed, as did their proliferation. They turned into normal-looking tissue.

My colleagues and I are hopeful, then, that YAP/TAZ may prove to be an Achilles' heel of cancer. Hyperactivation of the pair is common in a vast number of tumor types, and dampening that zeal might help normalize tumor cell behavior or prevent metastasis. This strategy is already being pursued by several research groups.

Yet we and other scientists are mindful that cancer is a complex disease. Indeed, different cancers may have different paths that connect outer forces to genes. Many therapeutic approaches that appeared promising at first in the lab have made little difference to cancer patients. For any future YAP/TAZ inhibitor, the challenge will be to spare normal stem cells while targeting cancer cells, specifically. If direct inhibitors cannot be found, drugs able to relax the cytoskeleton or the extracellular matrix in tumors might do the job indirectly.

The ancient Greek philosopher Aristotle considered shape as the soul of all living entities. Cell biologists are beginning to see the profound role of shape in a more modern sense. Shape exerts a powerful influence on life: on one hand, it affects how cells build and repair organs, and on the other hand, it can become malevolent, undermining health. As we refine our understanding of the power of shape, we may be able to bend it to help people. SA

MORE TO EXPLORE

Control of Stem Cell Fate by Physical Interactions with the Extracellular Matrix. Farshid Guilak et al. in *Cell Stem Cell*, Vol. 5, No. 1; pages 17–26; July 2009.

Reconstituting Organ-Level Lung Functions on a Chip. Dongeun Huh et al. in *Science*, Vol. 328, pages 1662–1668; June 25, 2010.

Why Don't We Get More Cancer? A Proposed Role of the Microenvironment in Restraining Cancer Progression. Mina J. Bissell and William C. Hines in *Nature Medicine*, Vol. 17, pages 320–329; March 2011.

Transduction of Mechanical and Cytoskeletal Cues by YAP and TAZ. Georg Halder et al. in *Nature Reviews Molecular Cell Biology*, Vol. 13, pages 591–600; September 2012.

FROM OUR ARCHIVES

The Architecture of Life. Donald E. Ingber; January 1998.

Grow Your Own Eye. Yoshiki Sasai; November 2012.

An Indirect Way to Tame Cancer. Rakesh K. Jain; February 2014.

scientificamerican.com/magazine/sa

MAN-MADE NUGGET of frozen methane hydrate burns readily in air.

ENVIRONMENT

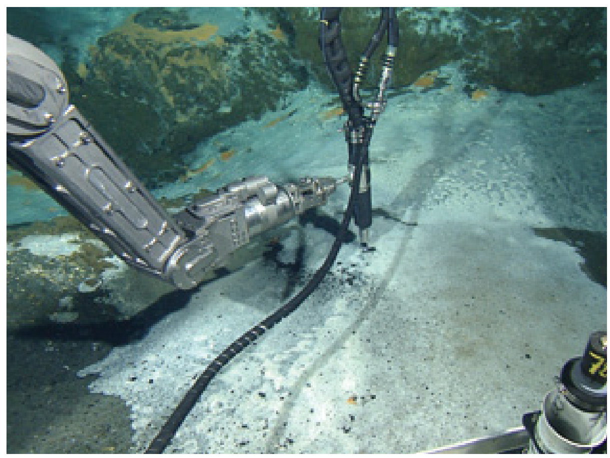
An Inconvenient Ice

Methane hydrates could solve the world's energy challenge—or make global warming worse

By Lisa Margonelli

Lisa Margonelli is author of *Oil on the Brain: Petroleum's Long, Strange Trip to Your Tank.* She is working on a book about termites for Scientific American/Farrar, Straus and Giroux.

ONE MORNING LAST AUGUST, THE MONTEREY BAY AQUARIUM Research Institute's deep-sea robot, named Doc Ricketts, was snooping around the ocean floor in 1,812 meters of very cold water off the coast of northern California. It was gliding over an oblong mound 2,000 meters long and 60 meters thick, draped in places with a thin layer of khaki-colored sediment. Video from the robot's underwater camera suddenly revealed what looked like a dirty yet nonetheless luminously white snowbank—the kind found at the edge of a plowed parking lot, except for the clams and fish around it. This glowing ledge showed that the mound contained methane hydrate, a lattice of frozen water that traps methane gas molecules within its icy cages. If you grabbed a snowball of the stuff, you could light it on fire.



Outcrops like this one are the proverbial tips of icebergs. Most methane hydrate deposits are trapped in sediments just below the seafloor, at the bottom of deep, cold oceans. Together the deposits are enormous, and scientists are finding them lurking everywhere, off the edge of every continent. The latest estimates indicate that, worldwide, methane hydrates under the sea hold at least as much carbon as all the coal, oil and natural gas reserves on the planet. Yet few have been studied in detail.

The goal of this 11-day expedition was to probe the large mound of hydrate and sediment, a tricky operation. The remotely operated robot, kitted out with mechanical arms, was tethered to the research ship *Western Flyer*. The institute's senior scientist, marine geologist Charlie Paull, clucked happily when the images appeared on the 20 video screens in the ship's small control room. More than a dozen scientists from the institute and the U.S. Geological Survey were jammed in the room with Paull, me and others, perched on old airplane seats and overturned plastic buckets. All these minds and equipment would bear down on the mound's secrets: How was it formed? Where did its methane come from? And did it start emerging from the seafloor 10 years ago, or had it been growing for a million years?

The team was seeking basic information that might help address larger issues. A recent geologic survey suggests that the hydrates off the coasts of the lower 48 states alone hold the

IN BRIEF

Methane hydrates are massive deposits of gas trapped in vast, icy structures underneath the coastal seafloor. They may hold more energy than all known reserves of oil, coal and natural gas worldwide.

Scientists are probing hydrate outcroppings to determine how easily the gas can be tapped for energy. They are also examining how readily the methane can escape on its own when heated by warming seawater. Deposits could potentially release enormous quantities of greenhouse gases.

In another hazard, deposits can expand rapidly when disturbed by earthquakes, setting off tsunamis.

PAGE 82: COURTESY OF MH21 RESEARCH CONSORTIUM; THIS PAGE AND OPPOSITE PAGE: COURTESY OF MBARI

RESEARCHERS onboard the *Western Flyer* lower a submersible robot, Doc Ricketts, to methane hydrates 1,300 meters down on the seafloor outside Vancouver. At the left, the robot's arm inserts a laser probe into an icy hydrate mound off Santa Monica, Calif.

equivalent of 2,000 years of natural gas supply at the country's current rate of consumption. If companies could harvest even a small percentage of that fuel, hydrates could be very useful; in March 2013 the Japanese research ship *Chikyu* became the first to extract natural gas from hydrate in the sea. But if warming oceans destabilize the hydrates so they release methane up through the water and into the atmosphere, the gas could hasten a climate catastrophe. Over a century methane has 20 times the global warming power of carbon dioxide. Are methane hydrates the next big thing in energy or the next big environmental worry? Scientists like Paull are trying to find answers.

AN ICY BLACK BOX

PAULL, A TALL MAN with a broad white moustache and a flat Rhode Island accent, began studying hydrates in the 1970s, when they were mainly known as a nuisance to the oil industry because their ice crystals clogged pipes in deepwater wells. If you ask him a question about hydrates, he nearly always starts, emphatically, with a burst of facts, only to end with a pained grimace when he gets to the things he does not know. During his career, hydrates have gone from esoteric curiosities to potentially massive players in the earth's carbon system, making them even more mysterious. Once upon a time, each sighting of a methane hydrate was exciting, but "now the question is: Where aren't they?" Paull says.

