ENERGY
New Threat to Global Climate

MEDICINE
How Children First Learn to See

BIOLOGY
Evil Genius of Tuberculosis

SCIENTIFIC AMERICAN

ScientificAmerican.com
JULY 2013

To Seek Out New Life

Watching exoplanet skies for signs that something is out there

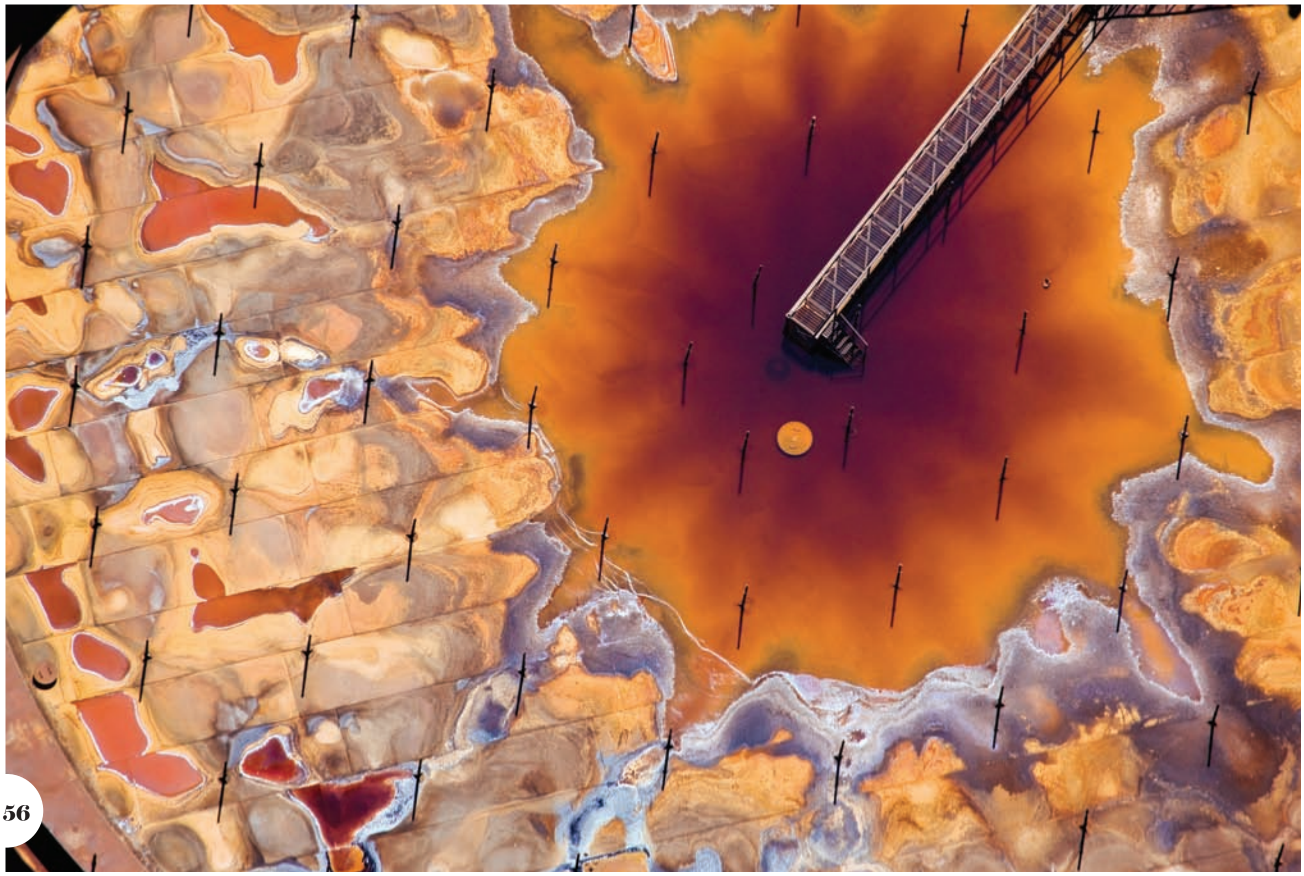
SPECIAL REPORT
Chemistry
« Past and Future »

ON THE COVER

Scientists recently thought it would take decades before they could examine the atmospheres around distant planets—that the host star's blinding light would overwhelm any useful observations. Yet ambitious young astronomers have devised clever new techniques that are now providing the first clear look into the skies of worlds beyond our solar system. Image by Don Foley.

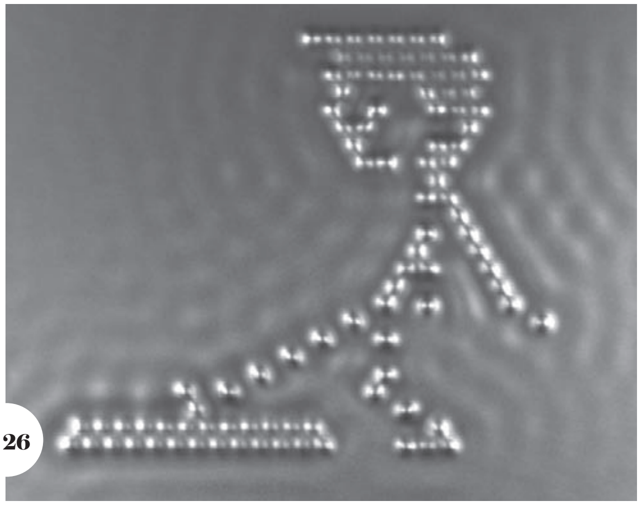
SCIENTIFIC AMERICAN

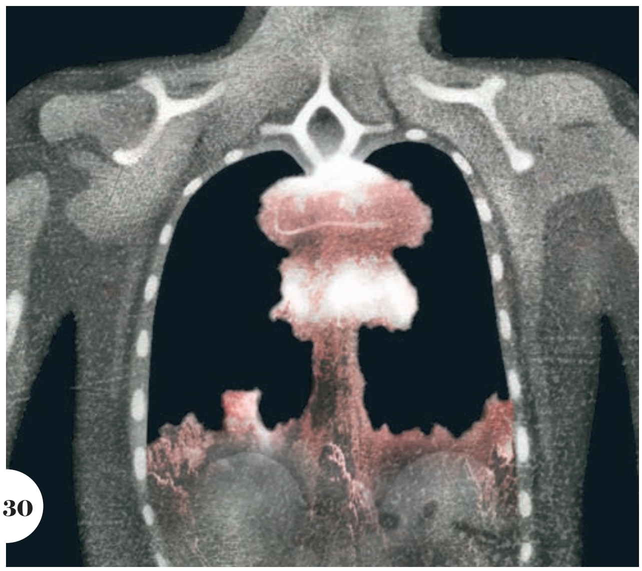
July 2013 Volume 309, Number 1



FEATURES

J. HENRY FAIR (*tar sands*)


26


30


90

SCIENTIFIC AMERICAN

DEPARTMENTS

ON THE WEB

Tracking the Cicada Cycle
In 2013 the cicadas of "brood II" emerged from the ground across the eastern U.S. to complete their 17-year life cycle. Find out where cicadas will appear in 2014 and whether a brood inhabits your region.
Go to www.ScientificAmerican.com/jul2013/cicada

Scientific American (ISSN 0036-8733), Volume 309, Number 1, July 2013, published monthly by Scientific American, a division of Nature America, Inc., 75 Varick Street, 9th Floor, New York, N.Y. 10013-1917. Periodicals postage paid at New York, N.Y., and at additional mailing offices. Canada Post International Publications Mail (Canadian Distribution) Sales Agreement No. 40012504. Canadian BN No. 127387652RT; TVQ1218059275 TQ0001. Publication Mail Agreement #40012504. Return undeliverable mail to Scientific American, P.O. Box 819, Stn Main, Markham, ON L3P 8A2. **Individual Subscription rates:** 1 year $39.97 (USD), Canada $49.97 (USD), International $61 (USD). **Institutional Subscription rates:** Schools and Public Libraries: 1 year $72 (USD), Canada $77 (USD), International $84 (USD). Businesses and Colleges/Universities: 1 year $330 (USD), Canada $335 (USD), International $342 (USD). Postmaster: Send address changes to Scientific American, Box 3187, Harlan, Iowa 51537. **Reprints available:** write Reprint Department, Scientific American, 75 Varick Street, 9th Floor, New York, N.Y. 10013-1917; fax: 646-563-7138; reprints@SciAm.com. **Subscription inquiries: U.S. and Canada (800) 333-1199; other (515) 248-7684. Send e-mail to scacustserv@cdsfulfillment.com.** Printed in U.S.A.

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

Scientific Citizens

FIFTEEN LANGUAGES, MULTIPLE PLATFORMS AND ONE GREAT institution: that is *Scientific American,* which celebrates its 168th year in August. I had another occasion to appreciate all of the above recently when we held our annual meeting of the international editions in New York City for the first time in many years. The multicultural mix, I have always thought, simply reflects the global collaborative nature of science itself.

During our meeting days, we shared ideas about how to improve what we do, discussed challenges in different markets and even had some laughs along the way. We held evening events at the New York Academy of Sciences (a panel discussion on fraud in science) and at the American Museum of Natural History (about a whale exhibit, including a demo of our Whale FM citizen science project with Zooniverse). You can find details on our @ScientificAmerican blog.

Our international assemblage seems nicely timed in light of this issue's cover story, "The Dawn of Distant Skies," by Michael D. Lemonick, starting on page 40. Rather than looking at experiences in other countries, however, we are peering at other solar systems. Whereas once we had thought distances would never allow us to glean useful information about those distant worlds, the cosmic picture is slowly brightening. Someday, we can hope, we will look at the atmospheres of those worlds for signatures of life. There's a pleasant symmetry to that, I think, as we contemplate our own global home. SA

AWARDS

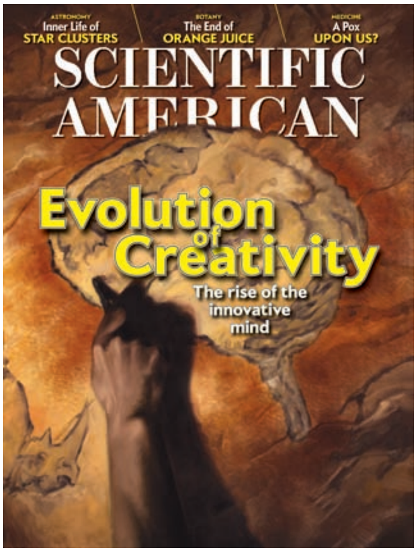
Science in Action News

The power to change the world for the better: that's Science in Action, also the name of a $50,000 special award sponsored by *Scientific American* for the annual Google Science Fair. On June 11 we will announce the finalists for Science in Action, now in its second year. The winner will follow on June 27. The Science in Action honoree will then travel to Mountain View, Calif., for the Google Science Fair awards event. I'll be there as chief judge. Updates will appear at www.ScientificAmerican.com. —*M.D.*

RICHARD ZINKEN

Illustration by Nick Higgins

editors@sciam.com



March 2013

"How long will real science be hobbled by the Buck Rogers fantasies of manned space missions?"

JOHN GAFFIN
MYERS FLAT, CALIF.

ASTRO-NAUGHT

In "Mission: Risk Averse" [Graphic Science], John Matson expresses concern about the apparent risk-averse attitude at NASA leading to a preponderance of Mars missions at the expense of exploration of the rest of the more challenging parts of the solar system. I would suggest that there is another psychology at play: catering to the persistent hope of manned exploration. If such exploration is at all feasible, then Mars is the place (never mind that it is also an obvious dead end), and it is then natural to put so many eggs in the Mars basket.

But this reveals the deeper choice that confronts NASA: How long will the capability to do real science be hobbled by the fabulously expensive Buck Rogers fantasies of manned missions? Given human psychology, this will not be readily resolved.

John Gaffin
Myers Flat, Calif.

SAVING ORANGE TREES

In "The End of Orange Juice," Anna Kuchment suggests orange growers can best defend against the citrus disease huanglongbing (HLB) by growing genetically modified trees or by applying chemicals to existing trees. But she fails to consider a third, more sustainable option: interplanting orange trees with other crops, such as guava.

Guava trees emit compounds that repel the insects responsible for HLB's transmission, and growers in Asia have for years deterred these insects by planting guava trees among their orange trees. Based on controlled studies, researchers at the U.S. Department of Agriculture have indicated that this approach deserves more attention in the U.S.

Rob Schaaf
via e-mail

ROBOT RISK

Who could object to developing cute little "RoboBees"—bee-size flying robots—as described in "Flight of the RoboBees," by Robert Wood, Radhika Nagpal and Gu-Yeon Wei? The article highlights beneficial uses such as searching for survivors of a natural disaster and acting as substitute pollinators for honeybees wiped out by colony collapse disorder. But the "gee whiz" factor masks numerous possible darker contingencies.

What if the RoboBees were slightly altered electronically and released as a colony of thousands to spread deadly bacteria, viruses or fungi? And what about more unregulated surveillance? Further, these machines are meant to be "disposable" (the researchers assert that there's no problem if individual units fail "periodically"). Yet are they not constructed with many of the same toxic materials found in all electronics?

Andrew Degen
via e-mail

STELLAR EVOLUTION

In "The Inner Life of Star Clusters," Steven W. Stahler proposes that binary stars—pairs of stars that orbit each other—in stable stellar groups called open clusters fuel the expansion of those clusters. A related diagram shows a heavy interloper forming a stable pair with the heavier of two stars in a pair, throwing out the lightest. Yet consider the last state depicted with all velocities reversed: the least massive star comes in and ends up throwing out the heaviest!

Ken Knowlton
Sarasota, Fla.

When a binary pair in an open cluster ejects a third star, Stahler explains, the latter encounters other members of the cluster and shares its energy with them, effectively "heating" the cluster and causing it to expand. But doesn't the ejecting pair lose energy in the process, perhaps orbiting more closely, and keep the cluster more compact?

K. Cyrus Robinson
via e-mail

Stahler states that stars "coalesce within vast clouds composed chiefly of hydrogen molecules, along with other elements and a small admixture of dust." The process by which elements were created has been established, but what is the nature of this "dust," and how was it created?

Harold W. Simons
Weiser, Idaho

STAHLER REPLIES: Regarding Knowlton's question, interacting systems of stars evolve along well-defined evolutionary paths. That they do so demonstrates that the system's entropy increases along these preferred directions. It is always possible, at least conceptually, to reverse all stellar velocities and cause the system to regress to a lower-entropy state. Yet the probability of such an occurrence becomes vanishingly small as the number of stars involved increases.

Robinson is correct that the binary pair left behind after the ejection of a lighter star has lower energy. Thus, its component stars orbit each other more tightly. But this separation is tiny compared with the overall size of the cluster, which increases.

As to the dust: interstellar dust grains are solid, submicron-size particles composed of silicates and other minerals, along with an outer mantle of water ice. They condense out of the slow winds emanating from red giant stars. During the process of star formation, these lowly grains form rocky planets—and therefore us!

GUN RESEARCH

"Ready. Aim. Investigate," by the Editors [Science Agenda], cites automobile safety research and policy implementation in arguing that research into the causes and prevention of gun violence, previously hampered by the National Rifle Association, is needed.

Research into making guns safer—without compromising speed and effectiveness—is a worthwhile goal. The analogy between automobile and gun deaths, however, is flawed. Automobile deaths are incidental, collateral damage to a car's purpose, whereas death or incapacitation is a gun's primary purpose.

Robert H. Miller
Prescott, Ariz.

I, as a legal gun owner, have taken due diligence that has ensured I have never had an incident. I cannot and will not suppose that owners of illegal firearms do the same. If research is to be conducted and solutions found, make sure it includes ways to keep the guns from entering the hands of the criminally minded. If this can't be done, and I suppose it can't, don't limit or remove our capability to defend ourselves from that element.

There will always be examples of poor firearm safety—even the best gun owner can slip. But most gun violence is perpetrated overwhelmingly by criminals and the psychologically challenged.

Ken Ridgley
via e-mail

DNA COLLECTION

In criticizing potential abuses of expanded DNA collection in "The Government Wants Your DNA," Erin Murphy cites the case of Shannon Kohler, who had initially refused a DNA test in a search for a serial killer but was then forced to submit DNA under a court order despite having exonerating details that included an alibi.

There is a long history of police departments publicly accusing and convicting innocent people without valid evidence, but this does not require DNA evidence. In fact, Kohler was exonerated because of the DNA testing; without it, he may have easily been convicted.

Ethan Solomita
via e-mail

LETTERS TO THE EDITOR

Scientific American
75 Varick Street, 9th Floor
New York, NY 10013-1917
or editors@sciam.com

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/jul2013

HOW TO CONTACT US

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

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

Reprints
To order bulk reprints of articles (minimum of 1,000 copies): Reprint Department, Scientific American, 75 Varick Street, 9th Floor, New York, NY 10013-1917; 212-451-8877; reprints@SciAm.com. For single copies of back issues: 800-333-1199.

Permissions
For permission to copy or reuse material: Permissions Department, Scientific American, 75 Varick Street, 9th Floor, New York, NY 10013-1917; randp@SciAm.com; www.ScientificAmerican.com/permissions. Please allow three to six weeks for processing.

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

Exploded Trust

A serious commitment to oversight could prevent fatal industrial disasters

Before it exploded this spring "like a nuclear bomb," as the mayor of West, Tex., put it, the West Fertilizer plant was an otherwise unremarkable piece of the American landscape. It sat just across from a subdivision in this town of 2,800 people. The West Intermediate School's baseball diamond was close enough to deliver the occasional foul ball. Officially, the plant held 27 tons of anhydrous ammonia. It also held, out of sight and mind, 270 tons of explosive ammonium nitrate. The blast damaged or destroyed 150 buildings, including the school and a nursing home. Fifteen people died.

The U.S. is home to around 6,000 fertilizer retail and production plants, 13,500 domestic chemical production plants and tens of thousands of mining and petroleum sites. We would like to assume that most of these facilities adhere to the rules that have been designed to minimize the danger to workers and neighboring communities. But the tale of West Fertilizer exposes a perilous status quo—a system in which potentially dangerous industrial sites have been trusted to police themselves.

Managers at the West plant never registered the ammonium nitrate with Homeland Security, even though the stockpile contained 1,300 times the amount that triggers a mandatory review. The most recent emergency planning report that the company filed with the Environmental Protection Agency stated there was no fire or explosion risk at the plant. Owners did inform Texas regulators about the ammonium nitrate, but inspectors issued nothing more than the occasional wrist slap.

In theory, this kind of case is where the federal government should bolster weak local oversight. But officials from the Occupational Safety and Health Administration last checked in on West in 1985. At that time, inspectors discovered five serious violations. The plant's management paid the $30 fine.

The incineration of this small town didn't have to happen. Yet such incidents will likely occur again, in Texas and well beyond it. The problem is not a lack of government. It's a lack of governance. It is a direct consequence of the well-documented late 20th-century allergy to effective regulation of the hazardous materials, energy and transportation industries in the U.S.

A particularly effective part of this push against regulation has been the reduction or elimination of inspectors who can monitor sites in the field. Homeland Security employs 242 people to oversee thousands of chemical plants; OSHA relies on about 2,200 inspectors to safeguard 130 million workers at more than eight million work sites in the U.S. Reports suggest that key oil and gas production states such as Texas, Pennsylvania and New Mexico each employ as few as a dozen inspectors to monitor thousands of active drilling sites. The 2013 federal budget sequester is further slicing away at these numbers.

One Texas politician said this spring that it was too early to draw conclusions about any additional regulations to address the West explosion. In a sense, he's right. Regulations abound, but they too often go overlooked. Increased staffing for inspectors at strapped federal agencies would curb the buck-passing, backslapping and voluntary reporting that apparently made it easy for West Fertilizer to skate past local regulators.

There is a particular meme in American politics today that regulation is an unnecessary burden—red tape that holds back the entrepreneurial spirit. But we should not forget that large industrial operations such as petroleum refineries, chemical plants and fertilizer facilities are as dangerous as they are common. A problem in one can reach far beyond its chain-linked perimeter.

Ronald Reagan said that the key to reducing the risk of a nuclear mishap was to "trust, but verify." Most local industries may be worthy of the trust their communities place in them. Still, we must verify. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/jul2013

G. J. McCARTHY *Corbis*

Commentary on science in the news from the experts

Philippe Kahn is co-founder and CEO of Fullpower Technologies, maker of the MotionX technology that is integrated in Nike and Jawbone products. In 1997 Kahn created the camera phone, combining an imaging sensor and a cell phone with software.

Wear Them, Forget Them

A prolific inventor argues that we are on the cusp of an explosion in truly useful and unencumbering wearable devices

If you're wearing a sleep monitor that is awkward and gets in the way, you might choose not to use it, and even if you do, the act of wearing it might change the way you sleep. It's a bit like the Heisenberg uncertainty principle: the observer changes the outcome of the experiment. If a sleep monitor has electrodes and wires that look like something from Frankenstein's lab, you might not wear it consistently, and the information it gathers and reports may be compromised.

In recent years wearable technology has improved drastically. Improvements in sensor technology are now making it possible to design wearable devices that are so noninvasive that we can forget we are wearing them. Inventors—myself included—are working to make sensors more accurate, smaller, with longer battery lives. The goal is to deliver great user experiences.

Sensors are rapidly evolving in important ways. As engineers, we are packing more capabilities into each sensor. We are coupling accelerometers with gyroscopes, shrinking them in size and decreasing their power consumption. We are also using new sensor-fusion algorithms that can make sense of all the data flowing through and among the sensors. For example, the Jawbone UP wristband, a 24-hour monitor (for which my team created hardware reference designs, firmware and other components) analyzes sleep and waking activity patterns. It is designed to be a step toward the "quantified self," which will improve Ms. and Mr. Everyone's health. It is meant to be fashionable and rugged, so you can keep it on in the shower. When you check your sleep patterns, you see your sleep, not the effects of wearing some strange device that disrupts your sleep.

Today's smartphones include sensors that capture images, motion, magnetic fields, geographical position and proximity, but they tend to use those sensors individually. With sensor-fusion technology, my phone could sense, say, that I'm in my car, which improves my experience significantly because my phone can automatically activate those functions that are most relevant to the situation. When I get out of my car and go jogging, or go to sleep, or do pretty much anything, my phone becomes a "context chameleon" and adapts automatically. A device like an iPhone, a SmartWatch or Google Glass could become my own personal communicator, integrated with my other wearable devices.

The technology behind such advances has existed for quite a while. Ten years ago we started developing the end-to-end components, power management systems, recommendation generators and other building blocks of the Jawbone UP wristband. Our original design back in 2005 had the wristband wirelessly synchronize with the phone and use the phone display in real time. Yet Bluetooth low-energy technology necessary to preserve battery life on the device is maturing only now. Just as it took 15 years after the invention of the camera phone for it to become ubiquitous, we are now likewise on the cusp of ubiquitous wearable devices that serve a wide array of functions.

Some of the most promising applications of wearable technology may be in the monitoring, prevention, treatment or even cure of medical conditions. For people with chronic conditions such as obesity, sleep apnea, diabetes, heart disease or Alzheimer's disease, wearable medical devices can make a huge difference in their quality of life and provide a scalable way to help control epidemics. They present a unique opportunity to tie into a new generation of therapies, including much more efficient personalized prescription dosages and delivery. For instance, a diabetic patch that releases medicine hand in hand with an advanced activity band provides a personalized and optimal dosage while improving both the therapies and the outcomes—the next step after insulin pumps. We now have the opportunity to revolutionize many people's health with our intellectual property and technology and provide a scalable solution to a planetary challenge. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/jul2013

Illustration by Viktor Koen

MEDICINE

Prickly Painkiller

An experimental plant extract may end intractable pain with a single injection

Although medicine has advanced far enough to treat basic headaches, strained muscles and the agony of having a cavity filled, inflammatory pain—the kind that results from osteoarthritis, bone cancer and back injuries—has proved to be a far more elusive target. Current remedies, including morphine and other opiates, flood all the nerves of the body, causing dangerous side effects. More localized remedies, such as steroid injections, wear off over time. Recently researchers have begun working with a toxin found in a Moroccan cactuslike plant that may be able to deliver permanent, local pain relief with a single injection.

The compound, called resiniferatoxin (RTX), works by destroying the neurons specifically responsible for inflammatory pain. These neurons extend from the body's periphery (including the skin and internal organs) to the spinal cord, carrying pain signals along their axons. The signals eventually travel up to the brain. When injected directly into spinal fluid, RTX homes in on and kills only those neurons that produce a protein called TRPV1, which transmits the sensation of noxious heat and inflammation. It does not harm normal tissue and other pain-sensing nerves, such as those that produce the feeling of pinpricks or pinches.

RTX has been tested in pet dogs that suffer from debilitating pain, and the studies have shown promising results. Unlike rodents, dogs experience pain much the way people do. "And they have personalities," says Andrew Mannes, chief of the department of perioperative medicine at the National Institutes of Health. "We can get insight into their psyches that we can't with rats."

The NIH is now running a trial of RTX in people with advanced cancer. Although Mannes and his colleagues cannot predict how soon they will have data, pain experts are watching the tria.l with interest. David Maine, director of the Center for Interventional Pain Medicine at Mercy Medical Center in Baltimore, says there are other ways to kill pain fibers, such as using alcohol to destroy nerves, but they sometimes cause the pain to come roaring back, far worse than before. "When you can streamline where a drug acts and avoid consequences outside of that, you potentially have a winner," Maine says. *—Arlene Weintraub*

Illustration by Matthew Billington

OCEANS

Going Deep

James Cameron donates his tricked-out ocean sub to science


DEEPSEA CHALLENGER

Before setting his sights once again on the far-off moon Pandora for the next *Avatar* adventure, filmmaker and aquanaut James Cameron has bequeathed arguably his greatest technological accomplishment to science. Cameron's *DEEPSEA CHALLENGER* submarine, which he drove to the deepest part of this planet last March, arrives this summer at Woods Hole Oceanographic Institution, ultimately helping researchers there better understand life in the earth's last unexplored frontier.

Cameron and his team of engineers outfitted the *DEEPSEA CHALLENGER* with cutting-edge technology that allowed it to become the first manned mission to the Pacific Ocean's Challenger Deep site, about 11 kilometers below the water's surface. Most immediately, Woods Hole scientists will install *DEEPSEA CHALLENGER*'s lightweight, highly maneuverable cameras and a lighting system that Cameron and his team designed onto the institute's *Nereus* robotic sub, which has been exploring the oceans' depths since 2009. The *Nereus* team is preparing for a six-week voyage—funded by the National Science Foundation to the tune of about $1.4 million—beginning in February 2014 to study the Pacific Ocean's Kermadec Trench, which is about 10 kilometers deep.

In addition to the *DEEPSEA CHALLENGER* itself, Cameron is kicking in nearly $1 million to help Woods Hole scientists and engineers make the sub's technology more widely available for deep-sea exploration. "To me, that's an infinitely better outcome than [the sub] sitting dormant until I'm done with my next two movies," said Cameron in April during a roundtable discussion in New York City with Woods Hole scientists.