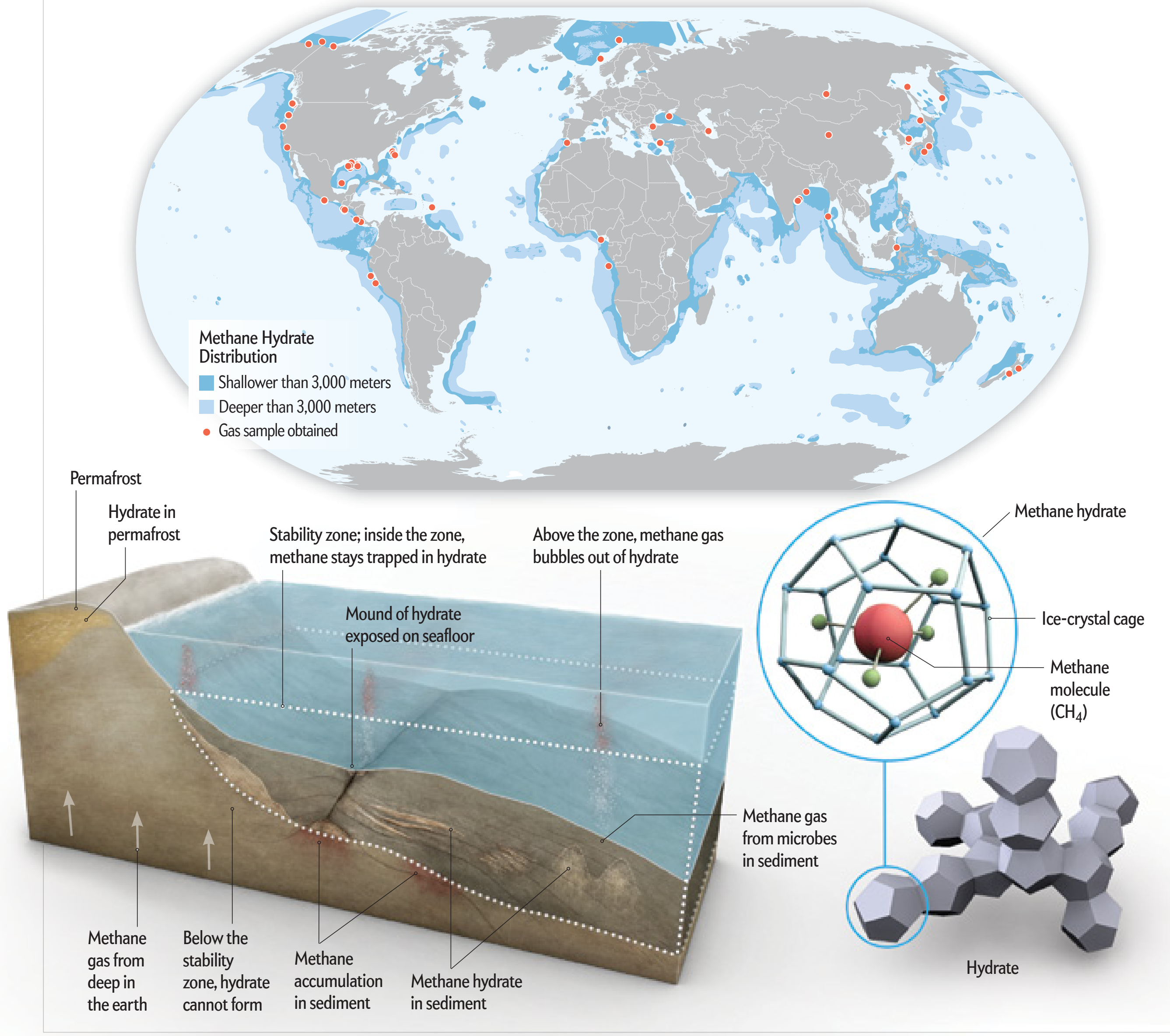
About 1 percent of methane hydrate is actually on land, sandwiched in layers of permafrost near the planet's poles. Most of the rest exists in what is called the hydrate stability zone, at low temperature and high pressure underneath at least 300 meters of seawater. There vast networks of crystals saturate layers of sediment up to 1,000 meters thick. Beyond 1,000 meters of sediment, methane simply exists as gas, warmed by the earth's deeper interior. Hydrates form constantly but not predictably, becoming solids in some pore spaces between sand grains while remaining a flowing gas in others. Scientists are not sure why a given state prevails in a particular location.

Pinning down the devilish details of hydrates—why they fluctuate between gaseous and solid states or how long they hold their methane in one place—is crucial for anyone trying to harvest their energy. These questions have become more urgent with successful tests. The *Chikyu* drilled into hydrate-rich sediments, then pumped out water from the surrounding area. Removing the water lowered the local pressure, which caused

METHANE HYDRATE BASICS

Frozen Gas Lurks Everywhere

Methane hydrates exist in the seabed along coastlines around the world (*blue regions on map*). Researchers have taken samples (*red dots*) mostly under shallow seas, but they think greater deposits lie below deeper water. Hydrates form in sediments on the seafloor (*bottom left*), as methane gas gets trapped inside ice crystals there (*bottom right*). The gas can originate from deep in the earth or from microbes that digest organic matter in the sediment. In certain spots, pieces of hydrate may rise through the water, giving off methane gas bubbles as they exit the stability zone (*dotted lines*). Hydrates can also form in permafrost on land.



SOURCES: "GLOBAL DISTRIBUTION OF METHANE HYDRATE IN OCEAN SEDIMENT," BY JEFFERY B. KLAUDA AND STANLEY I. SANDLER, IN *ENERGY & FUELS*, VOL. 19, NO. 2; MARCH 2005 (*base map*); USGS GAS HYDRATES PROJECT (*recovered sample data*)

methane to dissociate from its icy lattice amid the sediment. Gas flowed out of the well for five and a half days.

Japan leads the small but significant international race to develop hydrates for energy, spending $120 million on research last year. In 2010 the U.S. invested about $20 million, but by 2013 that had fallen to just $5 million. Germany, Taiwan, Korea, China and India have small research programs, as do oil companies Shell and Statoil. Although these expenditures are significant, they pale against the billions of dollars that the global oil industry spent on research and development in 2011 alone.

For a country that struggles with importing energy and is still cleaning up the Fukushima nuclear disaster, the sheer quantity of methane lying off Japan's coast makes harvesting it attractive. Americans are less motivated to explore hydrates as an energy source because the U.S. is already awash in inexpensive shale gas, which makes hydrates seem very costly by compari-

Map by XNR Productions, Illustration by Josemi Miguel Mayo son. Canada is rich in hydrates, too, but dropped its research program in 2013 for similar reasons.

If there were a "killer app" for mining methane hydrates, it would be a system that stabilizes their structures, sequesters greenhouse gases that the mining would release and provides fuel. In 2012 a team of researchers from the USGS, the U.S. Department of Energy, ConocoPhillips, Japan and Norway tried to do just that. They pumped a mixture of carbon dioxide and nitrogen (to prevent icing) into a hydrate that was capped by permafrost on Alaska's North Slope. The hope was that the CO_2 would push out methane and take its place, becoming trapped in the icy lattice to keep the hydrate structure intact.

Methane flowed from a test well for a month, but researchers could not be sure if the CO_2 had replaced methane. "The concept is straightforward, but nature is more complicated," says Ray Boswell, technology manager for hydrates at the DOE's National Energy Technology Laboratory. Boswell says data from the tests revealed "a messy black box underground."

Deep-sea hydrates bordering the lower 48 states could hold the equivalent of 2,000 years of natural gas supply at the country's current consumption rates.

Despite the relative success, ConocoPhillips has reassigned the employees who were involved. The DOE is looking for a new industry partner to continue the experiments.

To Paull, the experiment reflects our limited understanding of hydrate behavior. In 2010 he led a National Academy of Sciences committee that reviewed the DOE's work on methane hydrates as an energy resource. The panel concluded that engineers can probably surmount the technical challenges of producing fuel from hydrates but that many scientific, environmental and engineering questions remained to be answered before informed decisions could be made about whether to proceed. Unlike oil deposits, hydrates are inherently unstable and hard to map, and their effects on surrounding ecosystems are poorly understood. "I don't think we know enough about what it would mean to harvest them in an environmentally sound manner," Paull says.

STUCK IN A FROZEN AIRPORT LOUNGE

UNDERSTANDING THE SHIFTY, unpredictable nature of hydrates is fundamental to determining whether they can be reliably mined and whether they might amplify heating of the planet.

Simply touching hydrates, for instance, can cause them to shift from solid to gas, ruining an experiment. For that reason, Paull told the *Western Flyer* crew to avoid poking the icy outcrop until the very end of the dive. As the robot glided over the murky, greenish seafloor, the mound rose up like a mammoth blister, with small pockmarks in places, as though tiny meteorites had hit it. Paull suspects that the pockmarks are where pieces of hydrate broke off, from so little as a nudge from a fish. Wherever deposits are found in the sea, snowy pieces of fragile hydrate are seen drifting upward, led by gas bubbles—like comets being pulled toward the sea's surface by their tails.

Hydrates are constantly disassociating and forming throughout the stability zone. On one dive, sonar on Doc Ricketts located a stream of gas bubbles emerging from the mound. Paull wanted to know whether this gas was formed in a hot kitchen deep in the earth's crust, similar to where natural gas and oil are generated, or if it was made biologically in sediments by consortiums of microbes that process bits of organic material that drift in with sediments. Virtually all deposits contain gas from biogenic sources, and some contain gas from thermogenic sources; understanding the mix can help determine how a mound formed and what lies under it. Paull had the pilot lower the robot to the source of the bubbles, a dingy crevice surrounded by clams that consume bacteria that live using chemosynthesis—turning the methane into energy.

The crew landed Doc Ricketts on the outcrop, and the cameras immediately revealed a crab perched near the gas bubbles, furiously trying to wave them into its mouth with its claws. Because the water was only two degrees Celsius, and the pressure was immense, the gas formed small hydrate crystals quickly, crusting the crab's mouthparts with a ridiculous white beard, foiling its attempts to eat them. A biologist onboard said that crabs are often found attempting to gobble up methane bubbles, even though the critters do not appear to gain any nutrition from them.

To avoid having the same problem as the crab, the institute's engineers connected a heating unit to a funnel that leads into sampling bottles, all of which the robot can manipulate. Even so, the crew needed several dives over the next few days to get enough of a sample to determine the mix of thermogenic and biogenic gases in it.

Paull also wanted to find out how old the mound was to understand how quickly it had formed. The crew landed Doc Ricketts on one edge of a mound and manipulated its arms to take core samples by pushing specially designed tubes down into it. In some places, the robot easily drove the tubes into the icy, mucky sediments. In others, the tubes jammed against ledges of what may have been ice or another hard substance, such as calcium carbonate.

In the midst of the work, eerie bright-blue bubbles appeared in the robot's LED lights. In the control room, USGS geologist Thomas Lorenson suggested that the bubbles might be petroleum. Seeps from undersea oil and gas reservoirs are an ongoing

CHIKYU, **a Japanese ship, prepares to drill into methane hydrates in sediments 1,000 meters below the Pacific Ocean surface.**

AP PHOTO

natural oil spill on seafloors. A 2003 National Academy of Sciences publication estimated that 680 million liters of oil seep up into the world's oceans yearly. The seeps, which support large communities of clams, worms and other organisms, demonstrate just how difficult it would be to determine what constitutes a healthy environment if hydrates were harvested for energy.