Researchers want to explore every aspect of oceanography in the deepwater hadal regions—those anywhere below a depth of six kilometers. They want to know what lives there, how it evolved and what it eats, said Tim Shank, an associate scientist in Woods Hole's biology department and leader of its Hadal Ecosystem Studies (HADES) project. But most vehicles that can withstand the extreme pressure at those depths are heavier and more difficult to manage, making them more expensive and less fuel-efficient. Cameron's engineers developed new materials—including a syntactic foam made from millions of hollow glass microspheres suspended in an epoxy resin—to strengthen the sub's hull without adding a lot of weight. The vessel, which is 7.3 meters long but has an interior that is only 1.09 meters wide, also has a sphere-shaped, pressurized cockpit that collected evaporated moisture from Cameron's breath and sweat into a plastic bag, which would supply him with extra drinking water if necessary. The vessel descends vertically, with the cockpit near the bottom, underneath a 2.4-meter-long panel of lights and batteries.

The sub will arrive at Woods Hole shortly after the opening of the institution's new Center for Marine Robotics, which seeks to develop marine exploration technology with help from academe, the federal government and businesses. Some experts at the event pointed out that marine robotics has lagged behind terrestrial advances such as drones, in part because there is no Wi-Fi or GPS under the sea. That means there are many discoveries yet to be made. "So many people think we live in a postexploration age—it's all been seen, it's all been mapped," Cameron said. "The aggregate area of these trenches is greater than the size of the United States, greater than the size of Australia, so it's basically like a continent that's been unexplored that exists right here on earth."

—*Larry Greenemeier*

BY THE NUMBERS

88 *Percentage* of Americans who say fuel efficiency would be an "important" factor in their next vehicle purchase.

59 *Percentage* of Americans who say it would be a "very important factor," according to a survey by the Consumer Federation of America. In the past U.S. consumers were more focused on a car's power, safety, roominess or special features.

COURTESY OF MARK THIESSEN *National Geographic*

COCONUT RHINOCEROS BEETLE (*Oryctes rhinoceros*)

Mark Hoddle gathered this bug as it attacked a newly planted palm tree in Sumatra, Indonesia. A major pest of coconut palms, it hasn't arrived stateside, but Hoddle is prepared: he has its DNA for rapid identification.

AVOCADO SEED MOTH (*Stenoma catenifer*)

Avocado seed moth caterpillars drill holes into avocados, turning their insides to mush. Working in Guatemala, Peru and Mexico, the moths' native range, Hoddle and his colleagues gathered the insects' sex pheromones, which could serve as an early-warning system to signal their arrival here. He also collected their natural enemies, which could be released in the future to control the pests should they become established in California.

COCONUT PALM WEEVIL (*Rhynchophorus vulneratus*)

This palm tree killer likely arrived in Laguna Beach, Calif., from Bali, Indonesia, says Hoddle, who has studied the bugs' DNA. He suspects a traveler brought the insects to the U.S. as food (people in Indonesia eat them), tried breeding them at home and then let them go.

GOLDSPOTTED OAK BORER (*Agrilus auroguttatus*)

Native to southern Arizona, the oak borer has invaded California with disastrous results: it has killed up to 80,000 oak trees in the Cleveland National Forest in San Diego County. Hoddle believes campers spread it unwittingly by collecting firewood in Arizona and driving it to California.

WHAT'S IN THE FRIDGE?

Produce-Loving Pests

An entomologist and invasive species expert keeps his freezers full of bugs

Insects may be small, but they can wreak havoc on the environment or on a country's economy. Mark Hoddle, director of the Center for Invasive Species Research at the University of California, Riverside, travels the world, studying and battling insects that devour key exports or ecologically significant plants. Hoddle stores samples in his lab so he can study their DNA and donate them to research collections. He also sometimes traps bugs ahead of time—before they cause problems in the U.S.—and holds on to them for future reference. "It's hard to predict what the next invasive pest is going to be," he says. "This way, when they show up, I've got them marked as a target." —*Anna Kuchment*

Photographs by Spencer Lowell

TECHNOLOGY

Art from Above

Satellite surveillance could protect heritage sites

© DIGITALGLOBE, 2012

The Citadel of Aleppo (*aerial view at right*) rises above the old city in northern Syria and contains the remains of palaces, mosques and bathhouses dating back to the 10th century B.C. This World Heritage site has been threatened, however, by the country's civil war between rebels and the military of President Bashar al-Assad.

Armed conflicts and natural disasters threaten human life and cultural sites, but putting feet on the ground to assess damage can prove impossible. Instead experts are wielding satellite technology to monitor and protect endangered museums, monuments and other places of historical importance. The International Council of Museums (ICOM) first teamed up with the United Nations Institute for Training and Research's Operational Satellite Applications Program (UNOSAT) to report on the South Ossetia region during the 2008 Georgia-Russia War. UNOSAT leverages a network of publicly and privately owned satellites to capture the view from above. With those images and coordinates of the area's cultural sites, ICOM drew up a house-by-house assessment in just 24 hours. ICOM has since used satellites to survey damage to ancient mausoleums in Timbuktu during the 2012 civil war in Mali and plans to use them to assess destruction caused by the 2010 earthquake in Haiti.

Intervention may not be possible in regions where conflict still rages, but satellite technology and image analysis can give the council enough information to raise international awareness, appeal to combatants on the ground and make a plan for rehabilitation once the fighting stops.

—*Marissa Fessenden*

CONSERVATION

Cull of the Wild

Microscopic predators join the hunt for wolves in the Rockies

Two years after Congress removed gray wolves from the endangered species list in the northern Rockies, the animals are facing a new threat: disease. Outbreaks of infections such as sarcoptic mange, which is spread by mites, and canine distemper virus (CDV), have reduced wolf survival rates and contributed to an overall decline in Yellowstone National Park wolves.

Until recently, wolf populations in Yellowstone had been on a steady upswing. In 1995 park managers brought in 31 gray wolves from Canada to restore a population that had been virtually wiped out by hunting and other forms of depredation. (Montana veterinarians introduced the mange-carrying mite *Sarcoptes scabiei* to Yellowstone in 1905 in an effort to extirpate the wolves.) The most recent count put the regional wolf population at 1,727 in 2011, well above the lower limit set by federal agencies.

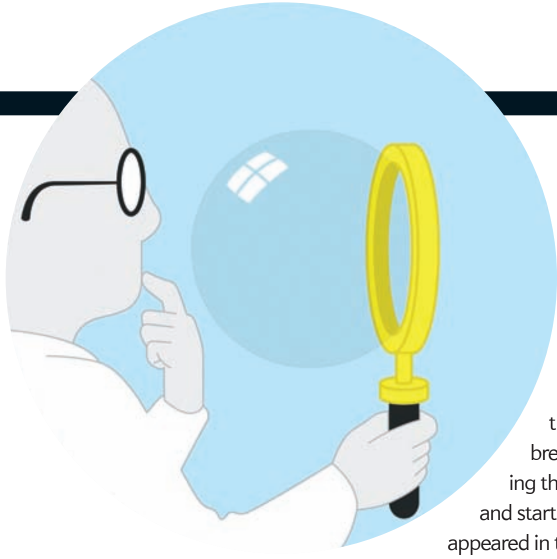
The Yellowstone wolves may be particularly susceptible to disease because, as transplants, they are relatively new to their environment. And wolf pups are the most at risk: only 16 survived this year, down from 34 in 2011.

Although scientists do not believe the illnesses pose a threat to the wolves' long-term survival, the new data may spur managers to tweak conservation plans. Wyoming has already reduced its hunting quota from 52 to 29, which experts say is a step in the right direction but may not be enough to shield the population from chance disturbances, be they trophy hunts or diseases. "Whether this is enough of a reduction will be evaluated following the next hunt," which begins in December, says Emily Almberg, a graduate ecology student at Pennsylvania State University who studies the wolves.

—*Shruti Ravindran*

TAMMY WOLFE *Getty Images*

COMMENT AT ScientificAmerican.com/jul2013



MATHEMATICS

Frothy Physics

A new mathematical model describes the complex evolution of bubbly foams

Few of us have not paused at one time or another to marvel at the beauty of a soap bubble. The iridescent, evanescent orbs, which can persist for minutes before vanishing in an instant, have captivated bubble-blowing children and pensive bathtub recliners alike.

They have also caught the eye of physicists and mathematicians, who have strived for hundreds of years to understand and predict the properties of bubbles at a fundamental level. Clusters of multiple bubbles carry a particular mathematical allure: they obey a series of geometric rules (such as bubble surfaces always meeting at certain angles) and behave as a kind of rudimentary computer, constantly shifting and rearranging to solve an optimization problem—how to limit the surface area of the bubbles.

Now a computer model that describes the behavior of ensembles of bubbles—better known as foams—may give researchers a better handle on bubble physics, which could in turn lead to better fire retardants, bicycle helmets and other foam-based products.

The new model, devised by two mathematicians at the University of California, Berkeley, breaks down the evolution of a foam into three discrete stages: First the foam rearranges its macroscopic structure as surface tension and the flow of air push the bubbles around until the foam settles into a stable configuration. Then liquid drains from the thin membranes, known as lamellae, that encase the individual bubbles until one of those lamellae is too weak to support the bubble. Finally, in the third stage, the thinned lamella breaks and the bubble pops, knocking the entire foam out of equilibrium and starting the process over. The research appeared in the May 10 issue of *Science.*

Each of the three stages of foam evolution plays out on its own scale of space and time. The microscopic thinning of a bubble's lamellae, for example, takes place very slowly, sometimes over hundreds of seconds, explains study co-author James Sethian, professor of mathematics at U.C. Berkeley. Then the rupture of those lamellae "happens at hundreds of meters per second," he adds. One of the hurdles in simulating the dynamics of a foam is capturing the requisite detail of the small-scale processes without bogging down the simulation on less salient details.

The solution put forth by Sethian and his co-author Robert Saye treats each scale differently—in effect, zooming in on the small-scale processes when they occur and zooming back out during the slower, macroscopic processes. "You can deal with them separately and then couple them together," says physicist Denis Weaire of Trinity College Dublin. The end results of each stage of the simulation feeds into the next stage in a feedback loop—the macroscopic motions of bubbles in a foam influence the microscopic draining of fluid from lamellae, which in turn triggers the rapid rupture of a thin lamella, thereby setting the bubbles in motion once more. But the simulation handles each of those processes in isolation. "It's way beyond anything we've attempted before," Weaire says.

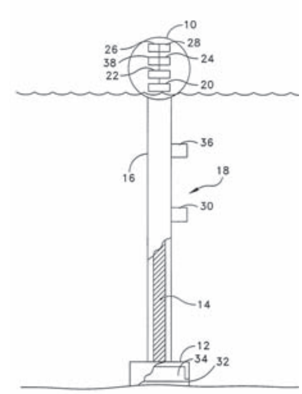
Relatively static foams, such as the bubbles in a head of beer—"foams that are just sitting there"—have been studied extensively, Weaire remarks. But there has been little progress on foams in flux, he adds, since he and a co-author published more than a decade ago a book called *The Physics of Foams,* in which they urged colleagues to advance the understanding of dynamic processes. The new work "is a step in that direction. It is a first step." He notes that the model has some limitations, such as dealing only with so-called dry foams—those with relatively low liquid contents. *—John Matson*

PATENT WATCH

Apparatus for underwater environmental energy transfer with a long lead zirconate titanate transducer: Buoys bobbing in the ocean do more than just mark navigational hazards. They help researchers track water and wind conditions, aid weather forecasters, listen for whale song and help the military detect underwater vehicles. Most buoys use batteries for power, but engineers have long tried to harness the crashing, roiling power of waves. Waves, however, do not move turbines fast enough to generate consistent current.

Instead build the buoy out of power-generating material, says Derke R. Hughes, a senior research engineer at the U.S. Navy's Naval Undersea Warfare Center. So-called piezoelectric compounds develop voltage when compressed. The compounds have a crystal-lattice structure with positive and negative poles. Under pressure, enough of the crystals align to produce a flow of charged particles or electricity.

Patent no. 8,274,167 describes a buoy that generates its own power. The floating section of the buoy is connected to a long cable anchored to the ocean floor or a weight. The cable has a core made of piezoelectric lead zirconate titanate, a chemical compound first synthesized at the Tokyo Institute of Technology. As currents flow around the cable, microeddies move it like the "strumming of a guitar string," Hughes says. The power generated depends on the cable's length and tension, but it theoretically could be enough to power a sonar array. Could a farm of buoys generate the megawatts needed for power back on land? "You could envision running enough of them together in a series," Hughes says. "It's just a matter of doing it right." The buoy has yet to be prototyped, so for now the idea is just on paper. *—Marissa Fessenden*



COURTESY OF U.S. PATENT AND TRADEMARK OFFICE

Illustrations by Thomas Fuchs

FROM "NEW CONTINENTAL RECORD AND NEW SPECIES OF *AUSTROMEROPE* (MECOPTERA, MEROPEIDAE) FROM BRAZIL," BY RENATO JOSE PIRES MACHADO, RICARDO KAWADA AND JOSÉ ALBERTINO RAFAEL, IN *ZOOKEYS*, VOL. 269; FEBRUARY 15, 2013

Best of the Blogs

ENTOMOLOGY

Don't Pince Me, Please

Two remarkable insects—one with giant genital forceps—join a list of new finds

Researchers working in Brazil have discovered a new species of forcepfly with enormous genital pincers (*right*), bringing the total number of known species in this family to three. And in Costa Rica a new fairyfly has been found: at 250 microns long, it is invisible to the naked eye and one of the smallest insects in the world.

Entomologist Renato Machado of Texas A&M University and his colleagues described the new forcepfly, a pale, golden-colored insect, in February in the journal *ZooKeys*. The team named it *Austromerope brasiliensis,* after its home near the Atlantic Forest of southeastern Brazil. Almost nothing is known about the biology of the nocturnal and secretive forcepfly. Scientists are not really sure how it lives, what it eats, how it mates or what its larvae look like. Most researchers assume that the males use their extraordinarily large terminal forceps to grip the females during copulation or to fight male rivals.

John Huber of Natural Resources Canada and John S. Noyes of the Natural History Museum in London named the new species of fairyfly *Tinkerbella nana,* after the fairy and the dog from *Peter Pan.* Happily, *nana* happens to be derived from *nanos,* the Greek word for "dwarf." Huber and Noyes described the species' light coloring, which includes yellows, browns and white, and spectacular wings, covered in delicate, long bristles called macrochaeta, in April in the *Journal of Hymenoptera Research.* The team suggests that this type of wing could help the fairyfly reduce drag and turbulence while in the air—fairyflies flap their tiny wings hundreds of times per second to keep aloft.

Though distinct in enough ways to earn itself a place in a new genus, *T. nana* is closely related to the world's smallest known winged insect, *Kikiki huna,* which is 158 microns long—about as small as a winged insect can be. Huber remarks, "If we have not already found them, we must surely be close to discovering the smallest insects and other arthropods." *—Becky Crew*

Adapted from Running Ponies at blogs.ScientificAmerican.com/running-ponies

ANTHROPOLOGY

Streams of Consciousness

A researcher documents people's internal monologues

On any given day, millions of conversations reverberate through New York City. All these conversations are matched in number and complexity by much more elusive discourses. Even when speaking with others—and especially when alone—we continually talk to ourselves in our heads.

Psychologists have attempted to capture what they call self-talk or inner speech in the moment, asking people to stop what they are doing and write down their thoughts at random times. Others have relied on surveys or diaries. Andrew Irving, an anthropologist at the University of Manchester in England, recently recorded the inner dialogues of people walking in New York City. He approached strangers, asked them to wear a microphone headset attached to a digital recorder and speak their thoughts aloud as he followed closely behind with a camera.

"I was surprised by how many said 'yes,'" Irving says—about 100 in all. By overlaying the recorded audio onto the videos, he has created portraits of individual consciousnesses on a particular day in New York.

Of course, people sometimes speak into the microphone as though trying to entertain someone else. And getting people's inner speech on tape captures only linguistic forms of thought, neglecting the kind of thinking that happens in images and scenes. Still, Irving's videos are permanent records of fleeting thoughts, of dynamic mental processes unfurling in real time.

In one video, a young woman named Meredith walks along Prince Street in downtown Manhattan. She briefly wonders if there is a Staples store nearby before reminiscing about a recent visit to her friend Joan, whom, we learn, has cancer. Meredith contemplates her friend's situation for the next two minutes, tearing up at the thought of "New York without Joan." Abruptly, she notices a café where she used to sit and people watch, laments how it has changed and resumes her search for a Staples.

Meredith's meandering thoughts recall Clarissa Dalloway's roaming mind in Virginia Woolf's novel *Mrs Dalloway.* Woolf would likely have adored Irving's videos. She wanted to write about "an ordinary mind on an ordinary day." *—Ferris Jabr*

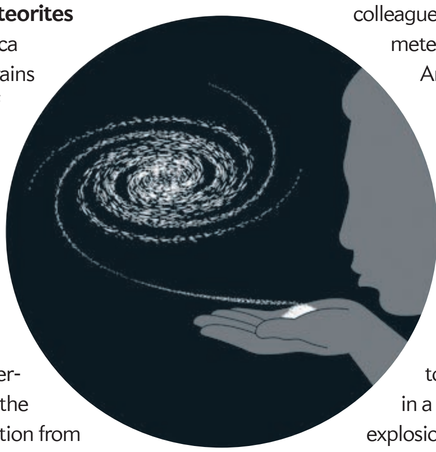
Adapted from Brainwaves at blogs.ScientificAmerican.com/brainwaves

COMMENT AT ScientificAmerican.com/jul2013

SPACE

A Star's Last Breath

Supernova dust fell to Earth in Antarctic meteorites



Two primitive meteorites collected in Antarctica appear to contain grains of silica—the stuff of quartz and sand—forged in a stellar explosion that predates the birth of the solar system. In fact, some researchers believe that it was just such an explosion, or supernova, that triggered the solar system's formation from a cloud of dust and gas billions of years ago. Whether or not the Antarctic meteorites contain a record of that fateful cataclysm, they do contain a supernova by-product that has never before been found on Earth.

Presolar grains stand out from the rest because of their unusual mix of chemical isotopes, "which cannot be explained by any known process acting in the solar system," according to a study in the May 1 issue of *Astrophysical Journal Letters.* Only nuclear reactions within stars can explain the grains' composition. Some presolar grains in the nascent solar system's cloud spilled from nearby supernovae, and some seem to have arrived on winds expelled from aging stars.

In the new study, Pierre Haenecour of Washington University in St. Louis and his colleagues analyzed two meteorites collected in Antarctica in 2003. Both harbor presolar grains of silica (SiO_2), the researchers found, as evidenced by the grains' enrichment in a heavy isotope of oxygen known as oxygen 18. That signature points to the grains' formation in a type II supernova—the explosion initiated by the collapse of a massive star's core. Other scientists had spotted presolar silica in meteorites before, but those grains had different isotopic signatures that indicated that they came from an aging star called an asymptotic giant branch (AGB) star rather than from a supernova.

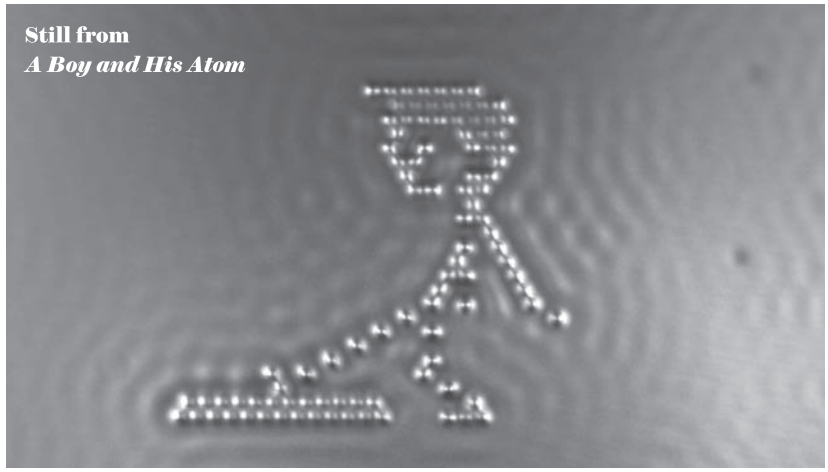
Amassing and analyzing these presolar grains is more than just an exercise in interstellar history—a shock wave from a nearby supernova or the gentler expulsions of an AGB star could have stirred a cloud of dust and gas to collapse into the system of sun and planets that we inhabit today. Collecting presolar detritus allows astrophysicists a glimpse into the violent inner workings of dying stars and may ultimately help pinpoint just how the solar system came to be. *—John Matson*

BY THE NUMBERS

77 *Percentage* of Republicans who support the Corporate Average Fuel Economy (CAFÉ) standards, requiring an automaker's fleet to average 35 miles per gallon by 2017 and 54.5 mpg by 2025.

87 *Percentage* of Independents who support CAFÉ standards.

92 *Percentage* of Democrats who support the standards.



Still from *A Boy and His Atom*

TECHNOLOGY

Lights, Camera, Atoms

IBM creates the world's tiniest movie

What is the "final frontier"? *Star Trek* fans will tell you it's space. IBM, however, is thinking much smaller.

The company's research division released a stop-motion movie in May whose main character is a stick figure only a few atoms in size. *A Boy and His Atom* is the story, not surprisingly, of a character named Atom who befriends a single atom and proceeds to play with his new friend by dancing, playing catch and bouncing on a trampoline. The performance marks a breakthrough in scientists' ability to capture, position and shape individual atoms with precision using temperature, pressure and vibrations.

"Think of this as Claymation—you shape your Wallace and Gromit, put them in your scene and take a picture of it," says Andreas Heinrich, principal investigator at IBM Research. "Then you change the position of the characters and take another picture." Heinrich and his team arranged and rearranged atoms to create 242 distinct frames, then later stitched them together to make their movie, which Guinness World Records has certified as the tiniest stop-motion film ever made.

Each of the dots used to make the character is actually a molecule of carbon monoxide resting on a copper surface, framed so that the audience can see only the oxygen atoms. The researchers used a two-ton scanning tunneling microscope to magnify the atoms' surfaces more than 100 million times. The microscope features an extremely sharp needle that the scientists used to move the molecules to specific locations. This ability to manipulate individual atoms has big implications for the future of computing and communications. "We're interested in exploring data movement and storage at the atomic scale," the stuff of quantum computing, Heinrich says. Whereas a classic computer uses bits—a 0 or a 1—to store information, a quantum computer lets you—in principle at least—have a 0 and a 1 at the same time in a quantum bit (or a qubit). Quantum computers could calculate faster than computers using classic bits, he says, adding that his laboratory's mission is to determine whether atoms can someday be harnessed for computation and data storage.

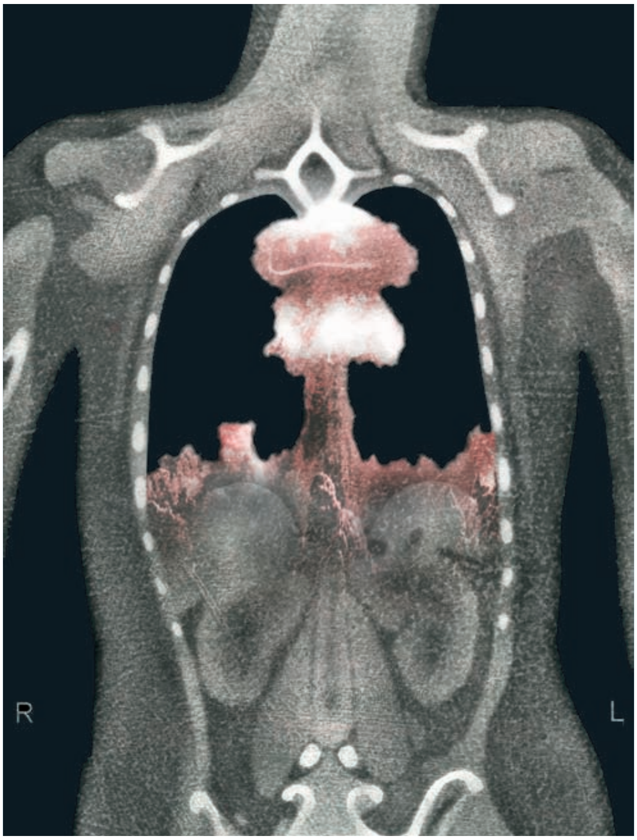
IBM sees the movie as one way of introducing the general public to this type of work. Although the story is told "in the language of science," Heinrich notes, it does not necessarily tell a scientific story: "It tells a human story of a boy dancing with his friend."

—Larry Greenemeier

COURTESY OF IBM

COMMENT AT ScientificAmerican.com/jul2013

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



Do CT Scans Cause Cancer?

Researchers reevaluate the safety of radiation used in medical imaging

Ever since physicians started regularly ordering CT (computed tomography) scans four decades ago, researchers have worried that the medical imaging procedure could increase a patient's risk of developing cancer. CT scanners bombard the human body with x-ray beams, which can damage DNA and create mutations that spur cells to grow into tumors.

Doctors have always assumed, however, that the benefits outweigh the risks. The x-rays, which rotate around the head, chest or another body part, help to create a three-dimensional image that is much more detailed than pictures from a standard x-ray machine. But a single CT scan subjects the human body to between 150 and 1,100 times the radiation of a conventional x-ray, or around a year's worth of exposure to radiation from both natural and artificial sources in the environment.

A handful of studies published in the past decade have rekindled concerns. Researchers at the National Cancer Institute estimate that 29,000 future cancer cases could be attributed to the 72 million CT scans performed in the country in 2007. That increase is equivalent to about 2 percent of the total 1.7 million cancers diagnosed nationwide every year. A 2009 study of medical centers in the San Francisco Bay Area also calculated an elevated risk: one extra case of cancer for every 400 to 2,000 routine chest CT exams.

The reliability of such predictions depends, of course, on how scientists measure the underlying link between radiation and cancer in the first place. In fact, most estimates of the excess cancer risk from CT scans over the past several decades rely largely on a potentially misleading data set: cancer rates among the long-term survivors of the atomic bomb blasts in World War II.

"There are major concerns with taking the atomic bomb survivor data and trying to understand what the risk might be to people exposed to CT scans," says David Richardson, an associate professor of epidemiology at the University of North Carolina Gillings School of Global Public Health who has done research on the atomic bomb survivors.

About 25,000 atomic bomb survivors were exposed to relatively low doses of radiation comparable to between one and three CT scans. The number of cancer cases that developed over the rest of their lives is not, however, large enough to provide the necessary statistical power to reliably predict the cancer risk associated with CT scans in the general population today. Given these difficulties, as well as renewed concerns about radiation levels and the lack of mandatory standards for safe CT exposure (in contrast to such procedures as mammography), a dozen groups of investigators around the world have decided to reevaluate the risk of CT radiation based on more complete evidence.

A growing number of clinicians and medical associations are not waiting for definitive results about health risks and have already begun figuring out how to reduce radiation levels. Two radiologists at Massachusetts General Hospital, for example, think that they can decrease the x-ray dosage of at least one common type of CT scan by 75 percent without significantly reducing image quality. Likewise, a few medical associations are trying to limit superfluous imaging and prevent clinicians from using too much radiation when CT scanning is necessary.