Once the core samples, two meters long, were stowed on Doc Ricketts, it took the crew an hour to draw the robot and its cache back to the ship. When the vehicle entered through a sliding air lock in the hull, it brought an overwhelming smell of petroleum and rotten eggs. Researchers put some of the samples into freezers for later analysis and processed others on the boat. The muddy cores resembled brownie batter, fizzing with the presence of so much dissolved gas.

Paull and his team began to quickly process the smaller cores, spilling them out into trays to measure each centimeter of sediment and determine when it was deposited. The muck in front of me was the scene of a wild microbial party: the cold sediments contain many different microbes that create methane, consume it, and swap molecules of sulfur and oxygen. Hydrate formations, big as they may be, are just way stations between methane in the sediment below the ocean floor and the seawater above. Lorenson compares the space to a "transit lounge at the airport," where everyone is waiting for his or her chance to take off.

Gerald Dickens, an earth scientist at Rice University, describes hydrates worldwide as a giant storage capacitor for methane that rises into, or is created within, sediments—holding the gas, then gradually releasing it into ocean water and, potentially, the atmosphere. What we do not know is how fast this capacitor is acting—how long hydrates wait in the lounge before emerging. The gas may wait as long as seven million years, or it may be released relatively quickly, which could exacerbate global warming.

Adding to the uncertainty is the fact that researchers are not sure about how much hydrate is really on standby in the capacitors down there. In 2011 Dickens referenced a variety of papers to arrive at an estimate of 170 to 12,700 gigatons of carbon, a wide range that speaks to the great uncertainty. The upper end of that estimate implies that methane hydrates could hold more than three times as much carbon as all other quantified reserves of fossil fuels, which is commonly estimated at 4,000 gigatons of carbon.

METHANE TSUNAMIS

AS CAPACITORS, hydrates also can release large amounts of energy at once, which concerns both energy and climate researchers. Because hydrates are powerfully buoyant, they can be dangerous when disturbed. A cubic meter of hydrate brought to ambient temperature and pressure expands to 164 cubic meters of methane gas and 0.8 cubic meter of water. When earthquakes rattle hydrates, the expansion can trigger landslides, which can cause tsunamis. Such a domino effect is blamed for the Storegga slides, which created a wave that hit what is now Great Britain 8,100 years ago, as well as the Sissano tsunami, which killed more than 2,000 people in Papua New Guinea in 1998.

Preventing such geohazards will be a challenge for anyone trying to mine hydrates for energy. Conventional oil and gas are produced by drilling through rocks to sealed underground reservoirs. But the methane in a hydrate is in a solid that must change phase to a gas for extraction, putting the entire structure in motion.

A broader planetary concern is where the methane goes when it dissociates. If it gets into the atmosphere instead of being absorbed by seawater, it could have a dramatic impact on the climate. I had the opportunity to watch a chunk of hydrate rise through the water column. On one dive, the robot removed a melon-size chunk of hydrate ice from the outcropping at 1,800 meters and struggled to put the buoyant lump into a mesh bag in a frustrating dance one observer described as "antigravity

SCIENTIFIC AMERICAN ONLINE For details about the 2012 hydrate mining test in Alaska, see ScientificAmerican.com/oct2014/margonelli

Underwater dives could settle a vigorous debate: whether warming oceans could release massive quantities of methane.

basketball." As I watched from the control room, the ball stayed mostly intact in deep water. But as the robot rose above the stability zone, more gas dissociated, and the bag became obscured by a lacy haze of bubbles. When the robot finally reached the surface, the volume of hydrate was just a few tablespoons.

On deck, Lorenson quickly plunged the disappearing sample into liquid nitrogen for later testing. He also lit a small piece of it on fire and offered me another shard to eat. It fizzed in my mouth and was about as unappetizing as you would expect a hydrocarbon sorbet to be, except for an aromatic aftertaste that was almost minty.

That wild upward ride could provide clues to how much methane might escape into the air. Ocean chemist Peter Brewer of the Monterey Bay Institute has used x-ray tomography to examine rising hydrate. He has found that hydrate dissociates from both the outside and the inside. Another experiment showed that the bubbles formed thin hydrate "skins" like Ping-Pong balls that fizzed and popped eccentrically as they rose. Unraveling the physics and chemistry of dissociation, Brewer says, will help researchers determine where it occurs in the water column, how it is consumed by ocean microorganisms, how much, if any, typically makes it to the surface and how much can be expected to enter the atmosphere.

SMOKING GUN

THOSE INSIGHTS COULD HELP settle a vigorous debate that scientists have held for more than a decade: whether warming seas could trigger a massive release of methane and whether that discharge would overwhelm the oceans' ability to absorb it. An early theory called the Clathrate Gun hypothesis suggested that hydrates build up and then catastrophically release methane in cycles that repeat over many thousands of years. This cyclical scenario is not borne out by the fossil record, but the possibility remains that a large, one-time release of methane from hydrates could have contributed to the rapid warming of the earth during its peak heating—the "thermal maximum" 55 million years ago.

In contrast, modeling by David Archer of the University of Chicago suggests that, over millennia, hydrates could continually release methane, leading to a big change in global warming, in which rising temperatures would cause some hydrates to oxidize to CO_2 in the ocean, prolonging the warming trend.

Hydrates that are trapped under permafrost on land in the Arctic, along with those submerged under shallow seas just offshore, could be a more imminent threat. In November 2013 a team led by Natalia Shakhova of the University of Alaska Fairbanks estimated that the East Siberian Arctic Shelf is venting 17 million metric tons of methane into the atmosphere every year—twice previous estimates. Shakhova found significant methane bubbles rising from permafrost-covered hydrate deposits in just 50 meters of seawater. During the area's frequent storms, these bubbles appear to get mixed directly with the atmosphere. Until more research is done, no one can tell whether this dynamic is occurring across the Arctic or even whether the methane is coming primarily from the hydrates or the permafrost. It is yet another "black box" in our understanding.

Work on the ship brought more mystery. During my last day onboard, Paull had been poking at the small core samples in the *Western Flyer*'s large wet lab, ahead of results that would come later from the USGS analysis of the long, frozen cores. Paull thought that the sediment w e saw on top of the mound was probably relatively recent—something he may be able to pinpoint by scanning for traces of DDT, which appear only after 1945. The fact that the sediments had pushed up and blistered the seafloor, however, suggested they had built up over perhaps 10,000 years—still relatively new on geologic time scales.

Analysis of the frozen hydrate shards, which Lorenson sent to the Colorado School of Mines, later revealed that the mound not only contained its own methane but was also capping a system of storehouses under it. The Colorado researchers discovered multiple carbon isotopes, suggesting that the hydrate was formed from two different deep, hot reservoirs and two kinds of gases from microbes.

That pattern meant that gas had flowed upward from a previously unknown kitchen deep in the earth's crust, picked up another gas from a shallower kitchen and then wiggled up through the sediments to pick up biogenic gases, including one formed by microbes that had processed light petroleum into methane. Lorenson was surprised: "It points out the complexity of the migration [of oil and gas]. We don't understand what all the principal actors are doing down there."

In trying to measure one mound, the robot had stumbled on a much larger world underneath. Our mound was a relatively small cork holding back a massive stash of methane and oil. Methane hydrate turns out to defy simple questions about whether it is an energy blessing or a climate curse, posing much larger puzzles about how global systems work and what their time frames are. Scientists need to answer those questions—with much greater investment in basic earth science—to understand how this mysterious substance connects the carbon from past life on earth to the future of the planet. SA

MORE TO EXPLORE

Methane Hydrates and Contemporary Climate Change. Carolyn D. Ruppel in *Nature Education Knowledge*, Vol. 3, No. 10, Article No. 29; 2013.

A blog about the methane expedition described in this article: www.mbari.org/expeditions/Northern13/Leg1/index_L1.htm

FROM OUR ARCHIVES

Methane: A Menace Surfaces. Katey Walter Anthony; December 2009.

scientificamerican.com/magazine/sa

Let the GAMES *Continue*

In what would be his centennial year, Martin Gardner, the longtime author of *Scientific American*'s celebrated Mathematical Games column, still inspires mathematicians and puzzle lovers

By Colm Mulcahy and Dana Richards

LIKE A GOOD MAGIC TRICK, A CLEVER PUZZLE CAN INSPIRE AWE, REVEAL MATHEMATICAL TRUTHS and prompt important questions. At least that is what Martin Gardner thought. His name is synonymous with the legendary Mathematical Games column he wrote for a quarter of a century in *Scientific American*. Thanks to his own mathemagical skills, Gardner, who would have celebrated his 100th birthday in October, presented noteworthy mathematics every month with all the wonder of legerdemain and, in so doing, captivated a huge readership worldwide. Many people—obscure, famous and in between—have cited Mathematical Games as informing their decisions to pursue mathematics or a related field professionally.

IN BRIEF

Martin Gardner, who would have turned 100 this month, penned a quarter of a century's worth of Mathematical Games columns in *Scientific American*.

Diverse interests and friends and a formidable intellect helped Gardner to introduce a broad audience to many important topics, including RSA cryptography, the Game of Life, fractals and Penrose tilings.

Many of his columns inspired generations of professional and amateur mathematicians and led to entire communities dedicated to further developments.

His fans continue to meet and generate new results. Old friends and devotees of all ages convene at biennial, invitation-only Gathering 4 Gardner events. Many other people host or attend Celebration of Mind parties worldwide every October in his honor.