OUTDATED DATA

FOR OBVIOUS ETHICAL REASONS, researchers cannot irradiate people solely to estimate the cancer risk of CT. So scientists turned to data about survivors of the atomic bombs dropped on Hiroshima and Nagasaki in August 1945. Between 150,000 and 200,000 people died during the detonations and in the months following them. Most individuals within one kilometer of the bombings perished from acute radiation poisoning, falling debris or fires that erupted in the immediate aftermath of the attack. Some people within 2.5 kilometers of ground zero lived for years after expo-

Illustration by Shannon Freshwater

sure to varying levels of gamma rays, from a high end of more than three sieverts (Sv)—which can burn skin and cause hair loss—to a low end of five millisieverts (mSv), which is in the middle of the typical range for CT scans today (2 to 10 mSv). A sievert is an international unit for measuring the effects of different kinds of radiation on living tissue: 1 Sv of gamma rays causes the same amount of tissue damage as 1 Sv of x-rays.

Several years after the blasts, researchers began tracking rates of disease and death among more than 120,000 survivors. The results demonstrated, for the first time, that the cancer risk from radiation depends on the dose and that even very small doses can up the odds. Based on such data, a 2006 report from the National Research Council has estimated that exposure to 10 mSv—the approximate dose from a CT scan of the abdomen—increases the lifetime risk of developing any cancer by 0.1 percent. Using the same basic information, the U.S. Food and Drug Administration concluded that 10 mSv increases the risk of a fatal cancer by 0.05 percent. Because these risks are tiny compared with the natural incidence of cancer in the general population, they do not seem alarming. Any one person in the U.S. has a 20 percent chance of dying from cancer. Therefore, a single CT scan increases the average patient's risk of developing a fatal tumor from 20 to 20.05 percent.

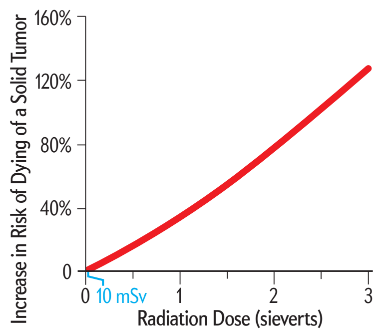
All these estimates share a serious flaw. Among survivors exposed to 100 mSv of radiation or less—including the doses typical for CT scans—the numbers of cancer cases and deaths are so small that it becomes virtually impossible to be certain that they are significantly higher than the rate of cancer in the general population. To compensate, the National Research Council and others based their estimates primarily on data from survivors who were exposed to levels of radiation in the range of 100 mSv to 2 Sv. The fundamental assumption is that cancer risk and radiation dose have a similar relationship in high and low ranges—but that is not necessarily true.

Another complicating factor is that the atomic bombs exposed people's entire body to one large blast of gamma rays, whereas many patients receive multiple CT scans that concentrate several x-rays on one region of their body, making accurate comparisons tricky. Compounding this issue, the atomic bomb survivors typically had much poorer nutrition and less access to medical care compared with today's general U.S. population. Thus, the same level of radiation might correspond to greater illness in an atomic bomb survivor than in an otherwise healthy person from today.

DIALING DOWN THE DOSE

TO CONCLUSIVELY DETERMINE the risk of low radiation doses and set new safety standards for CT radiation, researchers are beginning to abandon the atomic bomb survivor data and directly investigate the number of cancers among people who have received CT scans. About a dozen such studies from different countries examining rates of various cancers following CT scans will be published in the next few years.

ATOMIC BOMB survivors exposed to one sievert or more of radiation clearly had an increased risk of dying from cancer. Among survivors exposed to levels typical for a CT scan—two to 10 millisieverts (mSv)—so few developed cancer that the slightly increased risk is not a statistically reliable indicator of safety.



In the meantime, some researchers have started testing whether good images can be produced with radiation doses lower than those generated in typical CT scans. Sarabjeet Singh, a radiologist at Mass General, and his fellow radiologist Mannudeep Kalra have an unusual way of conducting such investigations. Rather than recruiting living, breathing human volunteers for their studies, they work with cadavers. In that way, they can scan bodies many times without worrying about making people sick and can perform an autopsy to check whether the scan has correctly identified a medical problem.

So far the researchers have discovered that they can diagnose certain abnormal growths in the lungs and perform routine chest exams with about 75 percent less radiation than usual—a strategy Mass General has since adopted. Singh and Kalra are now sharing their methods with radiologists and technologists from hospitals and scanning centers across the U.S. and around the globe.

Medical associations are stepping in to help as well. Because the FDA does not regulate how CT scanners are used or set dose limits, different centers end up using an array of radiation doses—some of which seem unnecessarily high. In the past year the American Association of Physicists in Medicine has rolled out standardized procedures for adult CT exams that should rein in some of these outlier centers, Singh says. Furthermore, an increasing number of CT facilities across the U.S. receive accreditation from the American College of Radiology, which sets limits for radiation doses and evaluates image quality. In 2012 accreditation became mandatory for outpatient clinics that accept Medicare Part B if the facilities want to get reimbursed for scans.

No matter how much clinicians lower the levels of radiation used in individual CT exams, however, a problem remains. Many people still receive unnecessary CT scans and, along with them, unneeded doses of radiation. Bruce Hillman of the University of Virginia and other researchers worry that emergency room physicians in particular order too many CT scans, making quick decisions in high-pressure situations. In a 2004 poll 91 percent of ER doctors did not think a CT scan posed any cancer risk. Doctors and their patients may finally be getting the message. A 2012 analysis of Medicare data suggests that the previously rampant growth in CT procedures is flattening out and possibly waning.

"The jury is still out on whether there is a small cancer risk," says Donald Frush, chief of pediatric radiology at Duke University Medical Center. "But the safest thing is to assume that no amount of radiation is safe. And if we find out in 20 years that a little bit was not harmful, then what did we lose by trying to minimize the dose?" SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/jul2013

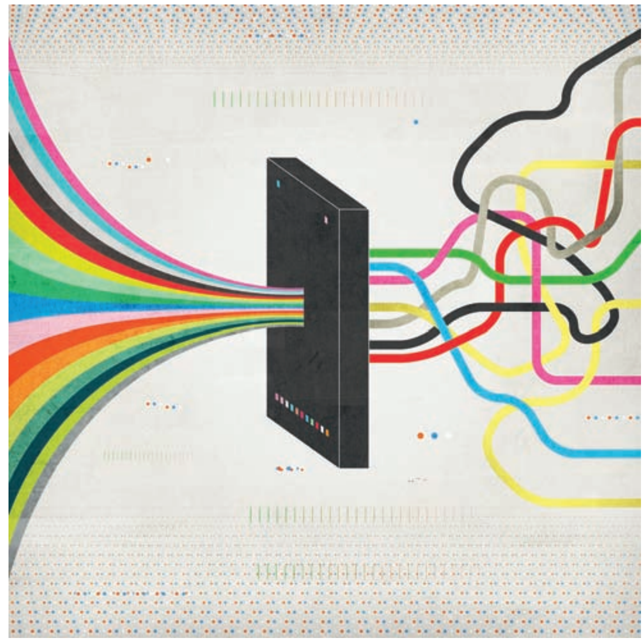
SOURCE: "STUDIES OF THE MORTALITY OF ATOMIC BOMB SURVIVORS, REPORT 14, 1950–2003: AN OVERVIEW OF CANCER AND NONCANCER DISEASES," BY KOTARO OZASA ET AL., IN *RADIATION RESEARCH*, VOL. 177, NO. 3; MARCH 2012

Graphic by Jen Christiansen

David Pogue is the personal-technology columnist for the *New York Times* and an Emmy Award–winning correspondent for *CBS News*.

In Search of a Mind-Reading Machine

How the dream of a perfectly cognizant computer continues to break our heart



The gadget blogs may work themselves into a frenzy over megapixels and processor speed. But if you want to know what really dazzles the masses, consider a feature that's rarely called out by name: machine recognition of real-world sights and sounds.

The success stories in this category represent triumphs of computation and software. Speech transcription on laptops and desktop computers is awesomely accurate. Gestures on touch screens are generally reliable (there are, after all, a limited number of movements to recognize). The Xbox Kinect and some Samsung television sets have brought us body-movement recognition. The handwriting recognition in Windows 7 and 8 is a hidden gem, whether you print or write in cursive.

Phone apps such as Shazam and SoundHound can recognize pop songs playing in the background—and display their titles, performers and album names. Google Goggles, one of Google's apps for Android phones and the iPhone, attempts visual recognition: snap a picture of a book cover, DVD box, wine label or painting, and the program instantly shows you the Google search results for that item.

Software can even pick out faces in a video, and YouTube's copyright-protection algorithms can compare your videos against known copyrighted material to make sure you're not posting a video that originated from some TV network.

That's all fantastic. When they work, sound, image and motion recognition really seem like magic. Unfortunately, the marketers realize that. They tempt us with myriad other computer-based recognition features that work about as well as cold fusion.

For decades now, I've fallen victim repeatedly to what can only be called recognition-failure heartbreak syndrome (RFHS). You buy something, drawn by its promised ability to recognize human commands, and it just doesn't work well enough to bother with.

Remember the Clapper? As a teenager, I bought one. Sometimes your two claps turned the lamp on, and sometimes it took a few attempts. I bought a Whistle Switch, too. It could turn on your appliances by recognizing sound—in this case, a high-pitched, squeezable whistle. Oh, it turned the lights on, all right—but so did teakettles, squeaky hamster wheels and sharp sneezes.

Predictably, I also fell for the Newton; $700 for handwriting recognition that worked maybe two out of five times.

More recently, Samsung has been promising that its Galaxy S4 phone can translate speech into another language, *Star Trek*-style. Hold it up to a French speaker saying, "*Où sont les toilettes?*" and the phone is supposed to say, out loud, "Where is the bathroom?"

In fact, Samsung has just added one not-there-yet recognition technology on top of another. The S Translator app can't even recognize foreign-language speakers' utterances, let alone convert them into spoken English. (I think Samsung knows that, too. If S Translator worked, it would be a headline in the ads, not just a bullet point.)

How many times will we get our hopes up before we start giving up on these features altogether? How many products will we return before manufacturers start to polish these technologies a little more before advertising their "miraculous" abilities?

Look, I sympathize; software-based recognition is no easy task. It's not a crisp problem with one correct outcome, like a spreadsheet adding numbers together. You are asking the software to process fuzzy, vague, variable inputs: sounds, pictures, movements, scrawls. That's why recognition isn't 100 percent. It's not consistent. No wonder it so often disappoints us.

Maybe a few more decades of better sensors, faster processors, bigger data sets and experimentation will finally bring us relief from continuous RFHS.

In the meantime, perhaps both electronics companies and their customers should do a little recognizing of their own: machine recognition of our world is exciting but still evolving. SA

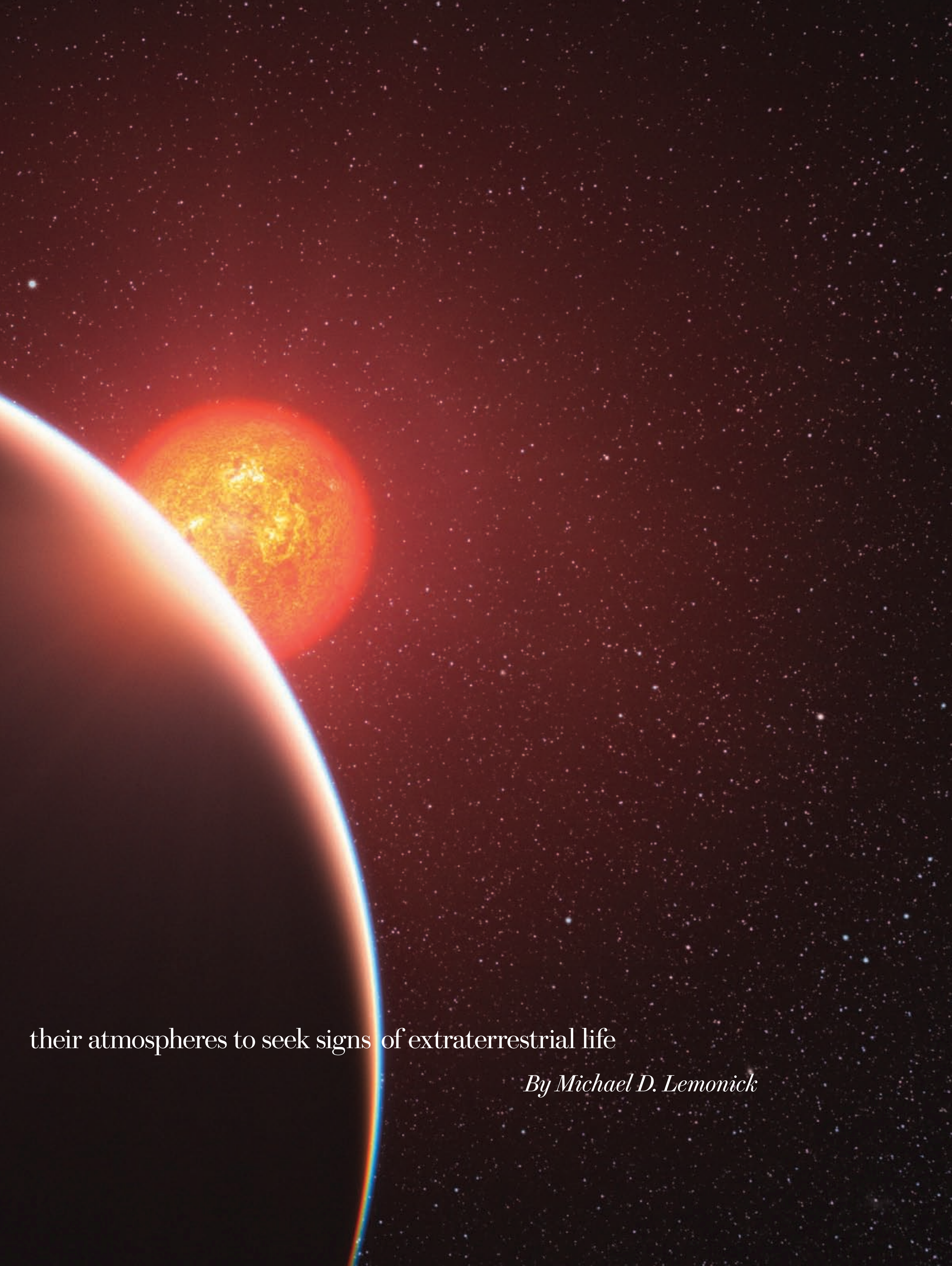
SCIENTIFIC AMERICAN ONLINE
Eight near-magic recognition apps: ScientificAmerican.com/jul2013/pogue

Illustration by John Hersey

ASTRONOMY

The Dawn of Distant Skies

The galaxy is teeming with planets. Scientists are straining to peer into



their atmospheres to seek signs of extraterrestrial life

By Michael D. Lemonick

Nobody who was there at the time, from the most seasoned astrophysicist to the most inexperienced science reporter, is likely to forget a press conference at the American Astronomical Society's winter meeting in San Antonio, Texas, in January 1996.

Michael D. Lemonick is a writer at Climate Central, a nonprofit news site, and author of *Mirror Earth: The Search for Our Planet's Twin* (Walker Books, 2012). For 21 years he was a science writer for *Time* magazine.

It was there that Geoffrey W. Marcy, an observer then at San Francisco State University, announced that he and his observing partner, R. Paul Butler, then at the University of California, Berkeley, had discovered the second and third planets ever found orbiting a sunlike star. The first such planet, 51 Pegasi b, had been announced by Michel Mayor and Didier Queloz of the University of Geneva a few months earlier—but a single detection could have been a fluke or even a mistake. Now Marcy was able to say confidently that it had been neither. "Planets," he told the crowd, "aren't rare after all."

The announcement shook the world of astronomy. Almost nobody had been looking for planets because scientists were convinced they would be too hard to find. Now, after searching a mere handful of stars, astronomers had discovered three worlds, suggesting billions more waiting to be found.

If Butler and Marcy had merely settled a question on planetary formation theory, their discovery would not have been such a big deal. But it showed unequivocally that so-called extrasolar planets did exist and, with them, the possibility of answering a question that had vexed philosophers, scientists and theologians since the time of the ancient Greeks: Are we alone in the universe?

After the initial celebration, scientists settled down to figuring out exactly how they were going to investigate the prospect of even a rudimentary form of life on a planet orbiting an alien sun. Short of picking up an extraterrestrial broadcast, à la Jodie Foster in the movie *Contact,* the only way to find out would be to search extrasolar planets for atmospheric biosignatures—evidence of highly reactive molecules such as oxygen that would quickly disappear unless some kind of metabolizing organisms were replenishing the supply.

Marcy, Mayor and their colleagues had seen only the gravitational effect the planets had on their parent star; to detect a biosignature, you would need to image an exoatmosphere directly. To do this, NASA planned to launch an increasingly powerful series of space telescopes, a program that would culminate in an orbiting telescope called the Terrestrial Planet Finder Interferometer that would cost billions of dollars and fly sometime in the 2020s. In short, astronomers knew that they wouldn't be learning anything about exoplanet atmospheres anytime soon.

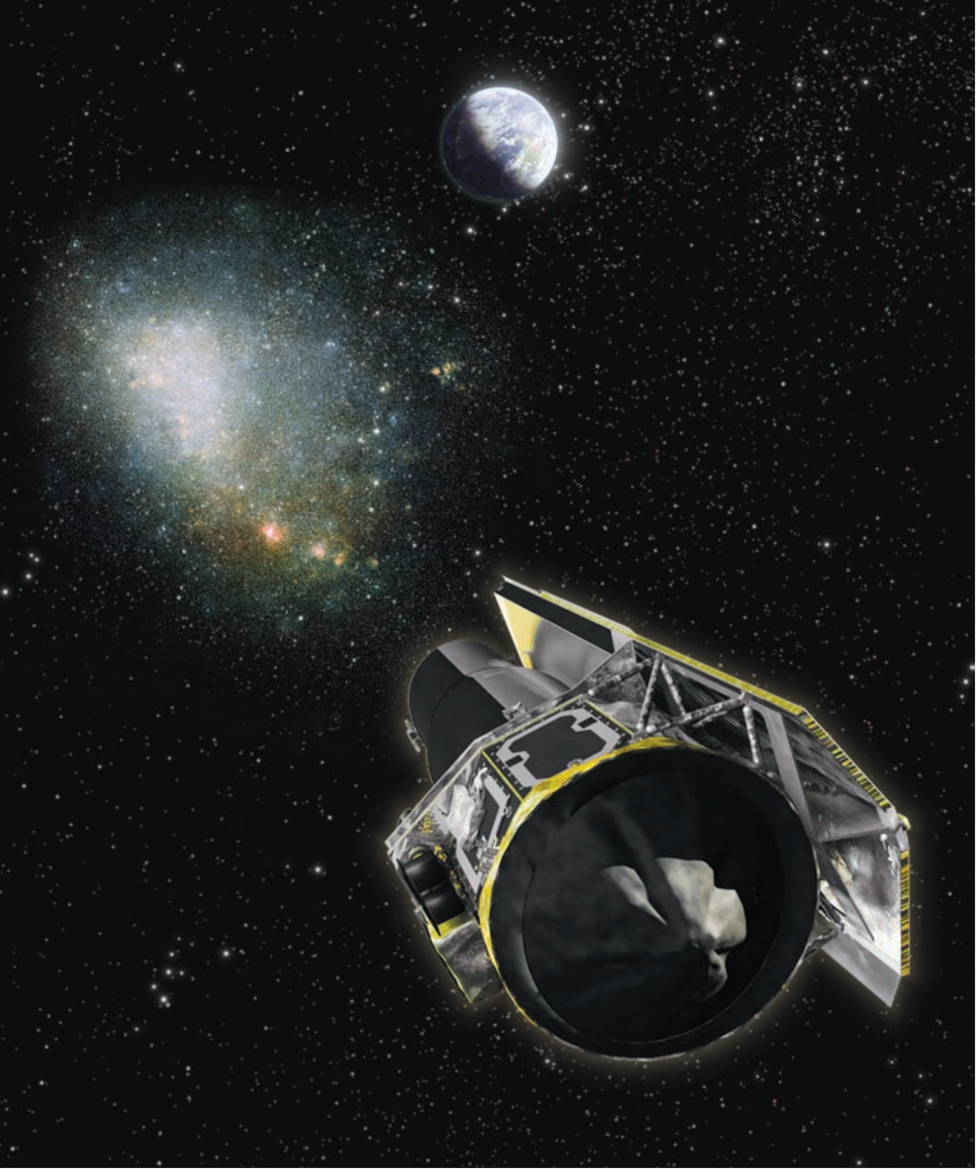
They were wrong. The discovery of those first few exoplanets inspired an entire generation of young scientists to get into what was suddenly the hottest specialty in astrophysics. It convinced many of their older colleagues to switch into exoplanetology as well. This sudden influx of brainpower led to fresh

IN BRIEF

Common wisdom once held that it would be nearly impossible to investigate the atmospheres of distant exoplanets—the glare from their parent star would be too bright.

Yet once scientists began to study exoplanets as they passed behind their star, they realized that the resulting change in stellar brightness could provide clues to what the atmospheres are made of.

Astronomers are now using these advanced techniques to detect atoms and molecules of exoplanetary atmospheres. They hope to soon extend their search to molecules that will provide evidence of distant life.



two planets less than twice Earth's size, both in orbits where temperatures might permit life to survive, was one more hint that life-friendly worlds are almost certainly plentiful. So while these planets, named Kepler 62e and 62f, are too distant to study in detail, astronomers are convinced it won't be many more years before observers can look for biosignatures in the atmospheres of planets that are essentially twins of Earth.

THE PARKING-LOT PLANET

ASTRONOMERS assumed it would take decades to start looking at planetary atmospheres because the first handful of exoplanets were discovered indirectly, through the influence each had on its parent star. The planets themselves were invisible, but because each star and planet orbit a mutual center of gravity, the gravitational tug of the planet makes the star appear to wobble in place. When a star moves toward us, its light subtly shifts toward the blue end of the visible-light spectrum; when it moves away, the light shifts to the red. The degree of shifting tells observers the star's radial velocity, or how fast it moves toward and away from Earth, which in turn tells us how massive the exoplanet is.

Another option for finding planets was also available, however. If the invisible planet's orbit were perfectly edge-on as seen from Earth, the planet would pass directly in front of its star, in what is known as a transit. Yet at the time of those first discoveries nearly two decades ago, few astrophysicists were thinking about transits at all, simply because the search for planets was itself so far out on the fringe. (A notable exception was William J. Borucki of the NASA Ames Research Center, whose Kepler spacecraft would eventually find transiting objects by the thousands.)

A few years later, in 1999, Timothy W. Brown, then at the National Center for Atmospheric Research, and David Charbonneau, at the time a graduate student at Harvard University, set up a tiny, amateur-size telescope in a parking lot in Boulder, Colo., and saw an exoplanet transit for the first time. The planet was HD 209458b, which had been detected earlier by the radial-velocity technique. Weeks later Gregory W. Henry of Tennessee State University, working with Marcy, watched the same planet transiting its star. Both teams have been given equal credit for the discovery because the two detections were published simultaneously.

The successful detection of transits not only gave astronomers a second way to find exoplanets, it also gave them a way to mea-

SOLAR ECLIPSE: **The Spitzer Space Telescope can detect the minute change in brightness that happens when a planet passes behind its host star.**

COURTESY OF CALTECH AND NASA

ideas for investigating exoplanet atmospheres and sped things up dramatically. By 2001 observers had identified sodium in the atmosphere of one exoplanet. Since then, they have identified methane, carbon dioxide, carbon monoxide and water as well. They have even found indirect hints, by examining exoplanet atmospheres, that some planets may be partly made of pure diamond. "At this point," says Heather Knutson, a California Institute of Technology astrophysicist who was involved in many of these pioneering observations, "we've learned something about the atmospheres on the order of 30 to 50 planets—if you count stuff that's not yet published."

These discoveries are still a long way from providing evidence of life—no surprise, since most of the worlds Knutson is talking about are hot, Jupiter-like planets that hug their star more tightly than fiery Mercury orbits the sun. Increasingly, however, Knutson and other observers have begun to probe the atmospheres of smaller planets, so-called super-Earths, which are between two and 10 times as massive as our home planet—something that nobody could have imagined just a decade ago. The announcement in April that the Kepler space telescope had found sure their density. The radial-velocity technique had revealed HD 209458b's mass. Now astronomers knew how physically large it was because the amount of starlight a planet blocks is directly proportional to its size. (Dividing its mass by its size showed HD 209458b to be 38 percent larger than Jupiter even though it is only 71 percent as massive, an unexpected result that Princeton University astrophysicist Adam Burrows calls "an ongoing problem to explain.")

By this time a number of astrophysicists had realized that transits also made it possible to study an exoplanet's atmosphere, in what Knutson calls a "wonderfully clever shortcut." Even before the first transit was reported, in fact, Sara Seager, an astrophysicist at the Massachusetts Institute of Technology, who at the time was Charbonneau's fellow grad student at Harvard, had co-authored a paper with her adviser, Dimitar D. Sasselov, in which they predicted what an observer should see as light from a star passed through a planet's atmosphere when the planet moved across the star's face [see "Planets We Could Call Home," by Dimitar D. Sasselov and Diana Valencia; Scientific American, August 2010]. Physicists have long known that different atoms and molecules absorb light at different wavelengths. If you look at planets in a wavelength that corresponds to the molecule you are searching for, any atmospheres containing that molecule will absorb the light. The wispy planetary atmosphere will become opaque, making the planet appear larger.

Seager and Sasselov suggested that sodium would be especially easy to detect. "Sodium is like skunk scent," Charbonneau says. "A little bit goes a long way." He knows this better than anyone: in 2001 Charbonneau, Brown and their colleagues went back to HD 209458b, their original transiting planet, not with a puny amateur telescope but with the Hubble Space Telescope. Sure enough, the sodium signal was there, just as predicted.

TOTAL ECLIPSE

Astronomers also realized that there was a second, complementary way to inspect the atmospheres of transiting planets. When a planet passes in front of its star, it presents its nightside to the observer. At other times, it shows at least part of its dayside, and just before the planet goes behind the star, the dayside is facing Earth. Although the star is far, far brighter, the planet itself also glows, mostly in the infrared.

That glow vanishes abruptly, however, when the planet moves behind the star; its contribution to the combined light of planet and star vanishes. If astrophysicists can do a before-and-after comparison, they can deduce what the planet alone would look like [*see box on opposite page*]. "It changes the nature of the problem," Knutson says. "Instead of having to detect a very faint thing close to a very bright thing, all you have to do is measure signals that change with time." As early as 2001, L. Drake Deming, then at the NASA Goddard Space Flight Center, aimed an infrared telescope on Hawaii's Mauna Kea at HD 209458b in an attempt to see this so-called secondary eclipse, but, he says, he couldn't make a detection.

He knew, however, that the Spitzer Space Telescope, scheduled for launch in 2003, would almost certainly be able to make such an observation, as did Charbonneau. Both astrophysicists, unbeknownst to each other, applied for time on Spitzer to make the observations. Both got the time and took their data. Then, one day in early 2005, Deming recalls, he got a voice message: "Drake, this is Dave Charbonneau of Harvard," the voice said. "I hear you made some interesting observations lately. Maybe we should talk."