Illustration by Tim O'Brien

Gardner was a modest man. He never sought out awards and did not aspire to fame. Even so, his written legacy of 100-odd books—reflecting an impressive breadth of knowledge that bridged the sciences and humanities—attracted the attention and respect of many public figures. Pulitzer Prize–winning cognitive scientist Douglas Hofstadter described him as "one of the greatest intellects produced in this country in this century." Paleontologist Stephen Jay Gould remarked that Gardner was "the single brightest beacon defending rationality and good science against the mysticism and anti-intellectualism that surrounds us." And linguist Noam Chomsky described his contribution to contemporary intellectual culture as "unique—in its range, its insight, and its understanding of hard questions that matter."

Although Gardner stopped writing his column regularly in the early 1980s, his remarkable influence persists today. He wrote books and reviews up until his death in 2010, and his community of fans now spans several generations. His readers still host gatherings to celebrate him and mathematical games, and they also produce new results. The best way to appreciate his groundbreaking columns may be simply to reread them—or to discover them for the first time, as the case may be. Perhaps our celebration here of his work and the seeds it planted will spur a new generation to understand just why recreational mathematics still matters in 2014.

Colm Mulcahy is a professor of mathematics at Spelman College and has written extensively about mathematical card tricks.
Dana Richards is a professor of computer science at George Mason University and is author of an upcoming biography of Martin Gardner. Both knew Gardner and serve on the Centennial Committee for the Gathering 4 Gardner Foundation.

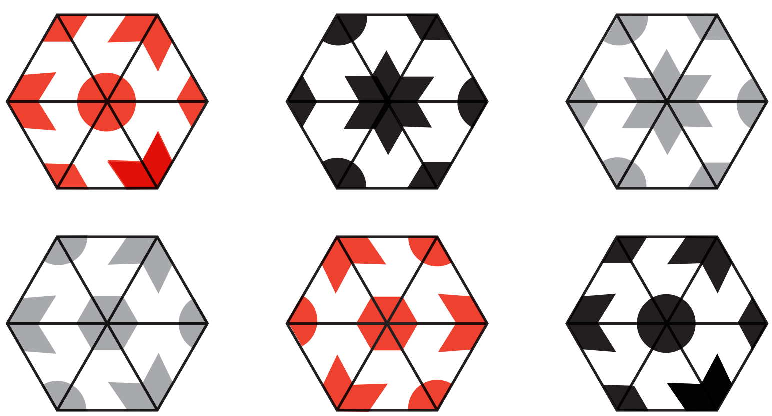
FROM LOGIC TO HEXAFLEXAGONS

FOR ALL HIS FAME in mathematical circles, Gardner was not a mathematician in any traditional sense. At the University of Chicago in the mid-1930s, he majored in philosophy and excelled at logic but otherwise ignored mathematics (although he did audit a course called "Elementary Mathematical Analysis"). He was, however, well versed in mathematical puzzles. His father, a geologist, introduced him to the great turn-of-the-century puzzle innovators Sam Loyd and Henry Ernest Dudeney. From the age of 15, he published articles regularly in magic journals, in which he often explored the overlap between magic and topology, the branch of mathematics that analyzes the properties that remain unchanged when shapes are stretched, twisted or deformed in some other way without tearing. For example, a coffee mug with a handle and a doughnut (or bagel) are topologically the same because both are smooth surfaces with one hole.

In 1948 Gardner moved to New York City, where he became friends with Jekuthiel Ginsburg, a mathematics professor at Yeshiva University and editor of *Scripta Mathematica,* a quarterly journal that sought to extend the reach of mathematics to the general reader. Gardner wrote a series of articles on mathematical magic for the journal and, in due course, seemed to fall under the influence of Ginsburg's argument that "a person does not have to be a painter to enjoy art, and he doesn't have to be a musician to enjoy good music. We want to prove that he doesn't have to be a professional mathematician to enjoy mathematical forms and shapes, and even some abstract ideas."

In 1952 Gardner published his first article in *Scientific American* about machines that could solve basic logic problems. Editor Dennis Flanagan and publisher Gerard Piel, who had taken charge of the magazine several years earlier, were eager to publish more math-related material and became even more interested after their colleague James Newman authored a surprise best seller, *The World of Mathematics,* in 1956. That same year Gardner sent them an article about hexaflexagons—folding paper structures with properties that both magicians and topologists had started to explore. The article was readily accepted, and even before it hit newsstands in December, he had been asked write a monthly column in the same vein.

Gardner's early entries were fairly elementary, but the mathematics became deeper as his understanding—and that of his readers—grew. In a sense, Gardner operated his own sort of social media network but at the speed of the U.S. mail. He shared information among people who would otherwise have worked in isolation, encouraging more research and more findings. Since his university days, he had maintained extensive and meticulously organized files. His network helped him to extend those files and to garner a wide circle of friends, eager to contribute ideas. Virtually anyone who wrote to him got a detailed reply, almost as though they had queried a search engine. Among his correspondents and associates were mathematicians John Hor-



SIX DIFFERENT PICTURES can be made to appear after a single decorated strip of paper is folded into a flat hexagonal structure called a hexahexaflexagon and then twisted and reflattened multiple times, as Gardner demonstrated in *Scientific American* in December 1956. (For a cutout you can use to make your own hexaflexagon, go to ScientificAmerican.com/oct2014/gardner)

PRECEDING PAGE: ILLUSTRATION REFERENCE COURTESY OF COLM MULCAHY ton Conway and Persi Diaconis, artists M. C. Escher and Salvador Dali, magician and skeptic James Randi, and writer Isaac Asimov.

Gardner's diverse alliances reflected his own eclectic interests—among them, literature, conjuring, rationality, physics, science fiction, philosophy and theology. He was a polymath in an age of specialists. In every essay, it seems, he found a connection between his main subject and the humanities. Such references helped many readers to relate to ideas they might have otherwise ignored. For instance, in an essay on "Nothing," Gardner went far beyond the mathematical concepts of zero and the empty set—a set with no members—and explored the concept of nothing in history, literature and philosophy. Other readers flocked to Gardner's column because he was such a skillful storyteller. He rarely prepared an essay on a single result, waiting instead until he had enough material to weave a rich tale of related insights and future paths of inquiry. He would often spend 20 days on research and writing and felt that if he struggled to learn something, he was in a better position than an expert to explain it to the public.

Gardner translated mathematics so well that his columns often prompted readers to pursue topics further. Take housewife Marjorie Rice, who, armed with a high school diploma, used what she learned from a Gardner column to discover several new types of tessellating pentagons, five-sided shapes that fit together like tiles with no gaps. She wrote to Gardner, who shared the result with mathematician Doris Schattschneider to verify it. Gardner's columns seeded scores of new findings—far too many to list. In 1993, though, Gardner himself identified the five columns that generated the most reader response: ones on Solomon W. Golomb's polyominoes, Conway's Game of Life, the nonperiodic tilings of the plane discovered by Roger Penrose of the University of Oxford, RSA cryptography and Newcomb's paradox [*see box on next page*].

POLYOMINOES AND LIFE

PERHAPS SOME OF THESE SUBJECTS proved so popular because they were easy to play with at home, using common items such as chessboards, matchsticks, cards or paper scraps. This was certainly the case when, in May 1957, Gardner described the work by Golomb, who had recently explored the properties of polyominoes, figures made by joining multiple squares side by side; a domino is a polyomino with two squares, a tromino has three, a tetromino has four, and so forth. They turn up in all kinds of tilings, logic problems and popular games, including modern-day video games such as Tetris. Puzzlers were already familiar with these shapes, but as Gardner reported, Golomb took the topic further, proving theorems about what arrangements were possible.

Certain polyominoes also appear as patterns in the Game of Life, invented by Conway and featured in *Scientific American* in October 1970. The game involves "cells," entries in a square array marked as "alive" or "dead," that live (and can thus proliferate) or die according to certain rules—for instance, cells with two or three neighbors survive, whereas those with no, one, or four or more neighbors die. "Games" start off with some initial configuration, and then these groupings evolve according to the rules. Life was part of a fledgling field that used "cellular automata" (rule-driven cells) to simulate complex systems, often in intricate detail. Conway's insight was that a trivial two-state automaton, which he designed by hand, contained the ineffable potential to model complex and evolutionary behavior.

PUZZLE SAMPLER

Test Yourself

Recreational math puzzles fall into many broad categories and solving them draws on a variety of talents, as the examples here, some of which are classics, show. (For the answers, go to ScientificAmerican.com/oct2014/gardner)

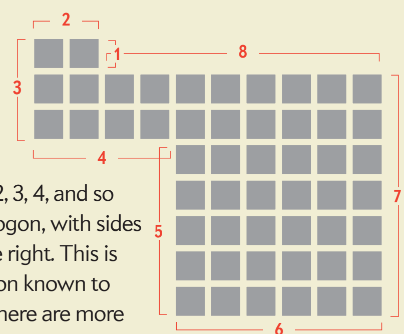
Some puzzles call for little more than basic reasoning. For instance, consider this brainteaser: There are three on/off switches on the ground floor of a building. Only one operates a single lightbulb on the third floor. The other two switches are not connected to anything. Put the switches in any on/off order you like. Then go to the third floor to see the bulb. Without leaving the third floor, can you figure out which switch is genuine? You get only one try.