It turned out that Deming (working with Seager) and Charbonneau had independently made the first secondary-eclipse detections in history, at virtually the same time, using the same observatory. The two groups announced their results for two different stars—the much-worked-over HD 209458b in Deming's case and a planet named TrES-1 in Charbonneau's—simultaneously. A year later Deming's team detected the secondary eclipse of a planet called HD 189733b. "This," wrote Seager and Deming in a 2010 review article, "unleashed a flood of secondary eclipse observational detections using *Spitzer*.... It is accurate to say that no one anticipated the full magnitude and stunning impact of the *Spitzer Space Telescope* as a tool to develop the field of exoplanet atmospheric studies." In fact, Seager says, "we're using the Hubble and the Spitzer in ways they were never designed to be used, going to decimal places they were never designed to reach."

ATMOSPHERIC LAYERS

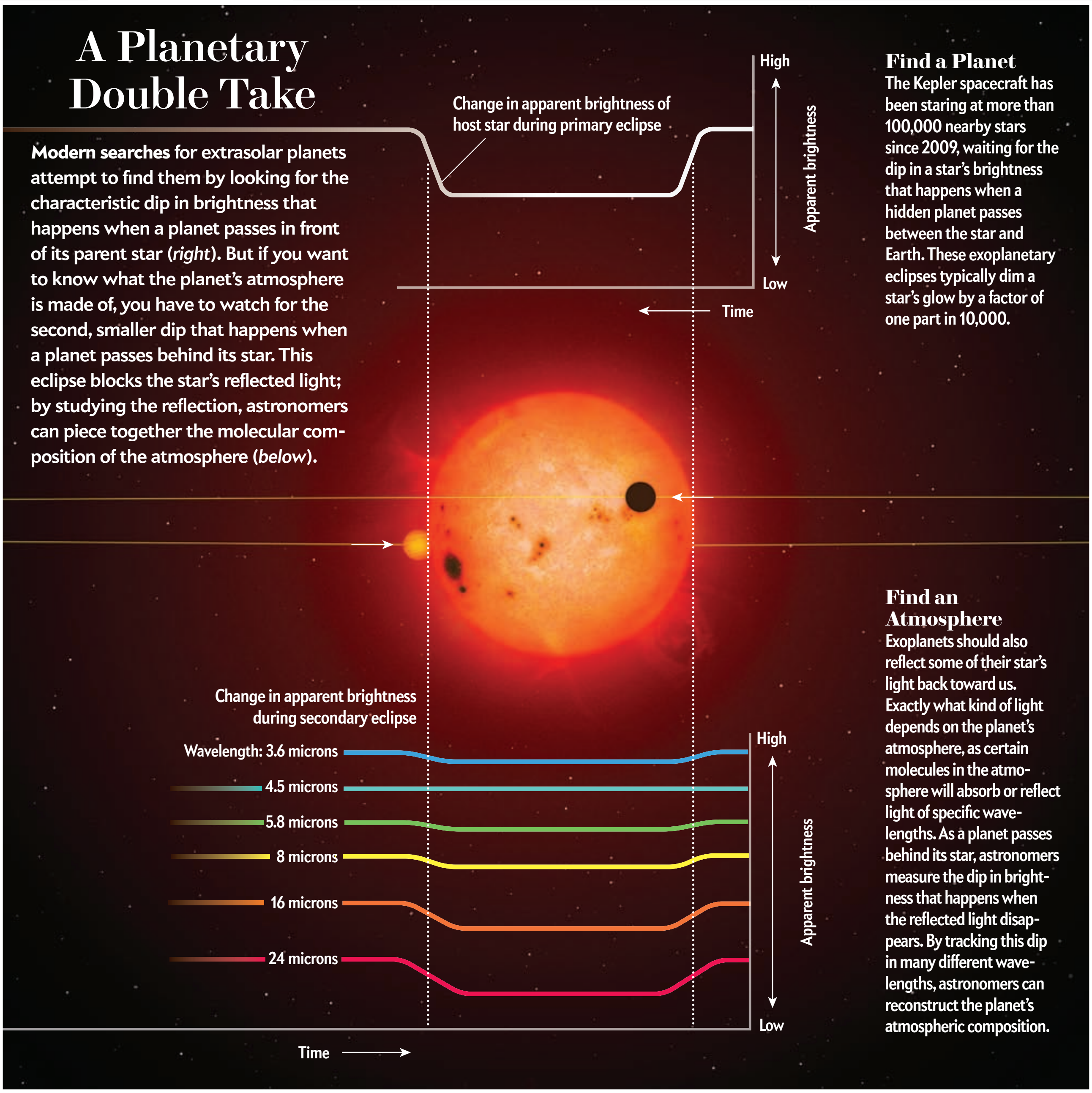
Those studies have shown a couple of things, Seager says. "This sounds trite in a way, but we've learned that hot Jupiters are hot. We've measured their brightness and temperatures," and what scientists have observed is consistent with how they expect stars to heat their planets. "Number two," she continues, "we've detected molecules. Now has [what we've found] been very different from what we expected? You know, not really." Seager notes that physicists can straightforwardly model a ball of gas at some temperature made of some combination of elements and ask what kind of molecules form. "The laws of physics and chemistry are universal," she says.

Seager and other astrophysicists have also learned, however, that despite the overall similarity of exoplanet atmospheres, individual planets can differ in several ways. One has to do with how temperature changes with altitude. Some planets, such as Jupiter and Saturn in our own solar system, show temperature inversions, in which temperature rises with altitude rather than falling. Others do not. "The problem," Knutson says, "is that we don't know what's causing the inversion, and we can't predict, therefore, which exoplanets will and won't have this feature." Some astrophysicists suggest that exoplanets with inversions might have some kind of heat-absorbing molecule, such as titanium oxide, but so far this is just a hypothesis.

Another question is whether certain planetary atmospheres are made from a different mix of molecules than others. Nikku Madhusudhan, now at Yale University, analyzed the visible and infrared signature of a planet named WASP-12b and deduced that its atmosphere is unusually rich in carbon, with about as much of that element as oxygen.

Theory suggests that a carbon-to-oxygen ratio of more than 0.8, if mirrored in other, smaller planets in the same system (as it presumably would be, given that planets in a solar system are thought to condense from a single disk of gas and dust), would lead to "rocks" made of carbides—carbon-rich minerals—rather than the silicon-rich silicate rocks found in our solar system. If that were true, an Earth-size planet in the WASP-12 system could have continents made of diamond.

Seager and others have written theoretical papers suggest-



SOURCE: NASA/JPL-CALTECH/K. STEVENSON *University of Central Florida (secondary eclipse brightness data)*

ing that there is nothing to rule out planets made largely of carbon or even of iron. In the case of WASP-12, however, it may not be correct. Knutson says that Ian Crossfield of the Max Planck Institute for Astronomy in Heidelberg, Germany, recently found that the light from WASP-12 is contaminated with light from a fainter double star in the background. "His data perhaps seem to cast some doubt on the interpretation for this particular planet," Knutson says.

WATER WORLD

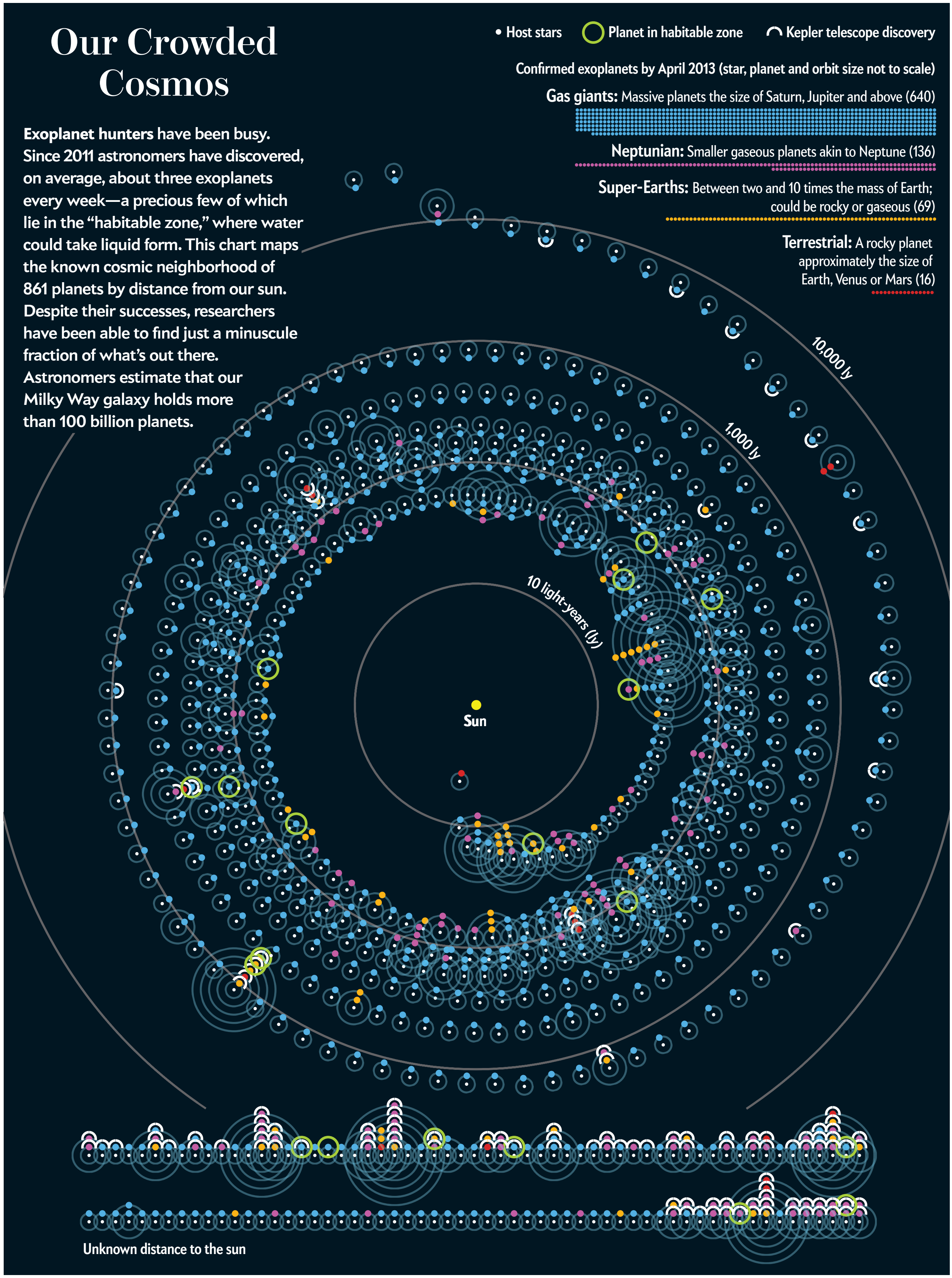
BY FAR THE MOST INTENSE FOCUS of observations has been concentrated on a planet known GJ 1214b, which orbits a small, reddish "M-dwarf" star lying about 40 light-years from Earth. Its proximity makes GJ 1214b relatively easy to study, and its size, just 2.7 times the width of Earth, makes it far closer to being Earth-like than the hot Jupiters found in the first years of planet hunting. "It is everybody's favorite super-Earth," says Laura Kreidberg, a grad student at the University of Chicago who is leading the data analysis on one such observing project.

GJ 1214b was found in 2009 during the so-called MEarth Project organized by Charbonneau to look for planets around M dwarfs. The idea was that small transiting planets would be easier to find around these small, dim stars than around bigger ones, for several reasons. First, an Earth-size planet would block a relatively greater percentage of the small star's light. Such a planet would also exert a relatively greater gravitational pull on

Illustration by Mark A. Garlick

Our Crowded Cosmos

Exoplanet hunters have been busy. Since 2011 astronomers have discovered, on average, about three exoplanets every week—a precious few of which lie in the "habitable zone," where water could take liquid form. This chart maps the known cosmic neighborhood of 861 planets by distance from our sun. Despite their successes, researchers have been able to find just a minuscule fraction of what's out there. Astronomers estimate that our Milky Way galaxy holds more than 100 billion planets.



SOURCE: DATA FROM NASA EXOPLANET ARCHIVE http://exoplanetarchive.ipac.caltech.edu

Graphic by Jan Willem Tulp

the star, making it easier to gauge the planet's mass and thus its density. The habitable zone for a small, cool star would also be much closer in than it is for a hot, sunlike star, which makes transits more likely to be spotted (because the orbit of a close-in planet does not have to be so precisely aligned for it to pass in front of the star). Finally, there are vastly more M dwarfs in the Milky Way than there are sunlike stars—about 250 of the former lie within 30 or so light-years of Earth, compared with only 20 of the latter.

GJ 1214b is not quite a second Earth: it is 2.7 times wider and six and a half times as massive as Earth, which gives it an overall density in between that of Earth and Neptune. Unfortunately, as Charbonneau and others realized immediately after the planet was discovered, this density can come about in several different ways. GJ 1214b could, for example, have a small, rocky core surrounded by a huge atmosphere of mostly hydrogen. It could also have a bigger core surrounded by a deep ocean of water, with a thin, water-rich atmosphere on top. It is impossible, given the density alone, to distinguish between those two possibilities—although the possibility of an ocean world is naturally more exciting, given that liquid water is considered a prerequisite for, if not a guarantee of, life as we know it.

Yet when University of Chicago astronomer Jacob Bean observed the planet in various wavelengths, hoping to see a change in its apparent size that would indicate just how thick the atmosphere is, he saw nothing. This could mean one of two things. The planet could have a puffy hydrogen atmosphere but one full of clouds and haze that would make it hard to detect. Or it could have a thin, watery atmosphere but one too thin to delineate with ground-based telescopes. The situation could be analogous to looking at a mountain range from a distance, says Kreidberg, who began working with Bean last year. "There may be peaks," she explains, "but if you're too far away, they might look like a flat line."

To try to resolve the issue, Bean and his colleagues have been awarded 60 orbits of the Hubble; they have already begun to make their observations. It is not the first time astronomers have observed GJ 1214b with the Hubble, but it is by far the most intensive program, and it will take advantage of the new, powerful Wide Field Camera 3, installed during the telescope's final servicing mission in May 2009. With any luck, this observing campaign will finally settle the question of whether GJ 1214b is a water world or not.

THE HUNT FOR OXYGEN

NOW THAT ASTRONOMERS have been in the planet-hunting business for some time, they have begun to find many more planets with long orbital periods. These planets are farther away from their stars and thus cooler than the early population of hot Jupiters. "For a long time we were limited to things that were 1,500 kelvins, 2,000 kelvins, so really quite hot," says Caltech's Knutson. In these conditions, "most of the carbon in the atmosphere gets bound up with oxygen, forming carbon monoxide," she says. "The really interesting thing that happens as you drop below around 1,000 kelvins is that it switches to being incorporated into methane instead."

Methane is especially intriguing because it could be a sign of biological activity—though an ambiguous one, since methane can be produced through purely geophysical processes. Oxygen—and especially ozone, a highly reactive molecule made from three oxygen atoms—would be far more likely to signal the presence of life. It would also be extremely difficult to detect because its spectral signature is subtle, especially so in the relatively small atmosphere of an Earth-size planet.

Astronomers are convinced it won't be many more years before observers can look for biosignatures in the atmospheres of planets that are essentially twins of Earth.

Yet for all the activity around medium-hot super-Earths, astronomers are still focused on the grand prize. "All of this is really just an exercise," Seager says. "I mean, it's interesting in and of itself, but for people like me, it's just a stepping-stone to when we finally get from super-Earths to studying the atmospheres of Earths."

That likely won't happen before the James Webb Space Telescope is launched into orbit, probably in 2018, and a new generation of huge, ground-based instruments, including the Giant Magellan Telescope and the Thirty Meter Telescope, come online by about 2020. Even with those powerful instruments, Seager says, "it's going to take hundreds and hundreds of hours" of observing time. It is not clear even then that it will be possible to detect the signature of life unambiguously; for that, observers might still need the Terrestrial Planet Finder, whose funding has been reduced so drastically that any hope of an actual launch date is pure guesswork at this point.

Yet it is remarkable that, so far ahead of any schedule anyone dreamed of in the 1990s, Seager can even talk about the realistic prospect of finding biosignatures. We are no longer merely hoping that an alien civilization will spot us and point a message our way. We are actively exploring the air above distant worlds, searching their skies for signs that something is home. SA

MORE TO EXPLORE

Planets We Could Call Home. Dimitar D. Sasselov and Diana Valencia in *Scientific American,* Vol. 303, No. 2, pages 38–45; August 2010.

Exoplanet Atmospheres. Sara Seager and Drake Deming in *Annual Review of Astronomy and Astrophysics,* Vol. 48, pages 631–672; September 2010.

The Kepler exoplanet-detection mission: **http://kepler.nasa.gov**

SCIENTIFIC AMERICAN ONLINE
What kinds of exoplanets have we found? Visit **ScientificAmerican.com/jul2013/exoplanets**

SCHOOLS FOR THE BLIND in India have helped find children eligible for vision-correcting surgery.

MEDICINE

ONCE BLIND AND NOW THEY SEE

SURGERY IN BLIND CHILDREN FROM INDIA ALLOWS THEM TO SEE FOR THE FIRST TIME AND REVEALS HOW VISION WORKS IN THE BRAIN

By Pawan Sinha

Pawan Sinha, a professor of vision and computational neuroscience at the Massachusetts Institute of Technology, studies the mechanisms and principles by which the brain recognizes objects and scenes.

MY MOTHER USED TO KEEP A SMALL BLUE GLASS BOWL OF CHANGE NEAR the door of our house in New Delhi. When she went out, she would take a few coins as alms for the poor that one inevitably sees on the city's streets. Given how quickly you can become desensitized to the abundance of human misery in India, I was always impressed by her unwavering adherence to this ritual.

The bowl lay unused for several months as my mother battled cancer. When I went back to India in 2002, a year after her death, I noticed that it was one of the few items of hers that my father had saved. Little did I realize that it was going to change my life.

One wintry afternoon during my visit, while stepping out of the house to visit a friend, I reached in the bowl for a few coins and put them into my pocket. It was bitterly cold, and I was glad to find a cab with windows that closed all the way, never a certainty in New Delhi. After a few minutes, the cab stopped at an intersection. Traffic was surprisingly light, and I noticed a small family huddled by the side of the road. I pulled out the coins, rolled down the window and beckoned to them.

They slowly made their way to me, with the two children holding on to the woman's sari. It was gut-wrenching to see the emaciated barefoot children dressed in thin cotton rags. Compounding my discomfort, I noticed that the children, who must have been six or seven years of age, were also blind. As the small family stood shivering outside my cab, I could see the cataracts in the children's eyes. This surprised me because I had only ever seen cataracts in older people. The traffic light turned green. I put the coins in the mother's hand and watched the family disappear as the cab pulled away. For the next several days, the children's faces haunted me. I tried to learn as much as I could about childhood blindness in India. What I read was shocking.

India is home to one of the world's largest populations of blind children, estimated at nearly 400,000. The visual handicap, coupled with extreme poverty, greatly compromises the children's quality of life; moreover, mortality rates are frighteningly high. The World Health Organization estimates that up to 60 percent of children die within one year of going blind. Less than 10 percent of these children receive any education. For blind girls, the outlook is even more dire. Many are confined to home and suffer physical or sexual abuse.

Distressing as these numbers are, they became even more disturbing to me as I read that much of the suffering was needless; blindness in nearly 40 percent of the children was treatable or preventable. Many youngsters, however, never receive medical care because the treatment facilities are concentrated in major cities, and nearly 70 percent of India's population lives in villages. These circumstances mean that a blind child in a financially strapped rural family is likely destined to live a dark and tragically short life.

I took in these numbers with a sense of incredulousness. After all, I had grown up in India. How could I have remained unaware of this problem? And how could such things run so counter to the popular narrative of India as a rising economic superpower? I decided to make another trip to India. I visited villages around Delhi, in the southern state of Andhra Pradesh

IN BRIEF

India is home to one of the world's largest populations of blind children, estimated at nearly 400,000. Many of these children receive no education, and girls are often victims of physical and sexual abuse.

As a neuroscientist, the author decided to try to help cataract-stricken children and young adults gain the ability to see the world far beyond the age at which developing vision was deemed to be possible.

Surgery often proved a success, even for some of those well into their 20s. The procedure also provided the scientists on the author's team with a new understanding of the functioning of the visual system.

PRECEDING PAGES: EILEEN HOHMUTH-LEMONICK

Putting Together a New Visual World

When children and young adults of Project Prakash see the world for the first time, they have difficulty assembling parts of a scene into an integral whole. A photograph of girls dancing demonstrates the problems involved. Fragments of color, brightness and texture need to be organized by the visual system into coherent objects. The middle illustration depicts the location of these diverse elements. Success comes when a collection of static objects, with defined borders (*right*), starts to move. The brain integrates rhythmic steps and upthrown arms into the perception of a single, integral entity, the shape of the dancers' bodies.

COURTESY OF PROJECT PRAKASH

and in the delta of the Ganges in West Bengal. The many blind children I met convinced me that the statistics were based in fact. And the desperate poverty I saw in these villages helped me understand why so many of them remained untreated.

My experience on that winter afternoon in New Delhi marked the beginnings of a personal journey that has yet to end. I resolved to help these blind children gain sight. And as a scientist, I realized that doing so presented a valuable opportunity to answer one of the most challenging questions in neuroscience: How does the brain learn to see?

AN ANSWER IN A QUESTION

SINCE MY DAYS IN GRADUATE SCHOOL at the Massachusetts Institute of Technology, this question had both fascinated and frustrated me. How does the confusing mess of colors, brightness and textures that impinges on our retina every waking moment organize itself into a meaningful collection of objects that transforms into, say, the outlines of the arms and torso of a dancing girl—and the crisscrossing blue and green on her plaid skirt?

The main approach for studying how the visual system develops involves experimenting with infants. Although it has yielded valuable results, it also has significant shortcomings. These experiments are difficult to perform. An infant's limited ability to comprehend and respond and even to stay awake for long periods strongly limits the scope of questions that can feasibly be asked. Another complicating factor is the simultaneous changes that can occur in related but distinct brain subsystems as the child grows—such as regions responsible for motivation, focusing attention and controlling eye movements.

Knowing all of this, in the summer of 2002 I found myself grappling with two seemingly unrelated questions. How does the brain learn to make sense of visual information? And, with memories of my experience in New Delhi still fresh, how could I help provide sight-restoring surgeries to congenitally blind children?

I still remember the thrill of realizing that the two questions were complementary—one held the answer to the other. Following the progress of a newly sighted child could help us understand visual learning, and scientific funding applied to such a research undertaking could help provide treatments. I marveled at how well the two needs fit together and, somewhat self-centeredly, how relevant they both were to my life.

On returning to M.I.T., I described to my colleagues a plan to pursue research that combined these scientific and humanitarian objectives. Most were enthusiastic, but a few cautioned against embarking on such an ambitious undertaking prior to receiving tenure. I understood the risk, but I felt compelled to move ahead with the plan.

I submitted an application to the National Eye Institute (part of the National Institutes of Health). I was a little concerned that asking a U.S. government agency for money to fund surgeries in India might be a nonstarter. Also, the endeavor was logistically complex and lacked pilot data about its practicality. But the review committee saw the scientific and humanitarian potential of the work and awarded me an exploratory grant to establish feasibility. I was thrilled. This was my first NIH grant, and it reinforced in me the image of American science as a force for global good that does not shy away from encouraging risky undertakings unbound by parochial considerations.

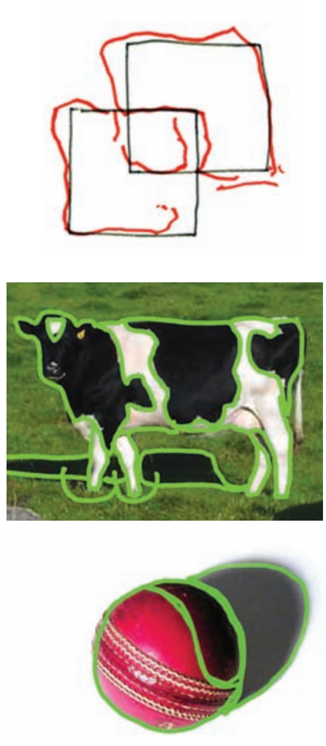
The next step was to identify a medical partner in India where blind children could receive world-class surgical care. One ophthalmic center stood out: Dr. Shroff's Charity Eye Hospital (SCEH) in New Delhi. It had outstanding pediatric facilities, and its physicians welcomed the project as an opportunity to help blind children and to engage in research.

All the pieces were in place. Still, we needed a name, one that would reflect our dual mission of bringing light into people's lives and casting light on scientific questions. I did not have to think too long. The word for light in the ancient Indo-European language Sanskrit is *prakash*. We now had a name with an appealing touch of alliteration: Project Prakash.

FIRST SIGHT

Only the Parts, Not a Whole

A newly sighted child's tracings reveal a piecemeal view of even two-dimensional figures. Each area of overlapping boxes was perceived separately, as indicated by red squiggles. The boy also saw segments of a cow and of a ball and its shadow—all delineated in green—to be distinct objects. Consequently, he was unable to identify any of these images.



COURTESY OF PROJECT PRAKASH

WOULD SURGERY HELP?

WE UNDERTOOK the project in several stages. First, we identified children—and, in some cases, even young adults—who could benefit from treatment by setting up ophthalmic screening at camps in rural areas. A team of optometrists, ophthalmologists and other health care workers examined children for vision problems (refractive errors), eye infections and treatable blindness (primarily from congenital cataracts and damage to the cornea resulting from scarring). Children chosen as candidates for treatment went to the hospital in New Delhi for a more thorough examination, including ophthalmoscopy (to see to the back of the eye), ultrasound of the eyes, and assessment of the child's general health and fitness for surgery. Dates for surgery were then set after consultation with each child's guardian.

Cataract surgery for a child is much more complicated than for an adult. Pediatric surgery requires general anesthesia and intensive follow-up care. The surgical procedure involves breaking up the hardened opaque lens into little pieces, excising these fragments via a small incision at the edge of the cornea and replacing the damaged natural lens with a synthetic one. Project Prakash bears the roughly $300 cost—and children return for periodic postoperative checkups.

As this work got under way, one worry nagged me. I wondered whether our surgical intervention, though well intentioned, was coming too late to be of any help. Were we perhaps past a critical period early in life that requires intensive use of the eyes and visual brain circuits, an interval past which visual capacity is incapable of developing? The idea was not implausible. An English surgeon, William Cheselden, gave the first account of delayed sight onset in 1728 in a 13-year-old boy born with cataracts in both eyes. Cheselden noticed that the boy had severely impaired vision even after the removal of the occlusions.

Controlled studies of visual deprivation in animals painted a similarly dismal picture. Torsten Wiesel and David Hubel, both of whom went on to win the Nobel Prize in 1981, had described the dramatic adverse consequences of early visual deprivation in cats. In this context, it was natural to wonder whether providing eye surgeries late in childhood would serve any useful purpose.

I felt, though, that the treatments were worth undertaking. It was risky to read too much into the old accounts such as Cheselden's. The poor surgical outcomes could well have resulted from tissue damage to the eyes, a result of crude surgical techniques, such as couching, an antiquated method for cataract removal. And most of the animal studies had looked at the suturing shut of one eye, whereas the Prakash children had suffered occlusion in both eyes. Somewhat surprisingly, depriving vision in one eye has more adverse consequences for sight in that eye than if both eyes were to be deprived together. Whether any visual function could be acquired after treatment for blindness late in childhood was still a largely open question.

NOW WE SEE

THE GREAT AMERICAN psychologist William James described an infant's perceptual world as "a blooming, buzzing confusion" that precedes the maturation of the visual system. The question for Project Prakash was whether this period—a complex bombardment of color, shape and movement that is perhaps an early stage of normal visual development—mirrors the experiences of newly sighted Prakash children, some of whom are in their 20s when they first gain sight. Does their visual system ever undergo the anarchic but necessary first steps to organize the incoming images in any meaningful fashion? The term "organization" has two meanings here. For a person to "see," the various pieces of an image must cohere into distinct objects, a process termed *intra*modal organization. The second requirement, *inter*modal organization, has to do with the interaction of vision with other senses.

Our ability to partition an image into separate objects is so well honed that it seems effortless. We open our eyes, and the world falls into place, an orderly collection of things. Yet we have found that the experience of a Prakash child soon after gaining sight is different. The newly sighted exhibit profound impairments. They are unable to organize the many regions of different colors and brightness into larger assemblies. Many features of ordinary objects—the overlapping sections of two squares or a section of a ball delineated by the lacing on its surface—are perceived as entirely separate objects, not component parts of larger structures. It is as if the visual scene for a newly sighted person is a collage of many unrelated areas of color and luminance, akin to an abstract painting. This perceptual overfragmentation makes it difficult to detect whole objects.

The Prakash patients' failure raises a question that has preoccupied scientists for nearly a century: What cues allow us, as individuals with normal vision, to parse complex images correctly? The answer seems to lie in the way that the brain naturally arranges visual inputs by what are known as grouping heuristics (referred to as Gestalt cues of grouping, after the psychological research movement in the early 20th century). For instance, a basic rule programmed into the visual system induces aligned lines in an image to be grouped together because they most likely arise from boundaries of the same object.

Project Prakash is helping to lay out the landscape of what can and cannot be accomplished when a child gains vision at a late age.

None of these cues appears effective for the Prakash children immediately after gaining sight, but interesting changes occur over time. I vividly remember SK, the very first Prakash patient to give us this hint. He was a 29-year-old man we met in a cramped hostel for blind youth on the outskirts of New Delhi. A quick examination revealed that he had congenital aphakia (from *phakos,* Greek for "lens/lentil"), a rare condition in which a child is born without lenses in the eyes. The visual world for SK was highly degraded, far worse than what defines legal blindness in the U.S. He had adapted by walking with a white cane and conducting his studies in braille. Remarkably, all that was needed to correct his aphakia was a $20 pair of glasses that could compensate for his missing natural lenses, which SK could not afford.

We had glasses made for SK and then tested his vision. What struck us right away was that contrary to our naive expectations, SK did not appear particularly thrilled about his improved vision. His visual world, our tests revealed, was a bewildering collection of many regions of different colors and brightnesses, with little to glue them together into coherent entities. Even simple line drawings, such as a circle overlapping a square, appeared to him to be a set of strangely shaped interlocking pieces (despite his prior familiarity with the concepts of squares and circles through touch). SK had a hard time delineating whole objects in photographic images. Shading and shadows, overlaps and occlusions posed insurmountable hurdles for him; every region of a different hue or luminance seemed to him to be a distinct object.

Interestingly, this confusing soup of regions gelled into meaningful structure with the introduction of one particular visual cue: motion. Images that were hopelessly confusing for SK when static became interpretable when their constituent parts moved. Videos of SK inspecting an image show an almost magical transformation brought about in response to motion.

We followed SK's experiences with vision for several months. He continued exhibiting difficulties in interpreting static images. Just as we had begun to resign ourselves to the idea that SK's image-parsing abilities might be permanently compromised, things changed. A year and a half after the initial intervention, without any training other than his exposure to the visual world around him, SK made marked improvements. He was now able to correctly parse static images and even expressed the happiness he felt about his improved vision. It was a tremendously gratifying conclusion to a chapter that had held us in great suspense.

In subsequent studies with others much younger than SK, we found a recapitulation of his experience. Many months after encountering difficulties on the image-parsing task, they begin to succeed in organizing their perceptions into coherent objects. The time needed to acquire this skill appears to depend on the age at which the child received treatment, with younger children learning more rapidly than older ones.

What underlies this improvement? Theory suggests that motion may play the part of a "teacher," training the visual system to parse images even when they are static. With the rule "things that move together belong together," a person's visual system can eventually learn to group images via static attributes such as color and orientation.

The brain, of course, does more than pick out the elements of a visual scene. It also connects to the realms of sound, touch, smell and taste—creating a sensory panorama via intermodal organization. How sight is linked to sound and other senses has preoccupied philosophers and neuroscientists for centuries. In 1688 Irish scientist William Molyneux wrote to British philosopher John Locke: "Suppose a man born blind, and now adult, and taught by his touch to distinguish between a cube and a sphere of the same metal.... Suppose then the cube and sphere placed on a table, and the blind man be made to see: query, whether by his sight, before he touched them he could now distinguish and tell which is the globe, which the cube?"

Locke included Molyneux's question in the 1692 edition of his famous monograph entitled *An Essay on Human Understanding.* Molyneux's query crystallized a series of fundamentally important questions: How do we link the different senses into a unified perception of reality? Are we born with this mental mapping of the world, or does it need to be learned through experience? Can it be acquired late in life? The pursuit of these ideas by Locke, George Berkeley, David Hume and other empiricists now bears on many of the issues vital to contemporary neuroscience.

In assessing whether the Prakash children can come to associate vision with the other senses, we have had an opportunity to directly address the Molyneux question. We work with children right after their sight surgeries and have them participate in a "match-to-sample" experiment. The child sees or touches a simple object on a blank background (the sample) and subsequently has to choose it from a pair of two different objects presented visually or by touch.

The case of YS, an engaging eight-year-old boy, with dense congenital cataracts in both eyes, provides an illustrative example. Like most Prakash children, YS was feeling comfortable by the second day after surgery and ready to work with the research team.

SCREENING CAMPS: Outreach sessions in schools and villages seek out children who might benefit from eye surgeries.

GETTING READY: A child submits to an ophthalmological exam to further determine suitability for treatment.

In the test, an intervening sheet ensured that YS could not see his hands. He would be given one object (the "sample") to feel in his hands and then give back. He would then take the sample and another object in his hands and be asked to return the former. YS had no trouble at all picking out the sample for all object pairs presented to him. Similarly, in the purely visual domain, his performance was flawless. Yet in the crucial transfer task, recognizing visually what he had felt by hand, his performance plummeted. Four other children we worked with exhibited the same pattern of results.

Such findings lead us to believe that Molyneux's question most likely has a negative answer—no discernible transfer of information from touch to vision takes place immediately after onset of vision. Interesting as this result seems, there is perhaps an even more intriguing addendum.

When we tested YS a week later, we were stunned to discover that his performance on the transfer task had climbed from being no better than would have been predicted by chance to achieving a near-perfect level. Two other children we followed also exhibited similar improvements. In periods as short as a few weeks, the Prakash children begin to achieve proficiency in visually identifying an object they had felt by touch, pointing to a latent ability for rapid learning to associate different senses. Taken together, these studies suggest that many years of congenital blindness do not preclude the development of sophisticated visual ability at a relatively advanced age. That realization turns out to be good news for us from both the scientific and clinical perspectives. It suggests that neural plasticity—the ability of the visual system, for one, to adapt to new experiences—exists even late in childhood or in young adults and that, based on our experiences, children would benefit from eye surgeries.

This knowledge has laid the foundation for a continuing in-depth research program on visual development in late childhood. Working with Prakash participants ranging in age from six to older than 20 years, we have conducted assessments of a broad range of visual functions. The findings from these tests so far indicate that some key aspects of vision, such as acuity (how fine a visual pattern can be resolved), spatial contrast (changes in acuity as image contrast shifts) and optical stability, are compromised by extended deprivation. These deficits appear to be permanent because these measures do not reach normal levels even a year later.

When we look beyond these basic measurements toward so-called higher-order visual functions, however, we find evidence of significant skill acquisition—in particular, an ability to differentiate objects in an image and to link with other senses. The Prakash children also exhibit improvements in their ability to detect faces and mentally reason about the spatial arrangement of objects they observe.

THE NEW LANDSCAPE

THESE FINDINGS are beginning to give us a sense of the landscape of what can and cannot be achieved when a child gains vision at a late age. On the one hand, visual functions do not fade irretrievably if eyes and brain areas for visual processing are not subject to intensive use during the "critical period" that is believed to last for the first few years of childhood. On the other hand, early visual experience is undeniably important for the normal development of abilities such as high-resolution vision.

Early results provide a launchpad for a rich set of new investigations, some of which may be quite far removed from blindness. Based on the studies in Prakash, we are developing software for automatically discovering categories of visual objects in videos—faces, for instance. Moreover, the kinds of deficits we

IN SURGERY: A physician carefully excises cataracts, allowing a child to see clearly for the first time since birth.

FITTED FOR SEEING: A girl receives a postsurgical exam with the optometrist to get a prescription for eyeglasses.

have found in children integrating visual information soon after sight recovery bear similarities with those reported in studies of children with autism. This tentative link has now unfolded into a series of studies in my laboratory that seek to probe the causes of sensory-processing disorders in autism.

The journey ahead promises to be even more exciting than the terrain we have covered so far. A question that we have recently embarked on concerns the relation between the brain's structure and how it functions. We plan to use functional magnetic resonance imaging to look at changes in the cerebral cortex of a newly sighted child, comparing what happens when treatment begins at different ages to determine how late in life the brain can reorganize itself. We may also be able to determine, in cases where surgery is performed relatively late, whether other senses—touch or hearing, for instance—may have hijacked the area of cortex usually reserved for visual processing.

Project Prakash faces major challenges, foremost of which is to expand its outreach and treatment programs and to enable the integration of the children into mainstream society. Our plans to tackle these challenges are ambitious; we propose to start by setting up the Prakash Center for Children—a facility to integrate medical treatment, education and research. It will contain a pediatric hospital, a state-of-the-art neuroscience research center, and a rehabilitation unit for newly treated children to allow them to receive maximum benefits from their treatment.

The project's outreach effort has to date provided ophthalmic screening for about 40,000 children residing in some of northern India's poorest and most neglected villages. Around 450 visually impaired children have received surgical care and follow-up, and more than 1,400 have undergone pharmacological and optical treatments. Given the magnitude of the problem, however, this is only a beginning.

My students and I derive great satisfaction from the findings that have emerged from Project Prakash, but the work has also affected us on a deeper, more personal, level. Each blind child with whom we have worked has presented a unique story of hardships and social isolation. Equally unique is the change each child's life undergoes after treatment. SK moved back to his home state with renewed hopes for achieving his cherished goal—to be a schoolteacher. JA, who was treated at the age of 14, can now, six years later, navigate the chaos of Delhi traffic on his own.

The mother of three boys, all of whom were born with cataracts and received treatment last year, is no longer taunted by her village neighbors as carrying a curse. Two brothers who have had sight for just a few months after enduring over eight years of congenital blindness are now excited about the prospect of moving to a school for sighted children.

Such transformations serve as a testament to the power of collaboration: the debt Project Prakash owes to the scientists, clinicians, educators and sponsors who came together to advance both clinical and basic science. And I personally, of course, owe a debt of gratitude to a blue glass bowl and the very special person to whom it once belonged. SA

MORE TO EXPLORE

Pawan Sinha on How Brains Learn to See. TED, November 2009. **www.ted.com/talks/pawan_sinha_on_how_brains_learn_to_see.html**

The Newly Sighted Fail to Match Seen with Felt. Richard Held et al. in *Nature Neuroscience,* Vol. 14, No. 5, pages 551–553; May 2011.

Project Prakash Web site: **www.projectprakash.org**

SCIENTIFIC AMERICAN ONLINE
Watch the children of Project Prakash at **ScientificAmerican.com/jul2013/prakash**

OIL MINING: Alberta's tar sands region is one of the few places in the world where oil can be dug out of the ground.

ENVIRONMENT

greenhouse goo

The fate of the Alberta's tar sands mines—and the climate—may come down to the Keystone XL pipeline

By David Biello

Red lights are flashing, but Ben Johnson pays them no mind. The long, lean, weathered engineer rests against a counter lined with computer monitors, describing life in the tar sands mines of Alberta, Canada. His task is to take a mud made of ore and water and "liberate the bitumen," a tarlike oil that can be refined into conventional crude oil. He and two colleagues man a monitoring station that sits near the base of a cone-shaped structure the size of a three-story building. Mud and hot water flow into the middle of the inverted funnel. Bitumen rises to the top and spills over onto surrounding grates.

One time in 2012 bitumen bubbled up so fast that it cascaded down the sides of the cone and flooded the building shin high. To keep this kind of thing from happening again, sensors track temperatures, pressures and other parameters, and if something is amiss, a warning goes off. This happens so often—"1,000 alarms a day," Johnson says—that the engineers have taken to keeping the sound turned off. "It's not going 'bing, bing, bing,'" he says, "because that would drive us crazy."

Suncor Energy's North Steepbank mine, where Johnson operates one of many "separator cells," is a tiny portion of the current output of Alberta's tar sands, which underlie an area the size of Florida. High oil prices over the past decade have made such tar sands mines profitable, and Canada has rapidly expanded production. In 2012 alone Alberta exported more than $55 billion worth of oil, mostly to the U.S., so it is no wonder that Johnson's crew does not pause for alarms.

The rush to exploit the Alberta tar sands is triggering alarms of another kind, however—from climate scientists. Carbon dioxide emissions from burning fossil fuels are driving the world quickly toward a greenhouse gas threshold—an atmospheric concentration of 450 parts per million, which corresponds to two degrees Celsius or more of warming—beyond which some scientists fear that climate change could prove catastrophic. Coal constitutes a bigger source of fossilized carbon, but the Alberta sands require more energy to mine and refine than conventional oil, adding an extra overhead in greenhouse gas emissions. And the tar sands operations are growing far more quickly than most other sources of oil. Releasing the carbon now trapped in the tar sands would most likely dash any hope of avoiding the two degree C threshold.

The fate of Alberta's tar sands—and the climate, for that matter—now seems to be converging on the proposed Keystone XL pipeline. Keystone XL, which would run from Alberta to refineries in Texas along the Gulf of Mexico, would serve as a primary conduit for tar sands crude. For a decade or more advocates of Alberta's operations have argued that the tar sands constitute a much needed source of oil for the U.S. that is not subject to turmoil in the Middle East and abroad. All that was needed was a way to transport the tar sands oil from Canada to where it would be used—to the U.S. and beyond to Europe and Asia. And if a pipeline like Keystone XL could not be built, then other pipelines or rail could do as well. But independent experts suggest that Keystone XL is critical to the continued growth of Alberta's tar sands industry.

None of this had come to light when President Barack Obama postponed a decision on whether to build the Keystone XL pipeline during his reelection campaign. When the issue comes up again, a great deal more will be riding on his decision.

THE TRILLIONTH TONNE

EXPOSED TO THE BITTER CHILL of a northern Alberta winter at an overlook above Suncor's mine, I can't help but think that a little global warming might be nice. The mine is located in an industrial expanse of boreal forest some 30 kilometers north of Fort McMurray, a boom town where rents run as high as Manhattan's and truck drivers make $100,000 a year. Down below, along a gravel road, I can see a parade of Caterpillar 797Fs, the world's largest trucks, each carrying a 400-metric-ton load of clumped tar sands. (Women drivers are highly sought because they are easier on the equipment, but they are hard to come by because men outnumber women three to one in town.) The trucks shuttle back and forth between massive electric-powered shovels and Johnson's separation facility, a 40-minute round-trip.

The trucks dump the ore into an industrial grinder the size of a compact car, which feeds an oversized conveyor belt that brings the tar sands to the separation cell that Johnson helps to oversee. A chunk of ore can go from truck to liberated bitumen in a mere 30 minutes. This black and sticky but free bitumen froths from the top of the separator, is collected and then flows down a pipeline to a mini refinery, where it is cooked at high heat to remove carbon and create a hydrocarbon stew similar to crude oil. Alternatively, the bitumen is mixed with lighter hydrocarbons in squat, huge storage tanks; the resulting mixture, known as dilbit (for diluted bitumen), is liquid enough to flow on its own through long-distance pipelines like Keystone XL, bound for refineries in the U.S.

Suncor's North Steepbank is only a small fraction of the world's first tar sands mine—and just one of the company's complex of mines, which together produce more than 300,000 barrels of oil a day. Suncor's holdings make up about 30 percent of the total production from mining of the Alberta tar sands, which currently comes to nearly two million barrels a day—equal to the output of more than 80,000 oil wells and one twentieth of U.S. demand. The mines, with their vast lakes of toxic water residue and blocks of bright yellow elemental sulfur, are already big enough to see from space—an industrial patch steadily spreading in the boreal forest.

The invisible environmental impact of the mines may prove the most challenging, however. Avoiding the two degree C warming threshold means that humanity faces what some scientists have called a carbon budget: an estimated one-trillion-metric-ton limit on cumulative carbon emissions.

The carbon budget is the brainchild of physicist Myles Allen of the University of Oxford and six other scientists. In 2009 the team assembled observations of rising temperatures and plugged them into computer models of future climate change, which accounted for, among other things, the fact that CO_2 persists in the atmosphere, continuing to trap heat, for centuries. Their one-trillion-metric-ton budget encompasses all the carbon that human activity can safely generate between now and the year 2050, if we are to stay below the warming threshold. It doesn't matter how quickly we reach that limit. What matters is not exceeding it. "Tons of carbon is fundamental," argues now retired NASA climatologist James E. Hansen, who has been testifying about climate change since 1988 and has recently been arrested at protests against the Keystone XL pipeline. "It does not matter much how fast you burn it."

The source of that carbon does not matter, either. The world can burn through only a set amount of carbon-based fuels, whether tar sands, coal, natural gas, wood or any other source of greenhouse gases. "From the perspective of the climate system, a CO_2 molecule is a CO_2 molecule, and it doesn't matter if it came from coal versus natural gas," notes climate modeler Ken Caldeira of the Carnegie Institution for Science's department of global ecology at Stanford University.

To date, burning fossil fuels, clearing forests and other activities have put nearly 570 billion metric tons of carbon into the atmosphere—and more than 250 billion metric tons of CO_2 just since the year 2000, according to Allen. Currently human activi-

IN BRIEF

Turning tar sands into oil and burning it as fuel produce enormous amounts of carbon dioxide.

To prevent an average global temperature increase of more than two degrees Celsius, triggering potentially catastrophic climate change, cumulative carbon emissions must be kept below one trillion metric tons.

The earth's atmosphere is already more than halfway to the trillion-metric-ton target; expanding production of even more tar sands would accelerate emissions.

If built, the Keystone XL pipeline will be a spigot that speeds tar sands production, pushing the planet toward its emissions limit.

PRECEDING PAGES: GARTH LENZ

ties emit about 35 billion metric tons of CO_2 (9.5 billion metric tons of carbon) a year, a figure that is steadily climbing, along with the global economy. By Allen's calculations, at present rates society will emit the trillionth metric ton of carbon sometime during the summer of 2041. To stay on budget, on the other hand, emissions must drop by 2.5 percent a year, starting now.

UNDERGROUND TREASURE

ALBERTA'S TAR SANDS represent a lot of buried carbon, the remains of countless algae and other microscopic life that lived hundreds of millions of years ago in a warm inland sea, pulling CO_2 out of the atmosphere via photosynthesis. With today's technology, about 170 billion barrels of oil could be recovered from Alberta's tar sands, which would add roughly 25 billion metric tons of carbon to the atmosphere if burned. An additional 1.63 trillion barrels of oil—which would add 250 billion metric tons of carbon—waits underground if engineers could figure out a way to separate every last bit of bitumen from the sand. "If we burn all the tar sands oil, the temperature rise just from burning those tar sands will be half of what we've already seen," or roughly 0.4 degree C of global warming, notes mechanical engineer John P. Abraham of the University of St. Thomas–Minnesota.

Surface mining can reach deposits as deep as 80 meters, but that accounts for only 20 percent of the tar sands. In many places, the tar sands lie hundreds of meters underground, and energy firms have developed a method—known as in situ production—to melt out the bitumen in place.

In 2012 Cenovus Energy melted more than 64,000 barrels of underground bitumen every day at Christina Lake, a facility in Alberta named after nearby waters. The operation is one of the frontier camps of this latest tar sands boom. Clouds of steam rise from the nine industrial boilers on-site, burning natural gas to heat treated water into 350 degree C steam. Cenovus employees in a control room even bigger than Suncor's inject the steam deep below the surface to melt the bitumen, which is then sucked back to the surface through a well and piped off for further processing. Greg Fagnan, Christina Lake's director of operations, likens the complex to a giant water-processing facility "that happens to produce oil as well." Every once in a while, a blowout shoots steam and partially melted tar sands into the sky, like one Devon Energy caused in the summer of 2010 by using too much pressure.

At Christina Lake, engineers inject roughly two barrels of steam to pump back out one barrel of bitumen. All that steam—and the natural gas burned to heat it—means melting bitumen results in two and a half times more greenhouse gas pollution than surface mining, itself among the highest emitters for any kind of oil production. Greater production by this melting method has caused greenhouse gas emissions from Alberta's tar sands to rise by 16 percent since just 2009, according to the Canadian Association of Petroleum Producers. In 2012, for the first time, underground production of tar sands in Alberta equaled that of surface mining, and thanks to efforts such as Christina Lake, it will soon become the primary mode of production.

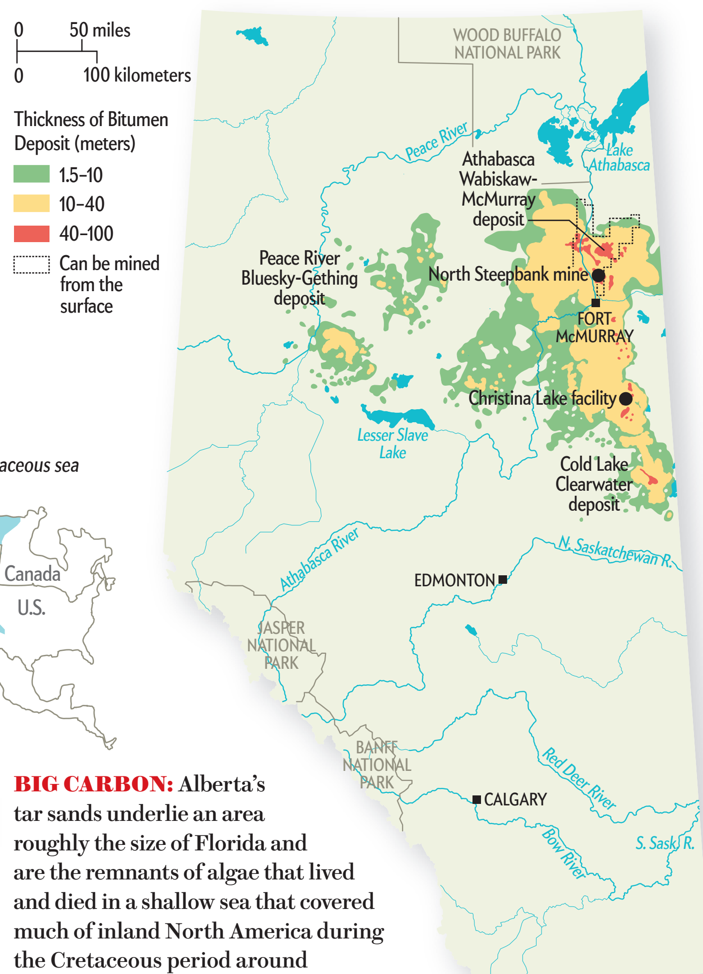
In situ production works only for bitumen that is buried below 200 meters, however. That leaves a gap of 120 meters or so that is too deep for surface mining but too shallow for in situ. So far engineers have not figured out how to tap the gap, which means burning all the fuel contained in the tar sands deposits is an unlikely prospect at present.

Yet burning a significant portion of tar sands will go a long way toward blowing the planet's carbon budget. The only way to do so and stay on budget would be to stop burning coal or other fossil fuels—or to find a way to drastically reduce tar sands' greenhouse gas emissions. Neither prospect seems likely. Tar sands "emissions have doubled since 1990 and will double again by 2020," argues Jennifer Grant, director of oil sands research at the Pembina Institute, a Canadian environmental group.

KEYSTONE CONNECTION

THIS CARBON BUDGET explains why Abraham, Caldeira and Hansen joined 15 other scientists to sign a letter to President Obama urging him to reject the proposed 2,700-kilometer-long Keystone XL pipeline. Building the pipeline—and thus enabling even more tar sands production—is "counter to both national and planetary interests," the scientists wrote.

Obama, who postponed approval of the pipeline just before the 2012 presidential election, struck a climate-friendly note in



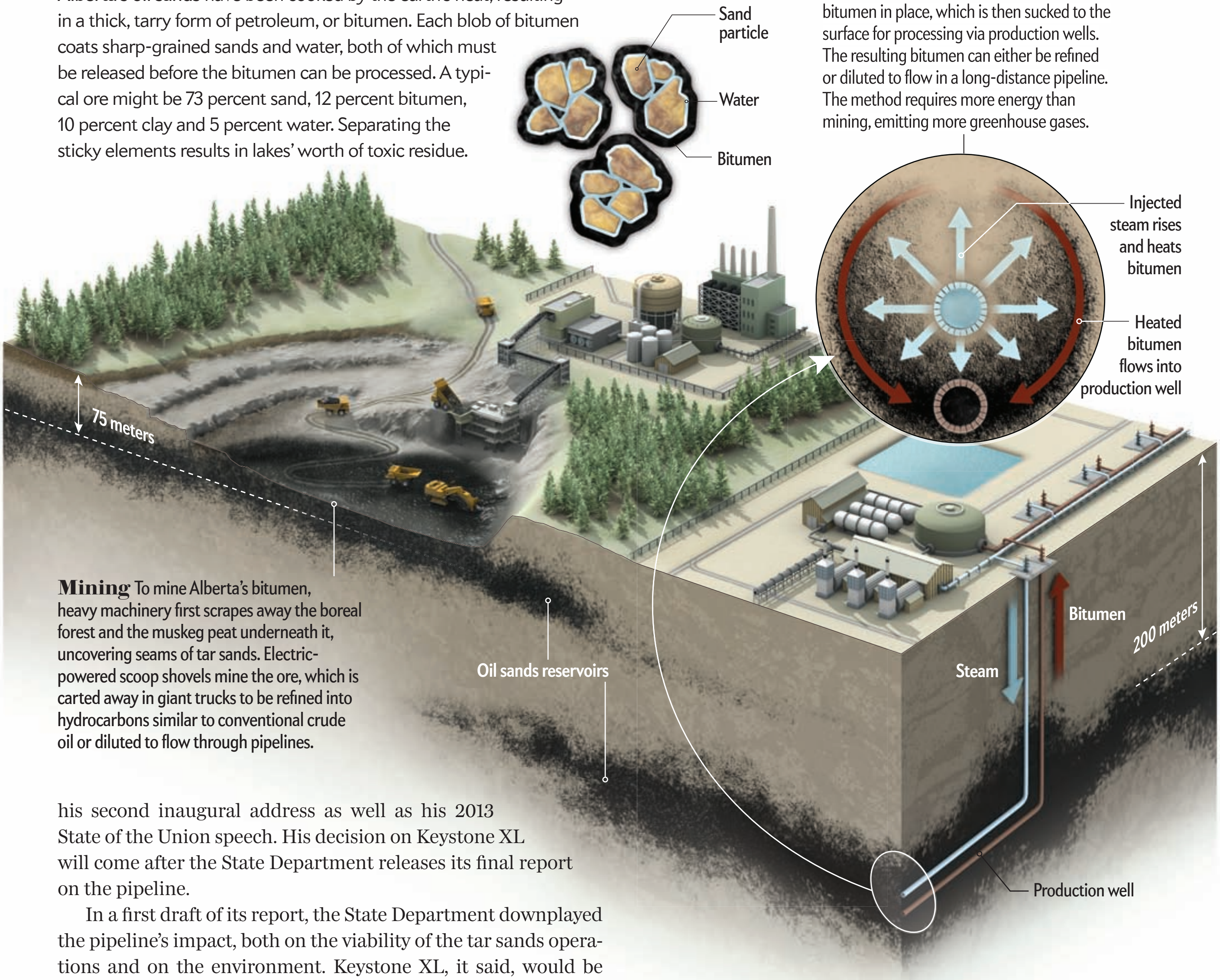
BIG CARBON: Alberta's tar sands underlie an area roughly the size of Florida and are the remnants of algae that lived and died in a shallow sea that covered much of inland North America during the Cretaceous period around 100 million years ago.