Cryptarithms serve up harder tests of a puzzler's abilities. In these problems, each letter corresponds to a single digit. For instance, can you figure out which digit each letter represents to make the sum at the right work?

```
  SEVEN
  SEVEN
  SEVEN
  SEVEN
  SEVEN
  SEVEN
+ SEVEN
-------
 FORTY9
```

A knack for visualization is helpful for solving geometric stumpers. Can you picture a solid pyramid consisting of a square base and four equilateral triangles, alongside a solid tetrahedron with four faces identical to those of the pyramid's triangles? Now glue one triangle face of the pyramid to a triangle on the tetrahedron. How many faces does the resultant polyhedron have? It's not seven!

Puzzlers, like mathematicians, must sometimes solve challenges that reflect general problems or require the construction of logical proofs. Think about the class of polygons known as serial isogons. All adjacent sides meet at 90 degrees, and the sides are of increasing length: 1, 2, 3, 4, and so on. The simplest isogon, with sides 1–8, is shown at the right. This is the only serial isogon known to tile the plane. But there are more isogons. Can you prove that the number of their sides must always be a multiple of 8?



The properties of chess pieces play a part in many challenges, including in a group of problems about unattacked queens. Imagine three white queens and five black queens on a 5×5 chessboard. Can you arrange them so that no queen of one color can attack a queen of the other color? There is only one solution, excluding reflections and rotations.

Newcomb's Paradox: Who Wants to Be a Millionaire?

Martin Gardner read about a problem known as Newcomb's paradox in a 1969 paper by philosopher Robert Nozick and made it the subject of columns in July 1973 and March 1974. This thought experiment, created by theoretical physicist William Newcomb, draws on the mystery of determinacy and free will and is still actively debated in philosophical circles.

Players are pitted against a Predictor—a superintelligent alien, psychic, all-knowing deity—who is gifted at foretelling the player's actions. The player, unaware of the predictions, is presented with two boxes: one that always contains $1,000, call it box A, and another, box B, that might contain $1,000,000. He or she has the choice of taking just box B or taking both boxes. Before the game starts, the Predictor anticipates what the player will do. If the Predictor thinks the player will take only box B, then that box will contain the million-dollar reward. If the Predictor thinks the player will take both boxes, box B will hold nothing.

The paradox arises because two opposing strategies for winning the most money both seem logical. The first strategy argues that taking both boxes always yields more money, regardless of the Predictor's prediction. If the Predictor foretells that the player will take both boxes, then the player who chooses both boxes wins $1,000; selecting just box B yields $0 (*table at right*). If the Predictor anticipates that the player will take only box B, the player who chooses both boxes gets $1,001,000; selecting only box B yields a bit less ($1,000,000).

But another argument says that the greatest winnings will always come from taking only box B. It reasons that the player can ignore the instances in which the player's choice differs from the prediction because those moves require the Predictor to make a mistake, which this deity, by definition, is extremely unlikely to do. The choice then is between taking both boxes for $1,000 or only box B for $1,000,000.

Gardner's readers produced bags of commentary, delineating various outcomes, but there is still no resolution as to whether one strategy is ever better than the other. In his original coverage, Nozick commented, "To almost everyone, it is perfectly clear and obvious what should be done. The difficulty is that these people seem to divide almost evenly on the problem, with large numbers thinking that the opposing half is just being silly."

PREDICTED CHOICE	ACTUAL CHOICE	PAYOUT
Both A and B	Both	$1,000
Both A and B	B only	$0
B only	Both	$1,001,000
B only	B only	$1,000,000

After Gardner's column appeared, the Game of Life quickly attracted a cultlike following. "All over the world mathematicians with computers were writing Life programs," Gardner recalled. His dedicated readership soon produced many surprising findings. Mathematicians had long known that a short list of axioms can lead to profound truths, but the Life community in the early 1970s experienced it firsthand. Some 40 years later Life continues to spark discoveries: a new self-constructing pattern known as Gemini—which copies itself and destroys its parent pattern while innovatively moving in an oblique direction—was reported in May 2010, and the first Life replicator that clones itself and its instructions was built in November 2013.

APERIODICITY AND PUBLIC KEYS

CONWAY ALSO INTRODUCED Gardner to the tilings discovered by Penrose, who is a mathematician and physicist, and they became the basis of another blockbuster column, featuring two tile shapes, called kites and darts for their resemblance to those toys [*see illustration on opposite page*]. Given an endless supply of each, combinations of these tiles can cover an infinite stretch of floor without gaps and display a remarkable property called aperiodicity. Ordinary tile shapes—squares, triangles, hexagons—cover the floor in a pattern that repeats periodically. In other words, there are multiple spots in which you might stand, and the pattern in the tiles underneath your feet would be identical. But when kites and darts, or other combinations of two or more Penrose tiles, are arranged according to certain rules, no such recurring patterns appear. These tilings were so beautiful that in January 1977 they graced *Scientific American*'s cover, based on a sketch by Conway.

The community exploring the properties of Penrose tilings has made a number of advances since, including finding that the patterns display a property called self-similarity, also enjoyed by fractals, structures that repeat at different scales. (Fractals, too, gained widespread popularity in large part because of Gardner's December 1976 column about them.) And Penrose tiles have also led to the discovery of quasicrystals, which have an orderly but aperiodic structure. Nobody was more delighted about the connection than Gardner, who commented, "They are wonderful examples of how a mathematical discovery, made with no inkling of its applications, can turn out to have long been familiar to Mother Nature!"

In August 1977 Gardner anticipated another modern-day development: the use of electronic mail for personal communication "in a few decades." This prediction opened a column that introduced the world to RSA cryptography, a public-key cryptosystem based on trapdoor functions—ones that are easy to compute in one direction but not in the opposite direction. Such systems were not new in the mid-1970s, but computer scientists Ron Rivest, Adi Shamir and Leonard Adleman (after whom RSA is named) introduced a different kind of trapdoor using large prime numbers (those divisible only by one and themselves). The security of RSA encryption stemmed from the apparent difficulty of factoring the product of two sufficiently large primes.

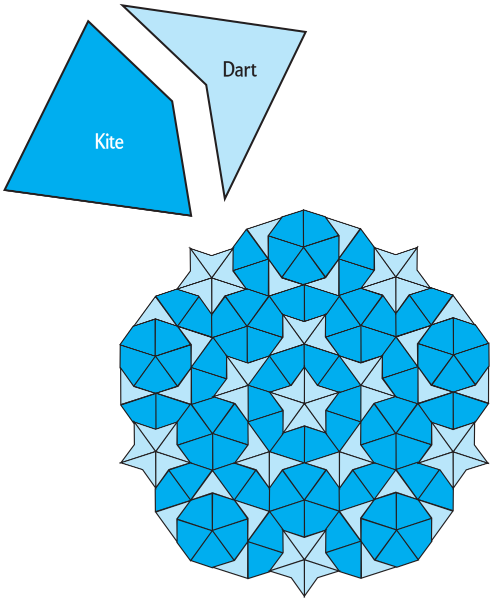
Before publishing their result in an academic journal, Rivest, Shamir and Adleman wrote to Gardner, hoping to reach a large audience quickly. Gardner grasped the significance of their innovation and uncharacteristically rushed a report into print. In the column, he posed a challenge, asking readers to attempt to decode a message that would require them to factor a 129-digit integer, an impossible task at that time. Gardner wisely prefaced the challenge with an Edgar Allan Poe quotation: "Yet it may be roundly asserted that human ingenuity cannot concoct a cipher which human ingenuity cannot resolve." And indeed, only 17 years later, a large team of collaborators, relying on more than 600 volunteers and 1,600 computers, cracked the code, revealing that the secret message read: "The magic words are squeamish ossifrage." RSA challenges continued for many years, ending only in 2007.

AFTER GARDNER

GARDNER'S LOVE OF PLAY went hand in hand with his impish sense of fun. A 1975 April Fools' Day column featured "six sensational discoveries that somehow or another have escaped public attention." All were plausible—and false. For instance, he claimed that Leonardo da Vinci invented the flush toilet. Allusions to "Ms. Birdbrain" and the psychic-powered "Ripoff rotor" were meant to alert readers to the gag nature of the column, but hundreds failed to get the joke and sent Gardner animated letters.

In 1980 Gardner decided to retire his column to concentrate on other writing projects. *Scientific American* quickly introduced a successor: Douglas Hofstadter. He wrote 25 columns, entitled Metamagical Themas—an anagram of Mathematical Games—many of which discussed artificial intelligence, his own specialty. A. K. Dewdney followed, penning seven years of Computer Recreations. Ian Stewart's Mathematical Recreations column ran for the next decade. Later Dennis Shasha wrote a long series of Puzzling Adventures, based on computing and algorithmic principles, subtly disguised. "Martin Gardner was an impossible act to follow," Stewart once commented. "What we did try to do was replicate the spirit of the column: to present significant mathematical ideas in a playful mood."

For the past two decades the spirit of the column has lived on at invitation-only, biennial Gathering 4 Gardner conferences, where mathematicians, magicians and puzzlers assemble to share what they wish they could still share via Mathematical Games. Gardner himself attended the first two. In recent years participants have ranged from old friends, such as Golomb, Conway, Elwyn Berlekamp, Richard Guy and Ronald Graham, to rising stars, such as computer scientist Erik Demaine and video maven Vi Hart, and some very young blood in the form of talented teenagers Neil Bickford, Julian Hunts and Ethan Brown. Following Gardner's death in 2010, spin-off Celebration of Mind parties, which anyone can attend (or host), have been held all over the world every October in his honor [see "More to Explore," at right].