SOURCE: ALBERTA GEOLOGICAL SURVEY AND ENERGY RESOURCES CONSERVATION BOARD

Map by Michael Newhouse

How Tar Sands Oil Is Made

Alberta's oil sands have been cooked by the earth's heat, resulting in a thick, tarry form of petroleum, or bitumen. Each blob of bitumen coats sharp-grained sands and water, both of which must be released before the bitumen can be processed. A typical ore might be 73 percent sand, 12 percent bitumen, 10 percent clay and 5 percent water. Separating the sticky elements results in lakes' worth of toxic residue.



Melting So-called in situ production involves piping superhot steam more than 200 meters underground where it melts the bitumen in place, which is then sucked to the surface for processing via production wells. The resulting bitumen can either be refined or diluted to flow in a long-distance pipeline. The method requires more energy than mining, emitting more greenhouse gases.

Mining To mine Alberta's bitumen, heavy machinery first scrapes away the boreal forest and the muskeg peat underneath it, uncovering seams of tar sands. Electric-powered scoop shovels mine the ore, which is carted away in giant trucks to be refined into hydrocarbons similar to conventional crude oil or diluted to flow through pipelines.

his second inaugural address as well as his 2013 State of the Union speech. His decision on Keystone XL will come after the State Department releases its final report on the pipeline.

In a first draft of its report, the State Department downplayed the pipeline's impact, both on the viability of the tar sands operations and on the environment. Keystone XL, it said, would be "unlikely to have a substantial impact" on greenhouse gas emissions. But the authors of the report seem to have assumed that if Keystone XL were not built, Canada would find some other economical way of transporting the oil to consumers.

The Environmental Protection Agency issued a response in April that cast the matter in a different light. According to Cynthia Giles, assistant administrator for EPA's Office of Enforcement and Compliance Assurance, the State Department report relied on faulty economics, among other oversights. The EPA, drawing on past experience with big environmental assessments, suggested that alternatives to Keystone XL were either significantly more costly or faced major opposition. Having to get by without Keystone XL, in other words, might constrain tar sands development. In May the International Energy Agency (IEA) confirmed this analysis in its own prediction for the tar sands.

Tar sands oil is already traveling south by train, but this is a stopgap measure. Moving tar sands by rail is three times more expensive than by pipeline at current rates. As the tar sands operations ramp up, rail alone could prove a prohibitive cost barrier to further development.

What about another pipeline, should Keystone XL fail? Canada has the option of going west to the Pacific Coast to reach supertankers bound for China. Or it could go east, through existing pipelines, to the Midwest or the Atlantic Coast. These options are problematic. A Pacific pipeline—the least viable choice—would have to traverse the Rocky Mountains, passing through land owned by First Nations and other native groups in British Columbia, who have opposed a pipeline for fear of spills and other impacts. An Atlantic pipeline could be cobbled together from pipelines that now link Alberta to the eastern coast of North America. Engineers would have to reverse the flow of oil, much as ExxonMobil did for the Pegasus pipeline, which now carries crude from Illinois to Texas. But older pipelines that have been

Illustration by Emily Cooper

reversed may be more prone to leaks. Pegasus, for instance, sprung a tar sands oil leak in Arkansas this past April. And retrofitting existing pipelines is likely to elicit strong protest from environmentalists and others.

Given these obstacles, the tar sands industry needs Keystone XL to further expand, according to the EPA and IEA reports. At present, Alberta's tar sands produce 1.8 million barrels of oil a day. Keystone XL would ship another 830,000 barrels daily.

Mindful of the environmental opposition, Alberta and energy firms have tried to minimize greenhouse gas pollution in the tar sands operations. Royal Dutch Shell is trying an expensive alternative to breaking down bitumen into oil that involves adding hydrogen, rather than cooking off carbon into pet coke, to reduce CO_2 emissions. The international oil giant has also begun developing plans for adding carbon capture and storage equipment to one of its mini refineries, a project dubbed Quest. When completed in 2015, Quest will attempt to annually store deep underground one million metric tons of CO_2, or roughly one third of the facility's pollution. Another similar project plans to capture CO_2 for use to flush more conventional oil out of the ground.

Alberta is also one of the only oil-producing regions in the world to have a tax on carbon. Currently capped at $15 per metric ton, discussions continue to potentially raise that price. The province has invested the more than $300 million collected to date in technology development, primarily to reduce CO_2 emissions from the tar sands. The tax "gives us some ammunition when people attack us for our carbon footprint, if nothing else," Ron Liepert, then Alberta's minister of energy, told me in 2011.

Efforts to reduce the carbon footprint of the tar sands add further to the cost of extracting the oil and have not had a big impact on the carbon footprint. The 1.8 million barrels of tar sands oil a day produced in 2011 resulted in more than 47 million metric tons of greenhouse gas emissions in 2011, according to the Canadian Association of Petroleum Producers.

The IEA, in a 2010 analysis of ways to stay below the two degree C threshold, suggested that tar sands production in Alberta cannot exceed 3.3 million barrels a day by 2035. Yet mining already approved or under construction in Alberta could raise production to five million barrels a day by 2030. It's hard to imagine how to mine the tar sands without blowing the carbon budget.

BREAKING THE CARBON BUDGET

IS IT UNFAIR TO SINGLE OUT THE TAR SANDS? After all, other forms of fossil fuel add more to the world's carbon budget, yet they do not draw as much ire. Perhaps they should. In 2011 U.S. coal-fired power plants emitted nearly two billion metric tons of greenhouse gases—roughly eight times the amount produced by mining, refining and burning tar sands. Many coal mines around the world create just as visible a scar on the landscape and an even bigger climate change legacy. Yet mines like those in Montana and Wyoming's Powder River Basin are not the targets of high-profile protests such as those facing Keystone XL; protesters do not tie themselves to the tracks to block the kilometers-long trains that carry coal from the basin day after day. The U.S. Geological Survey suggests that basin alone holds 150 billion metric tons of coal that could be recovered with existing technology. Burning it all would send the world flying beyond any trillion-metric-ton carbon budget.

Australia's plan to expand coal exports to Asia could add 1.2 billion metric tons of CO_2 to the atmosphere each year when that coal is burned. That amount dwarfs emissions from even the most optimistic tar sands expansion. The U.S. and countries such as Indonesia are also planning coal expansions. Shutting down or even curtailing the U.S. coal industry would more than compensate for any tar sands development as a result of Keystone XL, although the two fossil fuels are used for different purposes—coal for electricity, oil for transportation.

Canada also offers a target of some convenience, given that it is a friendly democracy susceptible to environmental pressure. Producers of "heavy oil"—similar in pollution to tar sands bitumen—in Mexico, Nigeria or Venezuela do not find themselves under as much scrutiny despite high rates of CO_2 pollution. In fact, scouring such heavy oil from an old field in California is the single worst CO_2 polluter among all oil-extraction efforts in the world, including the melted tar sands. "If you think that using other petroleum sources [than tar sands] is much better, then you're delusional," says chemical engineer Murray Gray, scientific director of the Center for Oil Sands Innovation at the University of Alberta. "Increasing coal use worldwide gives me a lot more pause."

These other sources of petroleum are not growing anywhere near as fast as Alberta's oil sands, where in the past decade production increased by more than a million barrels a day. To keep to the atmospheric carbon budget, the world must produce less than half of the known and economically recoverable oil, gas and coal reserves. That means much of the fossil fuel—especially the dirtiest forms of petroleum, such as that produced from the tar sands—will have to stay buried.

Economic forces may come to the aid of the global environment. Fracking for oil in North Dakota's portion of the Bakken Shale has begun to depress U.S. demand for Canada's dirty oil; in response, new infrastructure projects in Alberta's tar sands, such as the $12-billion Voyageur mini refinery, have been dropped. New mandatory fuel-efficiency standards for U.S. cars will reduce demand as well, at least in the short term. Regardless, the tar sands will be there, waiting, an ever tempting target for future extraction once the easier oil runs out.

If the Keystone XL pipeline is approved or other means are built to get the tar sands oil to China, exports could continue to rise, accelerating the invisible accumulation of CO_2 in the atmosphere. Instead of reducing emissions by 2.5 percent a year, starting now—the effort Oxford physicist Allen calculates is necessary to keep the planet clear of the two degree C threshold—global greenhouse gas pollution will continue to increase. Every bit of carbon from burning fossil fuels—tar sands or otherwise—counts. SA

David Biello is an associate editor at Scientific American.

MORE TO EXPLORE

Warming Caused by Cumulative Carbon Emissions towards the Trillionth Tonne. Myles R. Allen et al. in *Nature,* Vol. 458, pages 1163–1166; April 30, 2009.

The Alberta Oil Sands and Climate. Neil C. Swart and Andrew J. Weaver in *Nature Climate Change,* Vol. 2, pages 134–136; February 19, 2012.

The Facts on Oil Sands. Canadian Association of Petroleum Producers, 2013. Available as a PDF at **www.capp.ca/getdoc.aspx?DocId=220513&DT=NTV**

SCIENTIFIC AMERICAN ONLINE
For a more in-depth look at tar sands production, visit **ScientificAmerican.com/jul2013/tar-sands**

ANIMAL BEHAVIOR

When Animals Mourn

Mounting evidence from species as diverse as cats and dolphins indicates that humans are not the only species that grieves over the loss of loved ones

By Barbara J. King

ON A RESEARCH VESSEL IN THE waters off Greece's Amvrakikos Gulf, Joan Gonzalvo watched a female bottlenose dolphin in obvious distress. Over and over again, the dolphin pushed a newborn calf, almost certainly her own, away from the observers' boat and against the current with her snout and pectoral fins. It was as if she wanted to nudge her baby into motion—but to no avail. The baby was dead. Floating under direct sunlight on a hot day, its body quickly began to decay; occasionally the mother removed pieces of dead skin and loose tissue from the corpse.

When the female dolphin continued to behave in this way into a second day, Gonzalvo and his colleagues on the boat grew concerned: in addition to fussing with the calf, she was not eating normally, behavior that could be risky for her health, given dolphins' high metabolism. Three other dolphins from the Amvrakikos population of about 150 approached the pair, but none disrupted the mother's behavior or followed suit.

As he watched the event unfold in 2007, Gonzalvo, a marine biologist at the Tethys Research Institute in Milan, Italy, decided he would not collect the infant's body to perform a necropsy, as he would usually have done for research purposes. "What prompted me not to interfere was respect," he told me earlier this year. "We were privileged to be able to witness such clear evidence of the mother-calf bond in bottlenose dolphins, a species that I have been studying for over a decade. I was more interested in observing that natural behavior than interrupting it by abruptly interfering and disturbing a mother who was already in obvious distress. I would define what I saw as mourning."

Was the dolphin mother truly grieving for her dead calf? A decade ago I would have said no. As a biological anthropologist who studies animal cognition and emotion, I would have recognized the poignancy of the mother's behavior but resisted interpreting it as mourning. Like most animal behaviorists, I was trained to describe such reactions in neutral terms such as "altered behavior in response to another's death." After all, the mother might have become agitated only because the strange, inert status of her calf puzzled her. Tradition dictates that it is soft-hearted and unscientific to project human emotions such as grief onto other animals.

Now, though, especially after two years' research for my book *How Animals Grieve,* I think Gonzalvo was correct in his judgment that the mother dolphin was mourning. In the past few years a critical mass of new observations of animal responses to death has bubbled to the surface, leading me to a startling conclusion: cetaceans, great apes, elephants, and a host of other species ranging from farm animals to domestic pets may, depending on circumstances and their own individual personalities, grieve when a relative or close friend dies. That such a broad range of species—including some quite distantly related to humans—lament the passing of loved ones hints that the roots of our own capacity for grief run very deep indeed.

Barbara J. King is a professor of anthropology at the College of William and Mary. Her studies of monkeys and apes have led her to examine emotion and intelligence in a wide range of animal species.

DEFINING GRIEF

SINCE CHARLES DARWIN'S DAY, two centuries ago, scientists have debated hotly whether some animals display emotions beyond those associated with parental care or other aspects of survival and reproduction. Darwin thought that, given the evolutionary connection between humans and other animals, many emotions must be similar across species. He granted to monkeys, for instance, grief and jealousy, as well as pleasure and vexation. But the attribution of emotions such as these to animals fell increasingly out of mainstream scientific favor. By the early 20th century the behaviorist paradigm held sway, with its insistence that only observable behavior of animals, not their interior lives, could be studied with rigor. Gradually the scientific embrace of animal emotion has revived, thanks originally in part to anecdotes from long-term field studies on large-brained mammals. From Tanzania, Jane Goodall recounted in heart-wrenching detail young chimpanzee Flint's decline and death from grief only weeks after the death of his mother, Flo. From Kenya, Cynthia Moss reported that elephants attend to dying comrades and stroke the bones of deceased relatives. Field biologists and anthropologists began to ask questions about whether, and how, animals mourn.

To study and understand grief among animals, scientists need a definition that distinguishes it from other emotions. Whereas "animal response to death" embraces any behavior by an individual following the death of a companion animal, researchers may strongly suspect grief only when certain conditions are met. First, two (or more) animals choose to spend time together beyond survival-oriented behaviors such as foraging or mating. Second, when one animal dies, the survivor alters his or her normal behavioral routine—perhaps reducing the amount of time devoted to eating or sleeping, adopting a body posture or facial expression indicative of depression or agitation, or generally failing to thrive. For his part, Darwin conflated grief with sadness. But the two differ, primarily in intensity: the grieving animal is more acutely distressed, possibly for a more prolonged period.

This two-part definition is imperfect. For one thing, scientists lack a metric for evaluating exactly what counts as "more acutely distressed." Should the criteria for grief differ according to species, and might grief in other animals assume forms that are difficult for humans to recognize as mourning? The data are not yet available on these questions. Furthermore, mothers or other caretakers that constantly provide food or protection to infants that subsequently die cannot be said to have met the first criterion (going beyond survival-oriented behaviors), yet they remain among the strongest candidates for suffering survivor's grief.

Future studies of animal mourning will help refine this definition. For now, it furthers our critical assessment of responses made by animals when others around them die. For instance, baboon and chimpanzee mothers in wild African populations sometimes carry the corpse of their dead babies for days, weeks or even months—a behavior that on the surface of things might look like grief. But they may not exhibit any significant outward indicator of agitation or distress. When the animals carry on with their routine behaviors, such as mating, their behavior does not meet the criteria for mourning.

A MENAGERIE OF MOURNERS

A WIDE RANGE of species do exhibit behaviors that fit the two-part definition of grief, however, elephants among them. A particularly compelling example of elephant mourning comes from Iain Douglas-Hamilton of Save the Elephants and his team at Kenya's Samburu National Reserve, who in 2003 tracked elephants' responses to the dying matriarch called Eleanor. When Eleanor

PRECEDING PAGES: TIM FLACH *Getty Images*

IN BRIEF

Animal behaviorists have traditionally shied away from attributing human emotions, such as grief, to responses by animals.

But a growing body of evidence indicates that species ranging from dolphins to ducks mourn the passing of relatives and close companions.

These observations suggest that although the ways in which we mourn may be uniquely human, our capacity for grief has deep evolutionary roots.

DOLPHIN MOTHER carries the body of her dead calf on her dorsal fin in the waters off Dana Point, Calif.

COURTESY OF CAPTAIN DAVE'S DOLPHIN AND WHALE WATCHING SAFARI, DANA POINT, CALIF. www.dolphinsafari.com

collapsed, a matriarch named Grace from another elephant family immediately came to her aid, using her tusks to support Eleanor back onto her feet. When Eleanor fell again, Grace stayed with her, pushing on her body, for at least an hour, even though her own family moved on. Then Eleanor died. During the course of the week that followed, females from five elephant families, including Eleanor's own, showed keen interest in the body. Some individuals appeared upset, pulling at and nudging the body with trunk and feet or rocking back and forth while standing over it. Based on the females' reactions (at no point during this period did a bull elephant visit the carcass), Douglas-Hamilton concluded that elephants show a so-called generalized response to dying and death—grieving not only for the loss of close kin but for individuals in other families.

Wild cetaceans also seem to exhibit a generalized grief response. In the Canary Islands in 2001 Fabian Ritter of Mammal Encounters Education Research observed a rough-toothed dolphin mother pushing and retrieving her dead calf's body in much the same way that the Amvrakikos dolphin mother had with her baby's corpse. She was not alone: two adult escorts swam synchronously with her at certain periods, and at other times a group of at least 15 dolphins altered their pace of travel to include the mother and dead baby. The mother's persistence was remarkable, and when on the fifth day it began to wane, the escorts joined in and supported the infant on their own backs.

Giraffes, too, appear to grieve. In 2010 at the Soysambu Conservancy in Kenya, a female Rothschild's giraffe gave birth to a baby with a deformed foot. The baby walked less and remained more stationary than most calves. During the youngster's four weeks of life, wildlife biologist Zoe Muller of the Rothschild's Giraffe Project, based in Kenya, never saw the mother more than 20 meters away. Although individuals in a giraffe herd often synchronize their activities, foraging together, for example, the mother deviated from this pattern, preferring to stay close to the baby. Like the dolphin mother in the Amvrakikos Gulf, she may have risked her own health in doing so—though in this case for a living offspring.

One day Muller discovered the herd engaged in highly atypical behavior. Seventeen females, including the calf's mother, were vigilant and restless as they stared into a patch of bush. The calf had died in that spot about an hour before. All 17 females showed keen interest in the body that morning, approaching and then retreating from it. By the afternoon 23 females and four juveniles were involved, and some nudged the carcass with their muzzles. That evening 15 adult females clustered closely around the body— more closely than they had been during the day.

Throughout the following day numerous adult giraffes attended the infant's body. Some adult males approached for the first time, although they showed no interest in the carcass, instead focusing on foraging or inspecting the reproductive status of the females. On day three Muller spotted the mother giraffe alone under a tree about 50 meters from where the calf had died. The body itself, however, was no longer in its resting spot. Following a search, Muller located it, half-devoured, in the spot under the tree where the mother had been earlier. By the next day the body was gone, taken by hyenas.

Giraffes are highly social animals. After caching a newborn out of sight for about the first four weeks of life, the mothers sometimes engage in a crèche system in which one looks after the infants while the others forage. Muller does not use the words "grief" or "mourning" in describing the incident she witnessed. Yet this case is especially instructive. Not only the mother's behavior but also that of many of the females in her herd changed significantly in the wake of the infant's death. Although it is impossible to rule out an alternative explanation, the fact that the females had mounted a protective response against predators taking the baby makes it overwhelmingly likely that grief was involved at some level.

Detailed observations of wild populations of animals, such as the ones Muller reported, are still relatively rare, for several reasons. Scientists may not be at the right place at the right time to observe post-death responses by survivors. And even when they are present, no remarkable grief behaviors may ensue. Especially at this early stage of research into animal grief, observations from sanctuaries, zoos and even our own homes may supply needed clues.

I cannot imagine describing the behavior of Willa the Siamese cat without invoking the word "grief." For 14 years Willa lived with her sister, Carson, at the home of Karen and Ron Flowe in Virginia. The feline siblings groomed each other, lazed together in favorite parts of the house and slept with their bodies entwined. If Carson was taken from the house to visit the vet, Willa acted mildly agitated until she reunited with her sister. In 2011 Carson's chronic medical issues worsened, and the Flowes took her again to the vet, where she died in her sleep. At first, Willa acted as she did when her sister was away for a brief period. Within two or three days, though, she began to utter an unearthly sound, a sort of wail, and to search the spots she and Carson had favored together. Even when this startling behavior faded, Willa remained lethargic for months.

FEMALE GORILLA clutches her dead baby in a zoo in Münster, Germany. Although such behavior is not sufficient to demonstrate mourning, mothers who lose infants are among the strongest candidates for experiencing survivor's grief.

OLIVER WERNER *Getty Images*

Of all the instances of animal grief I have compiled, the most surprising came from a sanctuary setting. In 2006 three mulard ducks arrived at Farm Sanctuary in Watkins Glen, N.Y. They suffered from hepatic lipidosis, a liver disease caused by force-feeding of the birds at a foie gras farm. Two of the rescued ducks, Kohl and Harper, were in bad shape physically and emotionally. Very afraid of people, Kohl had deformed legs and Harper was blind in one eye. The two forged a fine supportive friendship for four years. Ducks are social birds, but even so, the intensity of their bond was unusual. When Kohl's leg pain increased and he could no longer walk, he was euthanized. Harper was allowed to observe the procedure and to approach his friend's body afterward. After pushing on the body, Harper laid down and put his head and neck over Kohl's neck. There he stayed for some hours. In effect, Harper never recovered from his loss. Day after day, he snubbed other potential duck friends, preferring to sit near a small pond where he had often gone with Kohl. Two months later Harper died as well.

THE SORROW CONTINUUM

IT IS LOGICAL to think that long-lived species whose members partner most closely with others in tight-knit pairs, family groups or communities may more readily mourn the deaths of loved ones than other species do. But researchers do not yet know enough about animal grief to make such a claim. We need to test this hypothesis by systematically comparing responses to death in a variety of animal social systems, from gregarious ones to those in which animals come together only seasonally for food or mating.

Still, species-level differences in grieving will not be the whole story, because variation in the immediate social contexts and personalities of individual survivors will complicate matters. For instance, whereas the practice of allowing a survivor to view the body, as Harper did with Kohl, sometimes seems to prevent or reduce a period of distressed searching and vocalizing by the surviving animal, other times it seems not to help at all—attesting to the degree of individual variation in death responses within species. Likewise, evidence for grief in wild monkeys that live in cohesive social units is surprisingly limited so far, whereas in more solitary species such as domestic cats, bonds may develop between two or more kin or friends such that grief responses rival those of much more social animals. I would predict that field observations will show that some monkeys across varied social systems visibly mourn as much as some domestic cats. Indeed, in *How Animals Grieve,* I recount examples from cats, dogs, rabbits, horses and birds, as well as the other animals discussed here. In each species I find a grief continuum, with some individuals seeming indifferent to a companion's death and other individuals appearing distraught over such a loss.

Cognitive differences also play a role in animal grief. Just as there are different levels of empathy expressed by different species and even across individuals within a species, there must be varying levels of comprehension when animals grieve. Do some animals grasp death's finality or even have a mental concept of death? We simply don't know. No evidence suggests that any nonhuman animal anticipates death in the way we humans do, a capacity that underlies so much of our compelling literature, music, art and theater—and that costs our species a great deal in terms of emotional suffering.

Love in the animal world often entwines with grief in an acute mutuality.

Indeed, the capacity to mourn may become quite costly for any animal in both physical and emotional terms, especially in the wild where alert high-energy behavior is needed for foraging, predator avoidance and mating. Why then did grief evolve in the first place? Perhaps the social withdrawal that often accompanies an animal's grief, if not taken too far, allows time for rest and thus an emotional recovery that in turn leads to greater success in forging a new close bond. Or, as John Archer writes in *The Nature of Grief,* it may be that "the costs involved in grief can be viewed as a trade-off with the overall benefits conferred by separation responses" seen when two individuals are keenly attached but forced apart from each other. Under such circumstances, the missing partners may search for each other and thereby reunite and live to see another day. What is adaptive, then, may not be grief itself but instead the strong positive emotions experienced before grief comes into the picture, shared between two or more living animals whose level of cooperation in nurturing or resource-acquisition tasks is enhanced by these feelings.

THE PRICE OF LOVE

FROM THIS PERSPECTIVE, we may link grief with love, full stop. That is to say, grief results from love lost. Exploring emotions in a variety of species, ecologist and animal behaviorist Marc Bekoff of the University of Colorado at Boulder embraces the idea that many animals feel "love" as well as "grief," even as he acknowledges that those concepts are hard to define precisely. We humans, he notes, do not fully understand love, but we do not deny its existence—or its power to shape our emotional responses.

In his book *Animals Matter,* Bekoff tells the story of a coyote called Mom whom he observed for several years during behavioral studies in Wyoming's Grand Teton National Park. At one point Mom began to make short journeys on her own away from her pack. Her offspring would rejoice when she returned: they licked Mom and rolled over exuberantly at her feet. Then Mom left for good. Some of the coyotes in her pack paced; others searched for her, setting off in the direction Mom had departed. "For more than a week some spark seemed to be gone," Bekoff writes. "Her family missed her." Discussing animal emotion with me earlier this year, Bekoff attributed the family's response to its love for Mom. Generally, the potential for love is strong in species such as coyotes, wolves and many birds, including geese, he said, because male and female partners defend territories, feed and raise their young together, and miss each other when they are apart.

Love in the animal world often entwines with grief in an acute mutuality. Perhaps even more than the degree of social cohesion within a species, it is love between individuals that predicts when grief will be expressed. Can there be any real doubt that Willa, a representative of a species (the domestic cat) not known for its social nature, loved her sister, Carson, or that as the sole surviving sister, she suffered grief in the wake of her loss?

In our own species, grief increasingly became expressed through rituals rich in symbolism. By around 100,000 years ago, our *Homo sapiens* ancestors decorated dead bodies in red ocher, a behavior interpreted by archaeologists to be a kind of symbolic (rather than functional) ornamentation. At a site in Russia called Sunghir, two children younger than 13 years, a boy and a girl, were buried 24,000 years ago, together with elaborate grave goods ranging from mammoth tusks to animals carved from ivory. Most astonishing were the thousands of ivory beads found in the pair's grave, probably sewn onto the clothing (long since disintegrated) in which the children were buried. A good portion of this ancient human community at Sunghir must have come together in preparing this funeral ritual—each bead alone took an hour or more to manufacture. Although it is risky to project modern emotions onto past populations, the examples of animal grief reviewed here strengthen an emotion-based interpretation of the archaeological evidence: our ancestors of many thousands of years ago mourned their lost children.