PENROSE TILES are remarkable for producing "aperiodic" patterns: given an infinite supply, they will fill the floor without gaps such that the initial configuration never repeats exactly. Gardner wrote about Penrose tiles called kites and darts in January 1977. To ensure aperiodicity, the tiles must be laid according to certain rules. The starting grouping above is named "the infinite star pattern."

Although Gardner is gone, there are good reasons to take inspiration from his work and to champion recreational mathematics today. Noodling over puzzles and related activities often leads to important discoveries, as shown, if only briefly, in this article. Almost every essay Gardner wrote gave rise to communities of enthusiasts and specialists. A great number of his columns could now be expanded into books—entire shelves of books even. In addition, thinking about a problem from a mathematical perspective can be enormously valuable for clarity and rigor. Gardner never thought of recreational mathematics as a set of mere puzzles. The puzzles were a gateway to a richer world of mathematical marvels.

In his final, retrospective *Scientific American* article in 1998, Gardner reflected that the "line between entertaining math and serious math is a blurry one.... For 40 years I have done my best to convince educators that recreational math should be incorporated into the standard curriculum. It should be regularly introduced as a way to interest young students in the wonders of mathematics. So far, though, movement in this direction has been glacial."

Today the Internet hosts scores of math-related apps, tutorials and blogs—including many different Game of Life apps of varying quality—and social media can connect like-minded aficionados faster than Gardner ever could. But maybe that speed has a downside: Web-based experiences are perfect for quick "Interesting!" responses, but it takes careful reflection to reach revelatory "Aha!" moments. We believe that part of the success of Gardner's column was that he and his audience took the trouble to exchange detailed ideas and craft thoughtful answers. Only time will tell if a new community of puzzlers—in a less patient era—will pick up Gardner's mantle and propel future generations to fresh insights and discoveries. SA

MORE TO EXPLORE

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Celebration of Mind: www.celebrationofmind.org
A Tribute to Martin Gardner, 1914–2010. In-Depth Reports, ScientificAmerican.com, May 25, 2010. www.scientificamerican.com/report/martin-gardner-1914-2010
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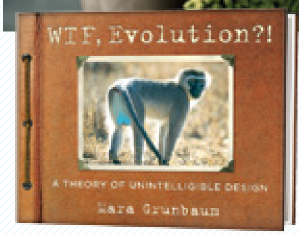
FROM OUR ARCHIVES

A Quarter-Century of Recreational Mathematics. Martin Gardner; August 1998.
The Great Explicator. Brian Hayes; October 2013.

scientificamerican.com/magazine/sa

MORE TO EXPLORE For more recommendations and an interview with *WTF, Evolution?!* author Grunbaum, go to **ScientificAmerican.com/oct2014/recommended**

WATER BEARS, or tardigrades, are just half a millimeter long.



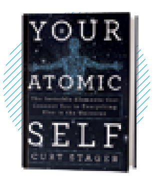
WTF, Evolution?! A Theory of Unintelligible Design

by Mara Grunbaum.
Workman, 2014 ($12.95)

Sea potatoes, pigbutt worms and hairy squat lobsters are among the odd, ugly and "unintelligible" creatures portrayed in this full-color compendium of unusual members of the animal kingdom. Science journalist Grunbaum, who writes a popular Tumblr blog of the same name as her book, accompanies photographs of bizarre organisms with hilarious commentary, often in the form of fictional conversations between the author and "evolution," who has this to say about the smalltooth sawfish: "You know how I usually put fish's teeth inside their mouths?… Well, what if I made a fish with teeth on the outside? Like, all around the edges of a really long snout? Like a gigantic face-saw!" Although many of the species profiled here have downright disgusting quirks (such as baby toads that crawl through their mother's skin), readers can't help but be awed by them.

Your Atomic Self: The Invisible Elements That Connect You to Everything in the Universe

by Curt Stager.
Thomas Dunne Books, 2014 ($25.99)



We often hear that we are literally "stardust," the atoms in our bodies having come from stars that exploded billions of years ago. A less commonly known fact is that some of the atoms inside us are much younger, such as the radioactive carbon 14 atoms created by atmospheric testing of nuclear weapons during the cold war. Ecologist and writer Stager details this and other atomic curiosities in a tour of our bodies' elements. These include nitrogen from thunder, carbon from exhaust pipes and iron from stellar cores. "Every scent you've ever savored," Stager writes, "every sight you've ever seen, every song you've ever enjoyed, every cry or sigh that ever passed your lips sprang from atoms at work within the atmosphere and the darkest recesses of your body."

Arrival of the Fittest: Solving Evolution's Greatest Puzzle

by Andreas Wagner.
Current, 2014 ($27.95)

Charles Darwin's theory of evolution transformed our understanding of life's diversity, but it could not fully answer a basic question that still vexes scientists: How does nature introduce complex traits? As evolutionary biologist Wagner puts it, natural selection "does not innovate, but merely selects what is already there." The latest evolutionary science, however, is beginning to reveal how new traits arise in the first place. "What we have found so far," Wagner writes, "already tells us that there is much more to evolution than meets the eye." Drawing on his own and other researchers' work, he explains how large numbers of random mutations within species can combine to form the intricate and innovative traits seen in our planet's vast diversity.

—Annie Sneed

Alive Inside: A Story of Music & Memory

by Michael Rossato-Bennett.
DVD available October 21, 2014

More than 35 million people worldwide have dementia, and many of them become unreachable as their cognitive impairment advances. Incredibly, though, when these same people listen to personally meaningful music, they can sometimes reconnect with their emotions, memories and identities. Filmmaker Rossato-Bennett follows social worker Dan Cohen as he brings iPods into nursing homes around the country. One resident with advanced dementia instantly awakens from a stupor when he hears music from his past and recalls decades-old details about his favorite singer, Cab Calloway. Cohen's ultimate goal is to make personalized music a standard tool at the tens of thousands of elderly care facilities in the U.S. "We need to use music to engage with people," Cohen says, "to allow them to express themselves, enjoy themselves, and live again."

—A.S.

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

Infrequencies

I just witnessed an event so mysterious that it shook my skepticism

Often I am asked if I have ever encountered something that I could not explain. What my interlocutors have in mind are not bewildering enigmas such as consciousness or U.S. foreign policy but anomalous and mystifying events that suggest the existence of the paranormal or supernatural. My answer is: yes, now I have.

The event took place on June 25, 2014. On that day I married Jennifer Graf, from Köln, Germany. She had been raised by her mom; her grandfather, Walter, was the closest father figure she had growing up, but he died when she was 16. In shipping her belongings to my home before the wedding, most of the boxes were damaged and several precious heirlooms lost, including her grandfather's binoculars. His 1978 Philips 070 transistor radio arrived safely, so I set out to bring it back to life after decades of muteness. I put in new batteries and opened it up to see if there were any loose connections to solder. I even tried "percussive maintenance," said to work on such devices—smacking it sharply against a hard surface. Silence. We gave up and put it at the back of a desk drawer in our bedroom.

Three months later, after affixing the necessary signatures to our marriage license at the Beverly Hills courthouse, we returned home, and in the presence of my family said our vows and exchanged rings. Being 9,000 kilometers from family, friends and home, Jennifer was feeling amiss and lonely. She wished her grandfather were there to give her away. She whispered that she wanted to say something to me alone, so we excused ourselves to the back of the house where we could hear music playing in the bedroom. We don't have a music system there, so we searched for laptops and iPhones and even opened the back door to check if the neighbors were playing music. We followed the sound to the printer on the desk, wondering—absurdly—if this combined printer/scanner/fax machine also included a radio. Nope.

At that moment Jennifer shot me a look I haven't seen since the supernatural thriller *The Exorcist* startled audiences. "That can't be what I think it is, can it?" she said. She opened the desk drawer and pulled out her grandfather's transistor radio, out of which a romantic love song wafted. We sat in stunned silence for minutes. "My grandfather is here with us," Jennifer said, tearfully. "I'm not alone."

Shortly thereafter we returned to our guests with the radio playing as I recounted the backstory. My daughter, Devin, who came out of her bedroom just before the ceremony began, added, "I heard the music coming from your room just as you were about to start." The odd thing is that we were there getting ready just minutes before that time, sans music.

Later that night we fell asleep to the sound of classical music emanating from Walter's radio. Fittingly, it stopped working the next day and has remained silent ever since.

What does this mean? Had it happened to someone else I might suggest a chance electrical anomaly and the law of large numbers as an explanation—with billions of people having billions of experiences every day, there's bound to be a handful of extremely unlikely events that stand out in their timing and meaning. In any case, such anecdotes do not constitute scientific evidence that the dead survive or that they can communicate with us via electronic equipment.

Jennifer is as skeptical as I am when it comes to paranormal and supernatural phenomena. Yet the eerie conjunction of these deeply evocative events gave her the distinct feeling that her grandfather was there and that the music was his gift of approval. I have to admit, it rocked me back on my heels and shook my skepticism to its core as well. I savored the experience more than the explanation.

The emotional interpretations of such anomalous events grant them significance regardless of their causal account. And if we are to take seriously the scientific credo to keep an open mind and remain agnostic when the evidence is indecisive or the riddle unsolved, we should not shut the doors of perception when they may be opened to us to marvel in the mysterious. SA

SCIENTIFIC AMERICAN ONLINE
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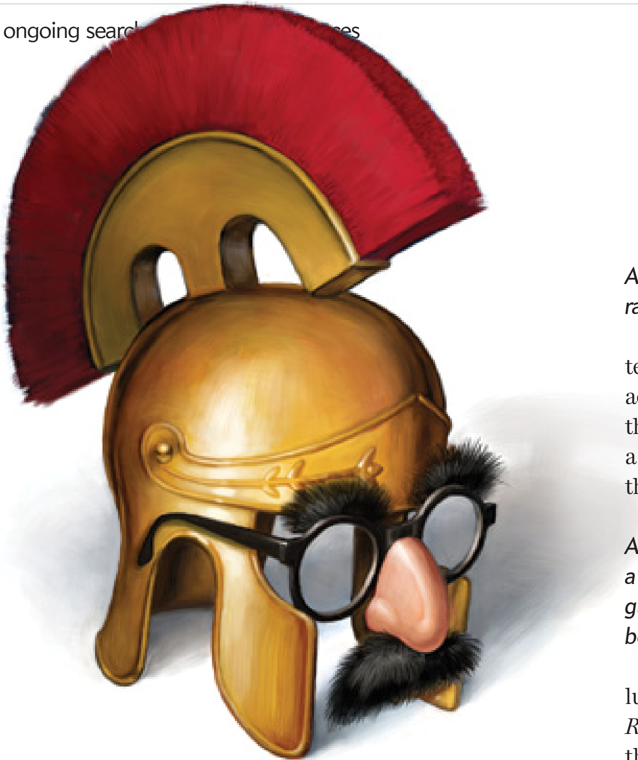
Illustration by Izhar Cohen

The ongoing sear … es

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



The 2,000-Year-Old Joke

When every party was a toga party

***An academic, a bald guy and a barber** traveling together stop to make camp for the night. They arrange to each take a watch while the other two sleep, with the barber on first watch and the academic to follow. The barber gets bored as the bald guy and the egghead sleep, so he shaves the academic's head to pass the time. At the end of his watch, the barber wakes up the academic, who rubs his now hairless head and says, "This barber is an idiot—he woke up the bald guy instead of me."*

That joke is so old that when it was first told the Dead Sea just had a bad cough. It's one of some 265 in a quip collection called *Philogelos,* which translates to "Laughter Lover," often cited as being the world's oldest book of jokes. If the story did not compel you to guffaw, no worries—when Samuel Johnson published parts of *Philogelos,* he said that the punch line left him befuddled.

Patient says to his doctor, "Every morning when I wake up I feel dizzy for a half hour." Doctor says, "Get up a half hour later."

That Henny Youngmanesque offering is also in *Philogelos,* which is the subject of intense scrutiny in the much newer book *Laughter in Ancient Rome: On Joking, Tickling, and Cracking Up,* by University of Cambridge classics professor Mary Beard. She points out that although *Philogelos* is thought to date back to the fourth or fifth century A.D., our copy "never existed in the ancient world, certainly not in the form in which we now read it." What we have, as is true for much literature from antiquity, is an amalgam of surviving bits of various versions. Think of a giant game of telephone played in numerous languages for a couple of millennia.

A guy from the nitwit town of Kyme was swimming when it began to rain, so he dived down to keep from getting wet.

I have taken the liberty to rework these jokes the way I might tell them, which may actually be in the spirit of the *Philogelos*—in addition to being the kind of tract that a Roman might peruse in the barbershop, the collection may have been what musicians call a "fake book," a compilation of simple versions of material that the performer then embellishes with his or her personal style.

A guy from the numbskull village of Abdera sees a eunuch talking to a woman and asks another guy if she's the eunuch's wife. The second guy says, "Eunuchs don't have wives." And the first guy says, "Must be his daughter."

Beard discusses theories of humor, power relationships, evolutionary psychology and much more in *Laughter in Ancient Rome.* But her focus is on the laughter itself. "One big question that hovers over the whole of the book," she writes, "is this: How comprehensible, in any terms, can Roman laughter now be?"

An academic bumps into one of a set of identical twins on the street and says, "Was it you who died or your brother?"

Indeed, we may laugh today at the jokes that lampoon the absent-minded professor types. (They made me think of the lecturing Nobel laureate I saw point with his microphone and talk into his laser pointer.) But contemplate such identity-confusion jokes in a society, Beard writes, "where formal proofs of identity were minimal: no passports, no government-issued ID … or any of those other forms of documentation that we now take for granted as the means of proving who we are."

Such caveats about the possible impenetrability of ancient wisecracks turn up frequently throughout the text. But Beard also cites University of California, Berkeley, emeritus historian Erich S. Gruen, whose problem is with "the comprehensibility of Roman laughter, not the reverse." And she quotes philosopher Simon Critchley of the New School: "The comedian is the anthropologist of our humdrum everyday lives." She then extends his observation: "[The comedian] turns those of who see the point of the joke—those who *get* it—into domestic anthropologists too."

Perhaps the superannuated material that still works, even under vastly different circumstances, nonetheless serves as a link between the shared anxieties of then and now—after all, identity theft is all the rage.

An academic sees a friend on the street and says, "I heard you died!" The friend says, "Well, you can see I'm alive." And the academic says, "Yeah, but I trust the guy who told me more than I trust you." SA

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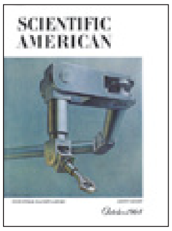
Illustration by Matt Collins

50, 100 & 150 Years Ago compiled by Daniel C. Schlenoff

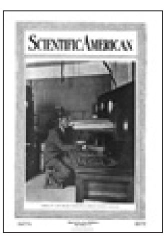
Innovation and discovery as chronicled in *Scientific American*



October 1964

Evolution and Creation

"Biblical fundamentalists are once again in conflict with biologists, this time as a result of efforts by the National Science Foundation to raise the level of high school biology teaching. After five years of preparation and classroom testing, three new textbooks have been offered to state and other educational agencies across the nation. All were produced by a $5 million Biological Science Curriculum Study (BSCS) project. All present the theory of evolution as a logical explanation of the known facts in biological history. Contrary to the practice of some publishers, none is issued in regional editions re-written to avoid conflict with local prejudices. During the school year 1963–1964 some 250,000 copies of the three texts were sold, a number sufficient to reach 12 percent of the high school biology students in the U.S. All three have been offered to and accepted by state adoption boards in Georgia and Florida. In Arizona an effort by one church group to place a referendum opposing 'atheistic teaching' on next month's ballot failed to obtain the required 55,000 petition signatures."



October 1914

Submarine Warfare

"It is certain that, from the very declaration of war, German submarines have been cruising at will in the North Sea; and they have at last scored a success, in the sinking of three British armored cruisers of 12,000 tons displacement, which must be recorded as the most brilliant naval success thus far achieved in the present war, and which establishes, at a stroke, the deadly efficiency of this, the latest form of naval warfare. It is in the moral prestige acquired, rather than in the material loss to the enemy, that the value of this German success is to be estimated."

For a slide show on naval warfare from 1914, see ScientificAmerican.com/oct2014/naval-warfare

SCIENTIFIC AMERICAN SUPPLEMENT, VOL. LXXVIII, NO. 2024; OCTOBER 17, 1914

"MARTHA," the last surviving passenger pigeon, died in 1914

Passenger Pigeon Extinction

"It became very evident that not a single Passenger Pigeon (*Ectopistes migratorius*) was left at large in the country, where formerly they migrated in flocks of billions. Meanwhile the sole survivor, the female in the Cincinnati 'Zoo' lived on; and at last, after it had survived for twenty-nine long years it succumbed to what was, apparently, nothing more than advanced age. This occurred at 1 o'clock in the morning on September 1st, 1914, and the body, as had been previously arranged, was sent to the Smithsonian Institution in Washington, D.C. For the side view of the head [*see illustration*], I restored the eye so that the portrait might have a more life-like appearance."

Public Electricity

"To the high school of Rupert, Idaho, belongs the distinction of being the first large building in the world to be exclusively run by electricity. In this building electricity is also used for a wide variety of other uses, and hence it has come to be called the 'Electric High School.' Rupert is the metropolis of the Government Minidoka Irrigation Project on the Snake River, a region which eight years ago was a sage brush desert, but which now is a densely settled farming community. The settlers on this project are intensely progressive and are determined to have for themselves and their children advantages, especially educational advantages."

The school served students until 1956.

October 1864

Iron Work

"Great improvement has been made of late years in forging light work. Instead of relying upon the hand and eye of some skillful workman, dies have been substituted, and the jobs thus produced have all the accuracy of castings while they are far superior in strength. Drop-presses have been used, also rapid-working trip-hammers, but these make such a tremendous racket that it is almost impossible to stay in their vicinity."