In our modern world, grief is no longer inevitably confined to kin, close social partners or immediate members of one's own community. Public commemoratives at the Peace Memorial Park in Hiroshima; the genocide memorial center in Kigali, Rwanda; the Foundation Memorial to the Murdered Jews of Europe in Berlin; or the site of the Twin Towers in Manhattan or Sandy Hook Elementary School in Newtown, Conn., all convey visibly the power of agonized global mourning. Our uniquely human capacity for sorrow at the deaths of those who are strangers to us is built on an evolutionary substrate. Our own ways of mourning may be unique, but the human capacity to grieve deeply is something we share with other animals. SA

MORE TO EXPLORE

Animals Matter: A Biologist Explains Why We Should Treat Animals with Compassion and Respect. Mark Bekoff. Shambhala, 2007.

How Animals Grieve. Barbara J. King. University of Chicago Press, 2013.

SCIENTIFIC AMERICAN ONLINE
For examples of animal responses to death that do not qualify as grief, go to **ScientificAmerican.com/jul2013/grief**

A NOBEL GATHERING

AS LAUREATES AND NEWCOMERS IN CHEMISTRY FORM NEW BONDS, WE CELEBRATE THEIR ACHIEVEMENTS, PAST AND FUTURE

EDITED BY FERRIS JABR
ILLUSTRATIONS BY BOMBOLAND

CHEMISTS TYPICALLY CONCERN themselves with the properties of matter at the level of atoms and molecules. That focus may seem narrow, but it is quite the opposite. Chemistry reveals a great deal about the world around us, including the origins of life, how the human body works and how tiny molecules can profoundly change the earth's atmosphere. And, of course, chemistry makes it possible to create useful materials not found in nature.

Such insights have been celebrated for more than a century, as evidenced by the long record of Nobel Prizes for advances in chemistry. This summer past winners of the prize are joining up-and-coming scientists in Lindau, Germany, to discuss previous breakthroughs and future prospects. In honor of the event—the 63rd Lindau Nobel Laureate Meeting—Scientific American is publishing excerpts from articles authored by Nobel Laureates in chemistry over the years, beginning on page 70. Many of the snippets resonate with researchers' priorities today.

It might come as a surprise that scientists did not put the initially abstract notions of atoms and molecules on a solid experimental footing until the beginning of the 20th century. Writing in *Scientific American* in 1913, Theodor (The) Svedberg described how Ernest Rutherford's work on the alpha particle (the nucleus of the helium atom), among other studies, established the existence of atoms and molecules beyond a reasonable doubt. Fast-forward 100 years, and techniques such as atomic force microscopy produce images of molecules in which atoms—and the chemical bonds between them—are clearly visible. If seeing is believing, such pictures leave little room for doubt.

Back in the early 20th century, the development of x-ray crystallography enabled scientists to produce the first images of the three-dimensional arrangements of atoms in various molecules. In *Scientific American* in 1961, John C. Kendrew likened the experience of glimpsing the 3-D structure of the oxygen-binding protein myoglobin to European explorers first sighting the Americas.

Even today many researchers rely on x-ray crystallography to

visualize the structures of proteins and other molecules in living things. Two of the last four Nobel Prizes in Chemistry (2009 and 2012) were awarded for research based, in part, on x-ray structural studies of large assemblies of molecules in cells, namely the ribosome and G-protein coupled receptors (GPCRs). In the case of the ribosome, x-ray crystallography has not only offered us a look at how this elaborate molecular machine strings amino acids into proteins but has also helped researchers develop more effective antibiotics that interfere with bacterial ribosomes. A more detailed understanding of GPCRs could similarly help researchers design more sophisticated medicines, because a third of all commercial drugs are thought to act on these abundant proteins embedded in cell walls. In 2011 scientists produced the first x-ray image of a GPCR in action, uncovering fresh details about the carefully choreographed steps involved in transmitting a signal through a cell membrane.

Although x-ray crystallography and other new tools allowed researchers to examine the biochemistry of living organisms in greater detail, the origin of life itself remained far more mysterious. In 1952 Harold C. Urey and his student Stanley L. Miller conducted what is now regarded as the classic chemical origins-of-life experiment. By re-creating conditions in the laboratory that ostensibly represented the earth's early atmosphere, they showed that simple compounds could form amino acids—the building blocks of proteins and all life on earth. Researchers continue to investigate how life first arose. One school of thought proposes that the biochemical machinery we know today (the DNA that makes RNA, which in turn makes proteins) was predated by an RNA world in which RNA did everything by itself.

The same year that Urey oversaw the origins-of-life experiment, he published an article in *Scientific American* about the beginnings of the earth's atmosphere. Over time, it has become increasingly clear that we have dramatically changed our planet's atmosphere with man-made chemicals. Chlorofluorocarbons (CFCs), for example, have contributed to the depletion of the ozone layer. The atmosphere's chemical complexity continues to surprise scientists. A study published just last year focused on the discovery of a previously undetected substance in the atmosphere that can convert sulfur dioxide into sulfuric acid, a component of acid rain. In turn, the discovery of new atmospheric compounds helps researchers refine their models of atmospheric processes, which we rely on to predict future changes.

Artificial substances produced through chemistry have also greatly improved people's everyday lives. During the past century, increasingly sophisticated synthetic chemistry has yielded useful materials and medicines that do not occur naturally. Synthetic polymers are a good example: they are large molecules made of repeating units (monomers) typically linked together in chains. Their trademarked names are probably quite familiar: Teflon, Styrofoam and Kevlar. In recognition of their development of catalysts that control the orientation of monomers as they are added to a growing polymer chain, Giulio Natta and Karl W. Ziegler received the Nobel Prize in Chemistry in 1963. Commercial plastics made using Ziegler-Natta (and related) catalysts are still produced on a massive scale today.

Because chemistry is so broad, one can envision a host of future breakthroughs worthy of Nobel Prizes. Perhaps scientists will build a functional cell from scratch or an artificial leaf that extracts energy from sunlight more efficiently than plants. Whatever discoveries come next, history suggests that they will reveal the hidden workings of the world around us and will help us to create what we need when nature fails to provide it.

—Stuart Cantrill

***Stuart Cantrill** is chief editor of* Nature Chemistry.

IN BRIEF

Every summer in Lindau, Germany, Nobel Prize recipients and up-and-coming researchers in a particular field gather and socialize. This year the meeting focuses on chemistry.

In celebration of the Lindau meeting, Scientific American has chosen 11 excerpts from articles in the magazine's archives authored by Nobel Laureates in chemistry.

The excerpts cover a surprisingly wide range of subjects, from the details of atoms and molecules to the chemical makeup of the earth's atmosphere. Some describe fundamental discoveries about natural elements; others recount researchers' attempts to create brand-new substances.

Some of the questions that preoccupied chemists many decades ago remain unanswered today, and certain man-made materials once considered unusual and of uncertain value have now become commonplace.

ATOMS & MOLECULES
FUNDAMENTAL FINDS

MODERN THEORIES OF ELECTRICITY AND MATTER

BY MARIE CURIE
PUBLISHED IN JUNE 1908

NOBEL PRIZE IN 1911

When one reviews the progress made in the department of physics within the last ten years, he is struck by the change which has taken place in the fundamental ideas concerning the nature of electricity and matter. The change has been brought about in part by researches on the electric conductivity of gas, and in part by the discovery and study of the phenomena of radioactivity. It is, I believe, far from being finished, and we may well be sanguine of future developments. One point which appears today to be definitely settled is a view of atomic structure of electricity, which goes to conform and complete the idea that we have long held regarding the atomic structure of matter, which constitutes the basis of chemical theories.

At the same time that the existence of electric atoms, indivisible by our present means of research, appears to be established with certainty, the important properties of these atoms are also shown. The atoms of negative electricity, which we call electrons, are found to

exist in a free state, independent of all material atoms, and not having any properties in common with them. In this state they possess certain dimensions in space, and are endowed with a certain inertia, which has suggested the idea of attributing to them a corresponding mass.

Experiments have shown that their dimensions are very small compared with those of material molecules, and that their mass is only a small fraction, not exceeding one one-thousandth of the mass of an atom of hydrogen. They show also that if these atoms can exist isolated, they may also exist in all ordinary matter, and may be in certain cases emitted by a substance such as a metal without its properties being changed in a manner appreciable by us.

If, then, we consider the electrons as a form of matter, we are led to put the division of them beyond atoms and to admit the existence of a kind of extremely small particles, able to enter into the composition of atoms, but not necessarily by their departure involving atomic destruction. Looking at it in this light, we are led to consider every atom as a complicated structure, and this supposition is rendered probable by the complexity of the emission spectra which characterize the different atoms. We have thus a conception sufficiently exact of the atoms of negative electricity.

It is not the same for positive electricity, for a great dissimilarity appears to exist between the two electricities. Positive electricity appears always to be found in connection with material atoms, and we have no reason, thus far, to believe that they can be separated. Our knowledge relative to matter is also increased by an important fact. A new property of matter has been discovered which has received the name of radioactivity. Radioactivity is the property which the atoms of certain substances possess of shooting off particles, some of which have a mass comparable to that of the atoms themselves, while the others are the electrons. This property, which uranium and thorium possess in a slight degree, has led to the discovery of a new chemical element, radium, whose radioactivity is very great. Among the particles expelled by radium are some which are ejected with great velocity, and their expulsion is accompanied with a considerable evolution of heat. A radioactive body constitutes then a source of energy.

According to the theory which best accounts for the phenomena of radioactivity, a certain proportion of the atoms of a radioactive body is transformed in a given time, with the production of atoms of less atomic weight, and in some cases with the expulsion of electrons. This is a theory of the transmutation of elements, but differs from the dreams of the alchemists in that we declare ourselves, for the present at least, unable to induce or influence the transmutation. Certain facts go to show that radioactivity appertains in a slight degree to all kinds of matter. It may be, therefore, that matter is far from being as unchangeable or inert as it was formerly thought and is, on the contrary, in continual transformation, although this transformation escapes our notice by its relative slowness. The conception of the existence of atoms of electricity which is thus brought before us plays an essential part in modern theories of electricity.

THE REALITY OF MOLECULES

BY THEODOR (THE) SVEDBERG
PUBLISHED IN FEBRUARY 1913
NOBEL PRIZE IN 1926

Anyone consulting a handbook of chemistry or physics written toward the end of the nineteenth century, to gain information regarding molecules, would in many cases have met with rather skeptical statements as to their real existence. Some authors went so far as to deny that it would ever be possible to decide the question experimentally. And now, after one short decade, how the aspect of things is changed! The existence of molecules may today be considered as firmly established. The cause of this radical change of front must be sought in the experimental investigations of our still youthful twentieth century. [Ernest] Rutherford's brilliant investigations on α-rays, and various researches on suspensions of small particles in liquids and gases, furnish the experimental substantiation of the atomistic conception of matter.

The modern proof for the existence of molecules is based in part upon phenomena which give us a direct insight into the discontinuous (discrete) structure of matter, and in part upon the "working model" of the kinetic theory furnished us in colloidal solutions. These last have been shown to differ from "true" solutions only in that the particles of the dissolved substance are very much larger in the case of colloids. In all respects they behave like true solutions, and follow the same laws as the latter. And, thirdly, the recent direct proof of the existence of indivisible elementary electric charges enable us to draw conclusions regarding the atomic structure of ponderable matter.

Among the first-mentioned class of proofs is Rutherford's great discovery (1902–1909) that many radioactive substances emit small particles which, after losing their velocity, as for instance by impact against the walls of a containing vessel, display the properties of helium gas. In this way it has been proved experimentally that helium is built up of small discrete particles, molecules. In fact, Rutherford was able actually to count the number of α particles or helium molecules contained in one cubic centimeter of helium gas at 0 degree Centigrade and one atmosphere pressure (1908).

The second class of proofs of the existence of molecules comprises a number of researches on the change of concentration with level which is observed in colloidal suspensions, and on the related phenomena of diffusion, Brownian movement, and light absorption in such systems.

Lastly, modern investigations of the conduction of electricity through gases, and of the so-called β rays, have shown conclusively that electric charges, like matter, are of atomic nature, i.e., composed of ultimate elementary charged particles, whose mass is only about 1/700 of a hydrogen atom. Quite recently [Robert Andrews] Millikan and [Erich] Regener have succeeded by entirely different methods in isolating an electron and studying it directly.

We see, then, that the scientific work of the past decade has brought most convincing proof of the existence of molecules. Not only is the atomic structure of matter demonstrated beyond reasonable doubt, but means have actually been found to study an individual atom. We can now directly *count* and *weigh* the atoms. What skeptic could ask for more?

HOT ATOM CHEMISTRY

BY WILLARD F. LIBBY
PUBLISHED IN MARCH 1950
NOBEL PRIZE IN 1960

One of the first things a beginning chemistry student learns is that the chemical behavior of an atom depends solely on the electrons circulating around the nucleus, and not at all on the nucleus itself. In fact, the classical definition of isotopes states that all the isotopes of a given element are identical in chemical activity, even though the nuclei are different. Like all generalizations, even this one has a little bit of falsehood in it. The truth is that the chemical behavior of an atom may be strongly influenced by events in its nucleus, if the nucleus is radioactive. The bizarre chemical effects sometimes produced by radioactive atoms have given rise to a fascinating new branch of investigation known as hot atom chemistry.

Unusual chemical reactions among hot atoms were noticed soon after the discovery of radioactivity. The serious study of hot atom chemistry began as early as 1934, when Leo Szilard and T. A. Chalmers in England devised a method, known as the Szilard-Chalmers process, for utilizing such reactions to obtain concentrated samples of certain radioactive compounds for research purposes. But not until the end of the recent war, when chemists began to work with large amounts of radioactive materials, did the subject begin to attract wide interest. Since the war, reports of investigations in this intriguing field have come from laboratories in all the leading scientific countries of the world.

The particular set of reactions we shall consider is the behavior of radioactive iodine in the compound ethyl iodide—CH_3CH_2I. We begin with an ordinary liquid sample of the compound and transform some of the iodine atoms in it into a radioactive variety by irradiating them with neutrons from a chain-reacting pile or a cyclotron. Neutrons have no chemical properties, since they consist of pure nuclear matter with no associated external electrons. Because they have no external electrons, and are themselves electrically neutral, their penetrating power is amazing. They readily proceed through several inches of solid material until they chance to interact with some of the tiny atomic nuclei in their path.

Suppose, then, we expose a bottle of liquid ethyl iodide to a source of neutrons. The neutrons penetrate the glass, and a certain proportion of them are captured by the iodine atoms. When the nucleus of a normal iodine atom, I-127, takes in a neutron, it is transformed into the radioactive isotope I-128. This new species is extremely unstable: in much less than a millionth of a millionth of a second it emits a gamma ray of huge energy—several million electron volts. After giving off this tremendous energy, the I-128 atom is reduced to a lower state of excitation. It is still unstable; the atom continues to decay, and gradually, with a half-life of 25 minutes, the I-128 atoms degenerate into xenon 128 by emitting beta particles. The emission of this energy gives the I-128 atom in the ethyl-iodide molecule a large recoil energy, just as the firing of a bullet from a gun makes the gun recoil. The atom's recoil energy is calculated to be some 200 million electron volts. Now the chemical energy with which the iodine atom is bound in the ethyl-iodide molecule is only about three or four electron volts. The energy of recoil is so much greater than the strength of the chemical bond that every I-128 atom is ejected from its molecule with considerable force. Hot atom chemistry is concerned with the unusual chemical reactions that these high-velocity iodine atoms undergo after they are expelled from the molecule. Since the 1-128 atoms are radioactive, it is relatively easy to trace them through their subsequent activities.

To what uses can hot atom chemistry be put? One of the obvious uses is the preparation of extremely concentrated sources of radioactivity. This technique should be of assistance in many purposes for which radioactive material is used, notably in biology. When a radioactive isotope is injected into the body, either as a tracer or in a treatment for disease, it is often essential that the amount of material injected be held to a minimum, in order to avoid disturbance of the normal constitution of the blood or the normal metabolism of the body.

Our picture was sharp enough to deduce the arrangement of the protein myoglobin's 2,600 atoms.
—John C. Kendrew, 1961

Biology

THE CHEMISTRY OF LIFE

THE THREE-DIMENSIONAL STRUCTURE OF A PROTEIN MOLECULE

BY JOHN C. KENDREW
PUBLISHED IN DECEMBER 1961

NOBEL PRIZE IN 1962

When the early explorers of America made their first landfall, they had the unforgettable experience of glimpsing a New World that no European had seen before them. Moments such as this—first visions of new worlds—are one of the main attractions of exploration. From time to time scientists are privileged to share excitements of the same kind. Such a moment arrived for my colleagues and me one Sunday morning in 1957, when we looked at something no one before us had seen: a three-dimensional picture of a protein molecule in all its complexity. This first picture was a crude one, and two years later we had an almost equally exciting experience, extending over many days that were spent feeding data to a fast computing machine, of building up by degrees a far sharper picture of this same molecule. The protein was myoglobin, and our new picture was sharp enough to enable us to deduce the actual arrangement in space of nearly all of its 2,600 atoms. We had chosen myoglobin for our first attempt because, complex though it is, it is one of the smallest and presumably the simplest of protein molecules, some of which are 10 or even 100 times larger.

In a real sense, proteins are the

"works" of living cells. Almost all chemical reactions that take place in cells are catalyzed by enzymes, and all known enzymes are proteins; an individual cell contains perhaps 1,000 different kinds of enzyme, each catalyzing a different and specific reaction. Proteins have many other important functions, being constituents of bone, muscle and tendon, of blood, of hair and skin and membranes. In addition to all this it is now evident that the hereditary information, transmitted from generation to generation in the nucleic acid of the chromosomes, finds its expression in the characteristic types of protein molecule synthesized by each cell. Clearly to understand the behavior of a living cell it is necessary first to find out how so wide a variety of functions can be assumed by molecules all made up for the most part of the same few basic units.

These units are amino acids, about 20 in number, joined together to form the chains known as polypeptides. The hemoglobin in red blood corpuscles contains four polypeptide chains. Myoglobin is a junior relative of hemoglobin, consisting of a single polypeptide chain.

Even in the present incomplete state of our studies on myoglobin we are beginning to think of a protein molecule in terms of its three-dimensional chemical structure and hence to find rational explanations for its chemical behavior and physiological function, to understand its affinities with related proteins and to glimpse the problems involved in explaining the synthesis of proteins in living organisms and the nature of the malfunctions resulting from errors in this process. It is evident that today students of the living organism do indeed stand on the threshold of a new world. Analyses of many other proteins, and at still higher resolutions (such as we hope soon to achieve with myoglobin), will be needed before this new world can be fully invaded, and the manifold interactions between the giant molecules of living cells must be comprehended in terms of well-understood concepts of chemistry.

Nevertheless, the prospect of establishing a firm basis for an understanding of the enormous complexities of structure, of biogenesis and of function of living organisms in health and disease is now distinctly in view.

GENETIC REPRESSORS

BY MARK PTASHNE AND WALTER GILBERT
PUBLISHED IN JUNE 1970

NOBEL PRIZE IN 1980 (GILBERT)

How are genes controlled? All cells must be able to turn their genes on and off. For example, a bacterial cell may need different enzymes in order to digest a new food offered by a new environment. As a simple virus goes through its life cycle its genes function sequentially, directing a series of timed events. As more complex organisms develop from the egg, their cells switch thousands of different genes on and off, and the switching continues throughout the organism's life cycle. This switching requires the action of many specific controls. During the past 10 years one mechanism of such control has been elucidated in molecular terms: the control of specific genes by molecules called repressors. Detailed understanding of control by repressors has come primarily through genetic and biochemical experiments with the bacterium *Escherichia coli* and certain viruses that infect it.

The repressor binds, or attaches, directly to the DNA molecule at the beginning of the set of genes it controls, at a site called the operator, preventing the RNA polymerase from transcribing the gene into RNA and thus turning off the gene. Each set of independently regulated genes is controlled by a different repressor made by a different repressor gene.

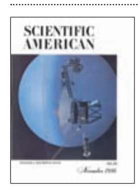
The repressor determines when the gene turns on and off by functioning as an intermediate between the gene and an appropriate signal. Such a signal is often a small molecule that sticks to the repressor and alters or slightly distorts its shape. In some cases this change in shape renders the repressor inactive, that is, no longer able to bind to the operator, and so the gene is no longer repressed; the gene turns on when the small molecule, which here is called an inducer, is present. In other cases the complex of the repressor and the small molecule is the active form; the repressor is only able to bind to the operator when the small molecule (here called a corepressor) is present.

Richard Burgess and Andrew Travers of Harvard University and Ekkehard Bautz and John J. Dunn of Rutgers University have shown that RNA polymerase, which initiates the synthesis of RNA chains at the promoters, contains an easily dissociated subunit that is required for proper initiation. This subunit, the sigma factor, endows the enzyme to which it is complexed with the ability to read the correct promoters. Travers has shown that the *E. coli* phage T4 produces a new sigma factor that binds to the bacterial polymerase and enables it to read phage genes that the original enzyme-sigma complex cannot read. This change explains part of the timing of events after infection with T4.

The first proteins made are synthesized under the direction of the bacterial sigma factor; among these proteins is a new sigma factor that directs the enzyme to read new promoters and make a new set of proteins. This control by changing sigma factors can regulate large blocks of genes. We imagine that in *E. coli* there are many classes of promoters and that each class is recognized by a different sigma factor, perhaps in conjunction with other large and small molecules.

Both the turning on and the turning off of specific genes depend ultimately on the same basic elements we have discussed here: the ability to recognize a specific sequence along the DNA molecule and to respond to molecular signals from the environment. The biochemical experiments with repressors demonstrate the first clear mechanism of gene control in molecular terms. Our detailed knowledge in this area has provided some tools with which to explore other mechanisms.

RNA AS AN ENZYME



BY THOMAS R. CECH
PUBLISHED IN NOVEMBER 1986

NOBEL PRIZE IN 1989

In a living cell the nucleic acids DNA and RNA contain the information needed for metabolism and reproduction. Proteins, on the other hand, are functional molecules: acting as enzymes, they catalyze each of the thousands of chemical reactions on which cellular metabolism is based. Until recently it was generally accepted that the categories are exclusive. Indeed, the division of labor in the cell between informational and catalytic molecules was a deeply held principle of biochemistry. Within the past few years, however, that neat scheme has been overturned by the discovery that RNA can act as an enzyme.

The first example of RNA catalysis was discovered in 1981 and 1982 while my colleagues and I were studying an RNA from the protozoan *Tetrahymena thermophila*. Much to our surprise, we found that this RNA can catalyze the cutting and splicing that leads to the removal of part of its own length. If one could overlook the fact that it was not a protein, the *Tetrahymena* RNA came close to fulfilling the definition of an enzyme.

What does the startling finding of RNA enzymes imply? The first implication is that one can no longer assume a protein lies behind every catalytic activity of the cell. It now appears that several of the operations that tailor an RNA molecule into its final form are at least in part catalyzed by RNA. Moreover, the ribosome (the organelle on which proteins are assembled) includes several molecules of RNA, along with a variety of proteins. It may be that the RNA of the ribosome—rather than its protein—is the catalyst of protein synthesis, one of the most fundamental biological activities. RNA catalysis also has evolutionary implications. Since nucleic acids and proteins are interdependent, it has often been argued that they must have evolved together. The finding that RNA can be a catalyst as well as an informational molecule suggests that when life originated, RNA may have functioned without DNA or proteins.

Having wandered back into the prebiotic past, it is fun to peer into the future and speculate about where the next examples of RNA catalysis might be found. In all known examples the substrate for the RNA enzyme has been RNA: another part of the same molecule, a different RNA polymer or a single nucleotide. This is probably not accidental. RNA is well suited to interacting with other RNAs, but it is more difficult to envision RNA forming a good active site with other biologically significant molecules such as amino acids or fatty acids. Hence I expect that future examples of RNA catalysis will also entail RNA as the substrate.

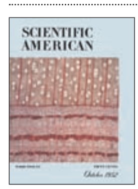
Two possibilities come to mind. One involves the small nuclear ribonucleoprotein particles (snRNPs) required for many operations in the nucleus. The other possibility is the ribosome.

The conclusion that protein synthesis is catalyzed by RNA would be a final blow to the idea that all cellular function resides in proteins. Of course, it may not be so; the ribosome may be such an intimate aggregation of protein and nucleic acid that its catalytic activity cannot be assigned exclusively to either component. Yet whether or not the synthetic activity of the ribosome can be attributed to the ribosomal RNA, a fundamental change has taken place in biochemistry in the past five years. It has become evident that, in some instances at least, information-carrying capacity and catalytic activity inhere in the same molecule: RNA. The implications of this dual capacity are only beginning to be understood.

EARTH SCIENCE

UP IN THE AIR

THE ORIGIN OF THE EARTH



BY HAROLD C. UREY
PUBLISHED IN OCTOBER 1952
NOBEL PRIZE IN 1934

Aristarchus of the Aegean island of Samos first suggested that the earth and the other planets moved about the sun—an idea that was rejected by astronomers until Copernicus proposed it again 2,000 years later. The Greeks knew the shape and the approximate size of the earth, and the cause of eclipses of the sun. After Copernicus, the Danish astronomer Tycho Brahe watched the motions of the planet Mars from his observatory on the Baltic island of Hveen; as a result Johannes Kepler was able to show that Mars and the earth and the other planets move in ellipses about the sun. Then the great Isaac Newton proposed his universal law of gravitation and laws of motion, and from these it was possible to derive an exact description of the entire solar system. This occupied the minds of some of the greatest scientists and mathematicians in the centuries that followed.

Unfortunately it is a far more difficult problem to describe the origin of the solar system than the motion of its parts. Indeed, what was the process by which the earth and other planets were formed? None of us was there at the time, and any suggestions that I may make can hardly be considered as certainly true. The most that can be done is to outline a possible course of events which does not contradict physical laws and observed facts.

A vast cloud of dust and gas in an empty region of our galaxy was compressed by starlight. Later gravitational forces accelerated the accumulation process. In some way which is not yet clear the sun was formed, and produced light and heat much as it does today. Around the sun wheeled a cloud of dust and gas which broke up into turbulent eddies and formed protoplanets, one for each of the planets and probably one for each of the larger asteroids between Mars and Jupiter. At this stage in the process the accumulation of large planetesimals took place through the condensation of water and ammonia. Among these was a rather large planetesimal which made up the main body of the moon; there was also a larger one that eventually formed the earth. The temperature of the planetesimals at first was low, but later rose high enough to melt iron. In the low-temperature stage water accumulated in these objects, and at the high-temperature stage carbon was captured as graphite and iron carbide. Now the gases escaped, and the planetesimals combined by collision.

So, perhaps, the earth was formed!

But what has happened since then? Many things, of course, among them the evolution of the earth's atmosphere. At the time of its completion as a solid body, the earth very likely had an atmosphere of water vapor, nitrogen, methane, some hydrogen and small amounts of other gases. J.H.J. Poole of the University of Dublin has made the fundamental suggestion that the escape of hydrogen from the earth led to its oxidizing atmosphere. The hydrogen of methane (CH_4) and ammonia (NH_3) might slowly have escaped, leaving nitrogen, carbon dioxide, water and free oxygen. I believe this took place, but many other molecules containing hydrogen, carbon, nitrogen and oxygen must have appeared before free oxygen. Finally life evolved, and photosynthesis, that basic process by which plants convert carbon dioxide and water into foodstuffs and oxygen. Then began the development of the oxidizing atmosphere as we know it today. And the physical and chemical evolution of the earth and its atmosphere is continuing even now.