Profits of Blockade Running

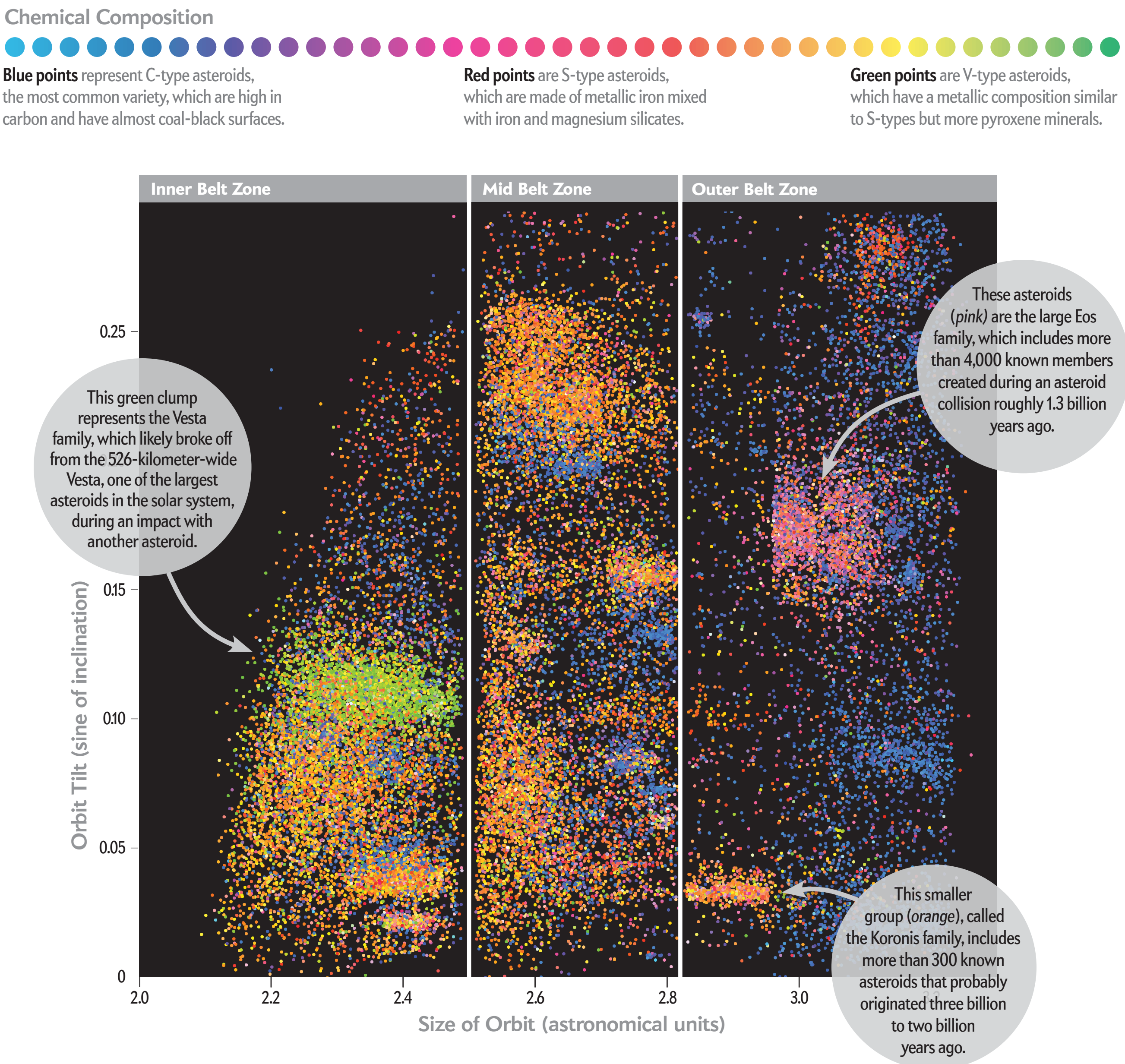
"The Liverpool *Courier* publishes some statistics in reference to the profits of blockade running. A single trip, it shows by a copy of bona fide account, costs $80,265. Of this amount five thousand dollars went to the captain for one month's service, three thousand dollars for pilotage out and in. Against this heavy expenditure the following is given on the credit side: 800 bales of cotton for Government, $40,000; 800 bales of cotton for owners, $40,000; Return freights for Government, $40,000; Return freight for owners, $40,000; Passengers, $12,000; Total $172,000. Thus, in case of a successful trip, the operators make a monthly profit of $91,735. It is to be remembered, however, that very often the vessels engaged in this business are captured at the first venture, entailing a heavy loss."

Family Histories

Space rocks tend to stick with their own kind

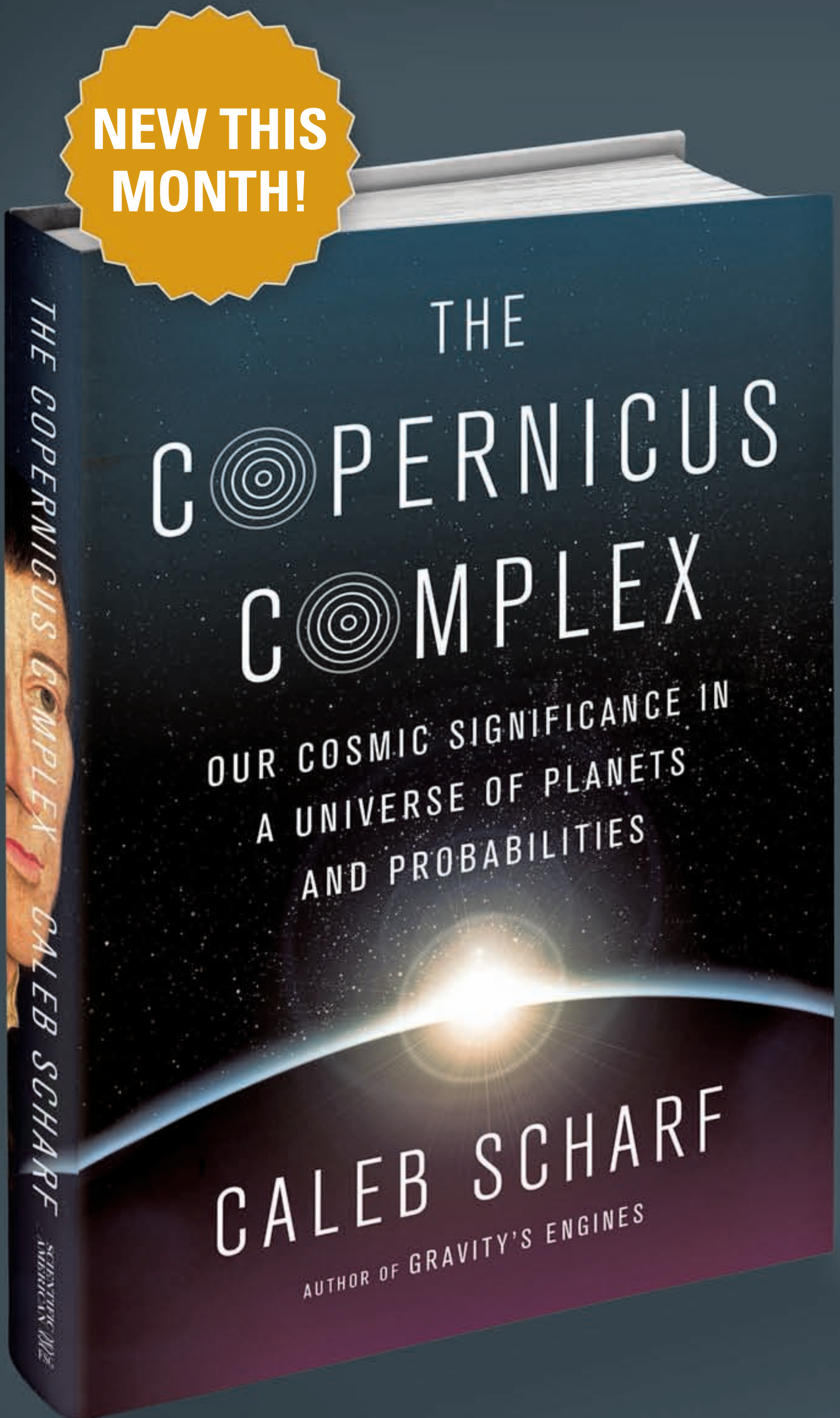
Asteroids are the oldest, most pristine samples of our early solar system and hold clues about how the current lineup of planets formed from what was once a giant cloud of gas and dust. This plot of roughly 45,000 asteroids that orbit between Mars and Jupiter reveals "families" of asteroids that share characteristics such as chemical composition (*colors*), orbit size (*horizontal axis*) and orbit tilt (*vertical axis*). Rocks with the same chemical composition tend to have similar orbital characteristics, which suggests a common origin—most likely a single larger body. These bodies probably broke up when they collided at high speed with other large asteroids in the crowded asteroid belt, says astronomer Jake VanderPlas of the University of Washington. (He and a team led by fellow Washington astronomer Željko Ivezić designed the plot on this page.) The extreme violence of those crashes, it turns out, is not enough to completely sever asteroid family ties. —*Clara Moskowitz*

SCIENTIFIC AMERICAN ONLINE
For more from Jake VanderPlas on data visualization in the service of astronomical research, see ScientificAmerican.com/oct2014/graphic-science



SOURCE: "THE SIZE DISTRIBUTIONS OF ASTEROID FAMILIES IN THE SDSS MOVING OBJECT CATALOG 4," BY A. H. PARKER, Ž. IVEZIĆ, M. JURIC, R. H. LUPTON, M. D. SEKORA AND A. F. KOWALSKI, IN *ICARUS*, VOL. 198, NO. 1; NOVEMBER 2008

Graphic by Jake VanderPlas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THE COPERNICUS COMPLEX
OUR COSMIC SIGNIFICANCE IN A UNIVERSE OF PLANETS AND PROBABILITIES
CALEB SCHARF
AUTHOR OF GRAVITY'S ENGINES
THE COPERNICUS COMPLEX CALEB SCHARF


WHEN THIS IS YOUR BACKYARD, YOU CAN'T HELP BUT EXPLORE.
When you've been in space long enough, you start to feel at home. We've been pushing the limits of what's possible out here since the dawn of the space age. For over 60 years, we at Northrop Grumman have been igniting the flame for space exploration—inspiring generations to stop and look up. From building the lunar module that led to one small step for man, to realizing the global dream that is the James Webb Space Telescope, the Great Pyramid of our generation. We've been here all along, and we aren't going anywhere but up.
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