THE CHANGING ATMOSPHERE

BY THOMAS E. GRAEDEL AND PAUL J. CRUTZEN
PUBLISHED IN SEPTEMBER 1989

NOBEL PRIZE IN 1995 (CRUTZEN)

The earth's atmosphere has never been free of change: its composition, temperature and self-cleansing ability have all varied since the planet first formed. Yet the pace in the past two centuries has been remarkable: the atmosphere's composition in particular has changed significantly faster than it has at any time in human history.

The increasingly evident effects of the ongoing changes include acid deposition by rain and other processes, corrosion of materials, urban smog and a thinning of the stratospheric ozone (O_3) shield that protects the earth from harmful ultraviolet radiation. Atmospheric scientists expect also that the planet will soon warm rapidly (causing potentially dramatic climatic shifts) through enhancement of the greenhouse effect—the heating of the earth by gases that absorb infrared radiation from the sun-warmed surface of the planet and then return the radiation to the earth.

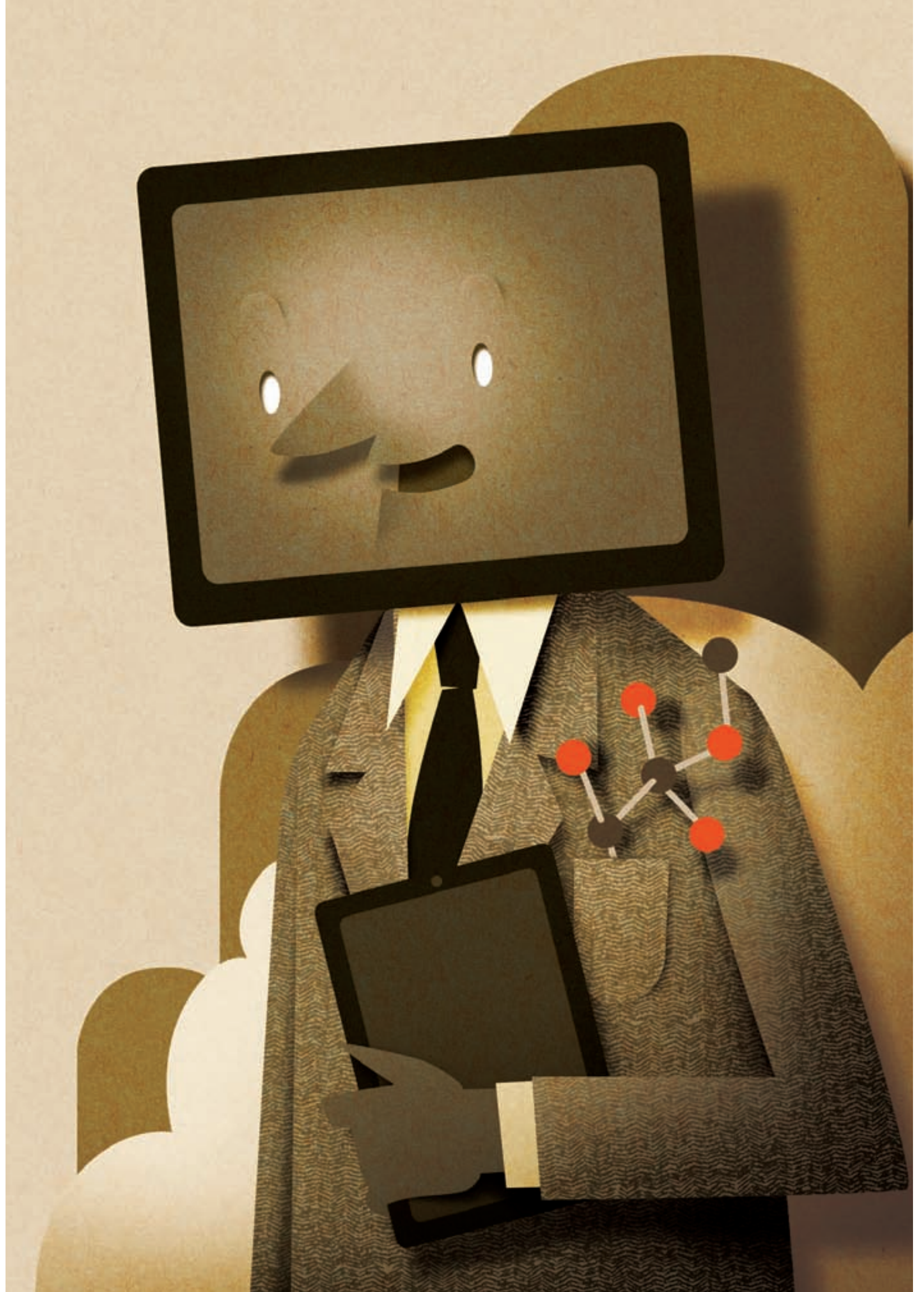
Certainly some fluctuation in the concentrations of atmospheric constituents can derive from variations in rates of emission by natural sources. Volcanoes, for instance, can release sulfur- and chlorine-containing gases into the troposphere (the lower 10 to 15 kilometers of the atmosphere) and the stratosphere (extending roughly from 10 to 50 kilometers above the surface). The fact remains, however, that the activities of human beings account for most of the rapid changes of the past 200 years. Such activities include the combustion of fossil fuels (coal and petroleum) for energy, other industrial and agricultural practices, biomass burning (the burning of vegetation) and deforestation.

Our projections for the future are discouraging if one assumes that human activities will continue to emit large quantities of undesirable trace gases into the atmosphere. Humanity's unremitting growth and development not only are changing the chemistry of the atmosphere but also are driving the earth rapidly toward a climatic warming of unprecedented magnitude. This climatic change, in combination with increased concentrations of various gases, constitutes a potentially hazardous experiment in which everyone on the earth is taking part.

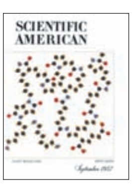
What is particularly troubling is the possibility of unwelcome surprises, as human activities continue to tax an atmosphere whose inner workings and interactions with organisms and nonliving materials are incompletely understood. The Antarctic ozone hole is a particularly ominous example of the surprises that may be lurking ahead. Its unexpected severity has demonstrated beyond doubt that the atmosphere can be exquisitely sensitive to what seem to be small chemical perturbations and that the manifestations of such perturbations can arise much faster than even the most astute scientists could expect.

Nevertheless, some steps can be taken to counteract rapid atmospheric change, perhaps lessening the known and unknown threats. For example, evidence indicates that a major decrease in the rate of fossil-fuel combustion would slow the greenhouse warming, reduce smog, improve visibility and minimize acid deposition. Other steps could be targeted against particular gases, such as methane. Its emission could be reduced by instituting landfill operations that prevent its release and possibly by adopting less wasteful methods of fossil-fuel production. Methane emission from cattle might even be diminished by novel feeding procedures.

We and many others think the solution to the earth's environmental problems lies in a truly global effort, involving unprecedented collaboration by scientists, citizens and world leaders. The most technologically developed nations have to reduce their disproportionate use of the earth's resources. Moreover, the developing countries must be helped to adopt environmentally sound technologies and planning strategies as they elevate the standard of living for their populations, whose rapid growth and need for increased energy are a major cause for environmental concern. With proper attention devoted to maintaining the atmosphere's stability, perhaps the chemical changes that are now occurring can be kept within limits that will sustain the physical processes and the ecological balance of the planet.



HOW GIANT MOLECULES ARE MADE



BY GIULIO NATTA
PUBLISHED IN SEPTEMBER 1957
NOBEL PRIZE IN 1963

A chemist setting out to build a giant molecule is in the same position as an architect designing a building. He has a number of building blocks of certain shapes and sizes, and his task is to put them together in a structure to serve a particular purpose. The chemist works under the awkward handicap that his building blocks are invisible, because they are submicroscopically small, but on the other hand he enjoys the happy advantage that nature has provided models to guide him.

By studying the giant molecules made by living organisms, chemists have learned to construct molecules like them. What makes high-polymer chemistry still more exciting just now is that almost overnight, within the last few years, there have come discoveries of new ways to put the building blocks together—discoveries which promise a great harvest of new materials that have never existed on the earth.

We can hardly begin to conceive how profoundly this new chemistry will affect man's life. Giant molecules occupy a very large place in our material economy. Tens of millions of men and women, and immense areas of the earth's surface, are devoted to production of natural high polymers, such as cellulose, rubber and wool. Now it appears that synthetic materials of equivalent or perhaps even better properties can be made rapidly and economically from coal or petroleum. Among other things, this holds forth the prospect that we shall be able to turn much of the land now used for the production of fiber to the production of food for the world's growing population.

Free radicals are one type of catalyst that can grow polymers by addition; another method involves the use of ions as catalysts. The latter is a very recent development, and to my mind it portends a revolution in the synthesis of giant molecules, opening up large new horizons. The cationic method has produced some very interesting high polymers: for instance, butyl rubber, the synthetic rubber used for tire inner tubes. But the anionic catalysts, a more recent development, have proved far more powerful. They yield huge, made-to-order molecules with extraordinary properties.

Early in 1954 our group in the Institute of Industrial Chemistry of the Polytechnic Institute of Milan, using certain special catalysts, succeeded in polymerizing complex monomers of the vinyl family. We were able to generate chains of very great length, running to molecular weights in the millions (up to 10 million in one case). We found that it was possible, by a proper choice of catalysts, to control the growth of chains according to predetermined specifications.

Among the monomers we have polymerized in this way are styrene and propylene, both hydrocarbons derived from petroleum. The polypropylenes we have made illustrate the versatility of the method. We can synthesize them in three forms: isotactic, atactic or "block isotactic," that is, a chain consisting of blocks, one having all the side groups aligned on one side, the other on the opposite side. The isotactic polypropylene is a highly crystalline substance with a high melting point (346 degrees Fahrenheit); it makes very strong fibers, like those of natural silk or nylon. The atactic product, in contrast, is amorphous and has the elastic properties of rubber. The block versions of polypropylene have the intermediate characteristics of a plastic, with more or less rigidity or elasticity.

The possibility of obtaining such a wide array of different products from the same raw material naturally aroused great interest. Furthermore, the new controlled processes created properties not attainable before: for example, polystyrene, which had been known only as a glassy material with a low softening point (under 200 degrees F), now could be prepared as a strong, crystalline plastic with a melting point near 460 degrees. The new-found power of the anionic catalysts stimulated great activity in polymer research, both in Europe and in the U.S. New polymers were made from various monomers. In our own laboratory we synthesized all of the regular polymers, and some amorphous ones, that can be made from butadiene; some of the products are rubber-like, others not. At about the same time the B. F. Goodrich Company and the Firestone Tire and Rubber Company both announced that they had synthesized, from isoprene, a rubber identical to natural rubber—a problem on which chemists throughout the world had worked in vain for more than half a century.

In some respects we can improve on nature. As I have mentioned, we shall probably be able to create many new molecules which do not exist in living matter. They can be made from simple, inexpensive materials. And we can manufacture giant molecules more rapidly than an organism usually does. Although it is less than four years since the new methods for controlled synthesis of macromolecules were discovered, already many new synthetic substances—potential fibers, rubbers and plastics—have been made.

> We can improve on nature. We shall probably create many new molecules which do not exist in living matter. *—Giulio Natta, 1957*

PLASTICS THAT CONDUCT ELECTRICITY

BY RICHARD B. KANER AND ALAN G. MacDIARMID

PUBLISHED IN FEBRUARY 1988

NOBEL PRIZE IN 2000 (MacDIARMID)

To most people the title of this article would have seemed absurd 20 years ago, when conceptual prejudice had rigidly categorized plastics as insulators. The suggestion that a plastic could conduct as well as copper would have seemed even more ludicrous. Yet in the past few years these feats have been achieved through simple modifications of ordinary plastics. Called conducting polymers, the new materials combine the electrical properties of metals with the advantages of plastics that stirred such excitement in the 1930s and 1940s.

To make a polymer conduct electricity, small quantities of certain chemicals are incorporated into the polymer by a process called doping. The procedure for doping polymers is much simpler than the one used to dope classical semiconductors such as silicon.

Once the potential of polymers as conductors had been demonstrated, the idea took off. In 1977 the first conducting polymer was synthesized; in 1981 the first battery with polymer electrodes was demonstrated. Last summer conducting polymers matched the conductivity of copper, and a few months ago the first rechargeable polymer battery was put on the market.

Subsequent advances suggest that polymers may be made that conduct better than copper; better, indeed, than any other material at room temperature. They may even replace copper wires in circumstances where weight is a limiting factor, as in aircraft. Conducting polymers also have interesting optical, mechanical and chemical properties that, taken together with their ability to conduct, might make them effective in novel applications where copper would not do. For instance, thin polymer layers on windows could absorb sunlight, and the degree of tinting could be controlled by means of an applied electric potential.

The human body is another "device" in which conducting polymers might someday play a part. Because they are inert and stable, some polymers have been considered for neural prostheses—artificial nerves. Polypyrrole in particular is thought to be nontoxic and can reliably deliver an appropriate electric charge. The dopant ion here might be heparin, a chemical that inhibits the clotting of blood and is known to function quite adequately as a dopant in polypyrrole. Alternatively, polymers could act as internal drug-delivery systems, planted inside the body and doped with molecules that double as drugs. The drug would be released when the polymer was transformed to its neutral state by a programmed application of an electric potential.

In many ways the status of conducting polymers in the mid-1980s is similar to that of conventional polymers 50 years ago. Although conventional polymers were synthesized and studied in laboratories around the world, they did not become technologically useful substances until they had been subjected to chemical modifications that took years to develop. Likewise, the chemical and physical properties of conducting polymers must be fine-tuned to each application if the products are to be economically successful. Regardless of the practical applications that might be found for conducting polymers, they will certainly challenge basic research in the years to come with new and unexpected phenomena. Only time will tell whether the impact of these novel plastic conductors will equal that of their insulating relatives.

FILMING THE INVISIBLE IN 4-D

BY AHMED H. ZEWAIL
PUBLISHED IN AUGUST 2010
NOBEL PRIZE IN 1999

The human eye is limited in its vision. We cannot see objects much thinner than a human hair (a fraction of a millimeter) or resolve motions quicker than a blink (a tenth of a second). Advances in optics and microscopy over the past millennium have, of course, let us peer far beyond the limits of the naked eye, to view exquisite images such as a micrograph of a virus or a stroboscopic photograph of a bullet at the millisecond it punched through a lightbulb. But if we were shown a movie depicting atoms jiggling around, until recently we could be reasonably sure we were looking at a cartoon, an artist's impression or a simulation of some sort.

In the past 10 years my research group at the California Institute of Technology has developed a new form of imaging, unveiling motions that occur at the size scale of atoms and over time intervals as short as a femtosecond (a million billionth of a second). Because the technique enables imaging in both space and time and is based on the venerable electron microscope, I dubbed it four-dimensional (4-D) electron microscopy. We have used it to visualize phenomena such as the motion of sheets of carbon atoms in graphite vibrating like a drum after being "struck" by a laser pulse, and the transformation of matter from one state to another. We have also imaged individual proteins and cells.

Although 4-D microscopy is a cutting-edge technique that relies on advanced lasers and concepts from quantum physics, many of its principles can be understood by considering how scientists developed stop-motion photography more than a century ago. In particular, in the 1890s, Étienne-Jules Marey, a professor at the Collège de France, studied fast motions by placing a rotating disk with slits in it between the moving object and a photographic plate or strip, producing a series of exposures similar to modern motion picture filming.

Among other studies, Marey investigated how a falling cat rights itself so that it lands on its feet. With nothing but air to push on, how did cats instinctively perform this acrobatic feat without violating Newton's laws of motion? The fall and the flurry of legs took less than a second—too fast for the unaided eye to see precisely what happened. Marey's stop-motion snapshots provided the answer, which involves twisting the hindquarters and forequarters in opposite directions with legs extended and retracted.

If we wish to observe the behavior of a molecule instead of a feline, how fast must our stroboscopic flashes be? My group attacked this challenge by developing single-electron imaging, which built on our earlier work with ultrafast electron diffraction. Each probe pulse contains a single electron and thus provides only a single "speck of light" in the final movie. Yet thanks to each pulse's careful timing and another property known as the coherence of the pulse, the many specks add up to form a useful image of the object.

Single-electron imaging was the key to 4-D ultrafast electron microscopy (UEM). We could now make movies of molecules and materials as they responded to various situations, like so many startled cats twisting in the air.

My colleagues and I investigated how quickly a short length of protein would fold into one turn of a helix by heating the water in which the protein was immersed—a so-called ultrafast temperature jump. (Helices occur in innumerable proteins.) We found that short helices formed more than 1,000 times faster than researchers have thought—arising in hundreds of picoseconds to a few nanoseconds rather than the microseconds commonly believed. Knowing that such rapid folding occurs may lead to new understanding of biochemical processes, including those involved in diseases.

Very recently, my Caltech group demonstrated two new techniques. In one, convergent-beam UEM, the electron pulse is focused and probes only a single nanoscopic site in a specimen. The other, near-field UEM, enables imaging of the evanescent electromagnetic waves ("plasmons") created in nanoscopic structures by an intense laser pulse—a phenomenon that underlies an exciting new technology known as plasmonics. This technique has produced images of bacterial cell membranes and protein vesicles with femtosecond- and nanometer-scale resolution.

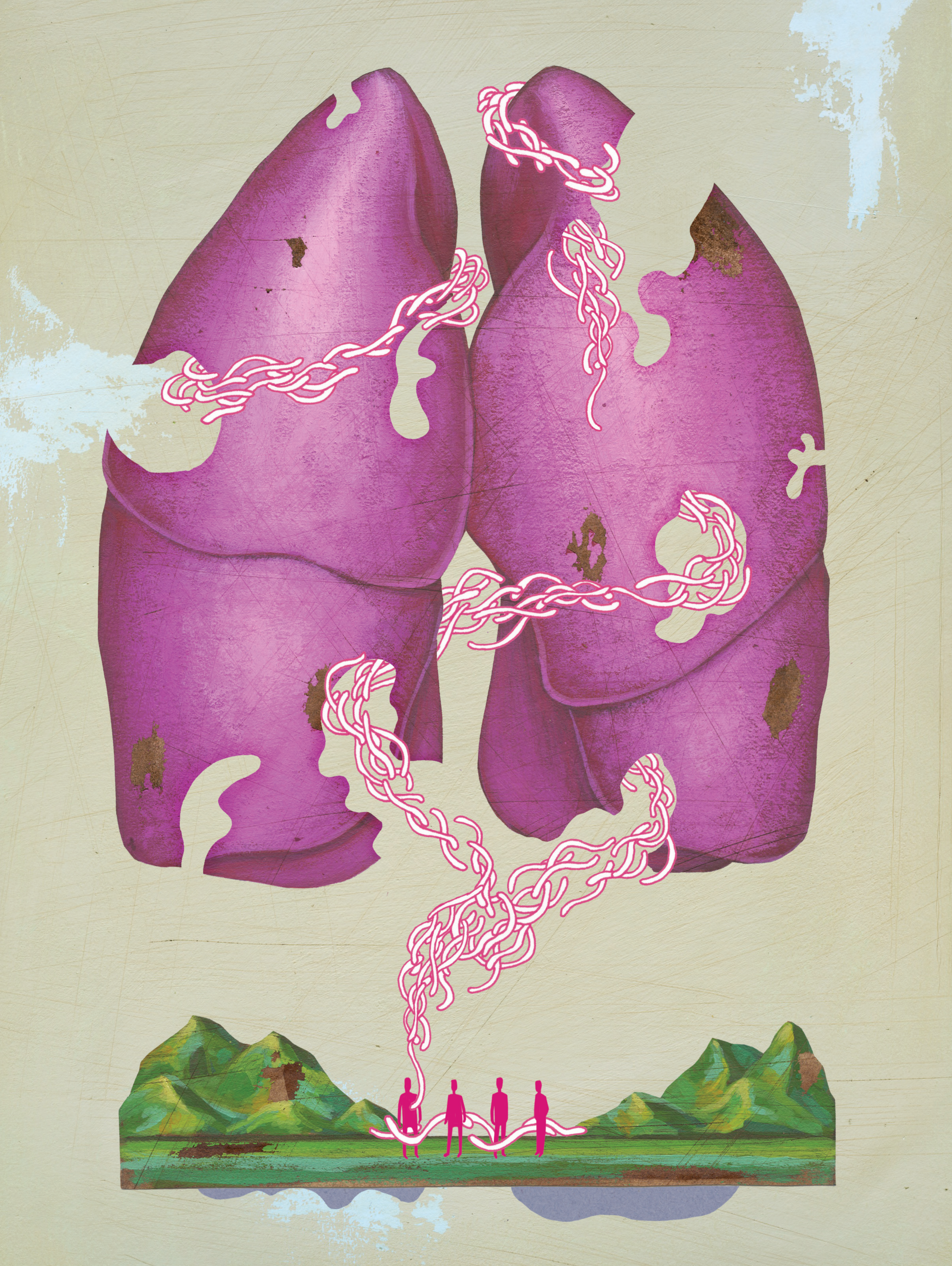
The electron microscope is extraordinarily powerful and versatile. It can operate in three distinct domains: real-space images, diffraction patterns and energy spectra. It is used in applications ranging from materials and mineralogy to nanotechnology and biology, elucidating static structures in tremendous detail. By integrating the fourth dimension, we are turning still pictures into the movies needed to watch matter's behavior—from atoms to cells—unfolding in time. SA

***Ferris Jabr** is an associate editor at* Scientific American.

MORE TO EXPLORE

A Nobel Celebration. Ferris Jabr in *Scientific American,* Vol. 304, No. 6, pages 54–63; June 2011.
10 Unsolved Mysteries in Chemistry. Philip Ball in *Scientific American,* Vol. 305, No. 4; pages 48–53; October 2011.
Nobel Pursuits. John Matson and Ferris Jabr in *Scientific American,* Vol. 307, No. 1, pages 62–73; July 2012.

SCIENTIFIC AMERICAN ONLINE
Read profiles of 30 up-and-coming chemists and view an interactive periodic table at **ScientificAmerican.com/jul2013/lindau**



GLOBAL HEALTH

The Diabolical Genius of an Ancient Scourge

Tuberculosis seems to be evolving in unexpected ways that outsmart humans

By Sally Lehrman

TODAY MOST PEOPLE IN THE RICHER PARTS OF THE WORLD THINK of tuberculosis, if they think of it at all, as a ghost of history. Throughout ancient times the tenacious bacterial infection consumed the bodies of untold millions, rich and poor, filling their lungs with bloody sputum. As TB spread in the centuries that followed, it continued to attack across economic and class lines, affecting both the famous and the obscure. Among its better-known victims: poet Manuel Bandeira, writers Emily and Anne Brontë, and sculptor Frédéric-Auguste Bartholdi, who designed the Statue of Liberty. By the early 20th century humanity had begun fighting back with public health campaigns, improved living standards, and eventually antibiotics and a modestly effective vaccine. Although in 2011 TB sickened nearly nine million people, killing 1.4 million of them, mostly in the poorer regions of the globe, the mortality rate has nonetheless fallen by more than a third since 1990. Things are looking up—or so it may seem.

Illustration by Daniel Chang

New genetic research, however, suggests that the bacterium responsible for TB could be poised to emerge stronger and more deadly than ever before—and not just because some strains have become resistant to treatment with the standard set of antibiotics. A small but increasingly influential group of investigators believes that the microbe, *Mycobacterium tuberculosis,* may have evolved along an unexpected and particularly dangerous path. The scientists have discovered that TB can be divided into seven families of genetically related strains, at least one of which is surprisingly virulent, prone to drug resistance and especially well suited to spreading disease in our increasingly interconnected, densely populated world.

At the same time, researchers worry that current approaches to treatment and the sole, partially effective vaccine may actually be helping the bacterium to become more intractable. Clinicians have long known that incomplete treatment can produce antibiotic-resistant TB strains. Yet they are now realizing that even successful interventions can be problematic if they are better at weeding out the milder, slower-growing groups of TB microbes. This divergent effect would allow the more aggressive, faster-spreading bacterial families to establish a stronger foothold.

What is more, efforts to develop new therapies and diagnostic tests may be doomed to fail if the strains being targeted are not the ones that are spreading around the planet. If these fears are realized, TB rates could one day begin rising again globally, and the disease could become harder to treat and spread more widely among populations that have so far been relatively free of the scourge.

Still, there is room for hope. The genetic work provides some insight into how to fight back against the more worrisome groups of TB germs. "Maybe the goal shouldn't be to eradicate the disease," suggests Clifton E. Barry III, chief of tuberculosis research at the National Institute of Allergy and Infectious Diseases. Instead of trying to eliminate all disease-causing TB microbes, he and others propose, the aim should perhaps be to favor bacteria that are milder and more likely to stay in a dormant state. Engineering such a successful standoff is, of course, a difficult and complex proposition.

A MYSTERIOUS OUTBREAK

THE LATEST FINDINGS grew out of research into another dismaying surprise that TB unleashed on public health experts, starting in 1986. That year officials in New York City were completely caught off guard by an aggressive outbreak of multidrug-resistant TB that took about a decade and hundreds of millions of dollars to bring under control—mostly by rigorously tracking patients with active illness and making sure that they finished six to nine months of treatment with a combination of antibiotics. (In some cases, it takes two years to kill all the bacteria present.)

Sally Lehrman is a journalist who covers medicine and science policy. She is writing a book about health disparities for Oxford University Press.

At the time, experts had become so confident in their ability to control TB that most programs meant to detect tuberculosis cases had been shut down and funding for research had slowed to a trickle. The National Institutes of Health reduced its spending on TB to a meager $300,000 in 1985, and the academics who studied TB could, according to one researcher, practically squeeze themselves into a single minivan. In New York City—which for more than a century had been the site of both the illness's worst ravages and the greatest public health strides against TB—only eight treatment clinics were still open by the late 1980s.

Within a few years the steady decline in cases stopped, and without apparent warning, the trend line reversed itself. Standard anti-TB medicines could no longer predictably tame the infection, even with a diligent patient who stuck to the arduous regimen.

Alarmed public health authorities considered all the possible explanations. Many of the new cases occurred in recent immigrants and some HIV patients, which made sense. About a third of the global population harbors a latent TB infection until something—such as stress or another illness—reactivates the bugs, leading both the bacteria and the body's own immune response to attack lung tissue, setting transmission to other individuals into motion. Immigrants were arriving from Southeast Asia, East Asia and Mexico, where TB rates were 10 to 30 times higher than in the U.S. The high incidence in HIV patients in the mid-1980s also seemed logical because those individuals often had compromised immune systems, which might allow a latent infection to become active.

Yet those standard explanations for the outbreak did not fit all the facts. This time around, tuberculosis was spreading faster through New York City's vulnerable populations than anyone had seen for at least a couple of generations, and people were dying at a much higher rate than normal. Something else had to be driving TB's reemergence, which quickly began claiming lives in Florida, Hawaii, Texas and California as well.

NEW INSIGHT

THE ANSWER, at least in part, turned out to be activity by a formerly unrecognized group of TB bacteria that spread more readily and are more deadly than the classic bug, which tends to proliferate slowly and enters a long quiescent phase after the

IN BRIEF

More than one million men, women and children around the globe die of tuberculosis every year, and about a third of the world's population harbors a latent infection.

A growing number of studies suggest that TB may be evolving into a new bug that is far more deadly, spreads more quickly and is more likely to become resistant to treatment with antibiotics.

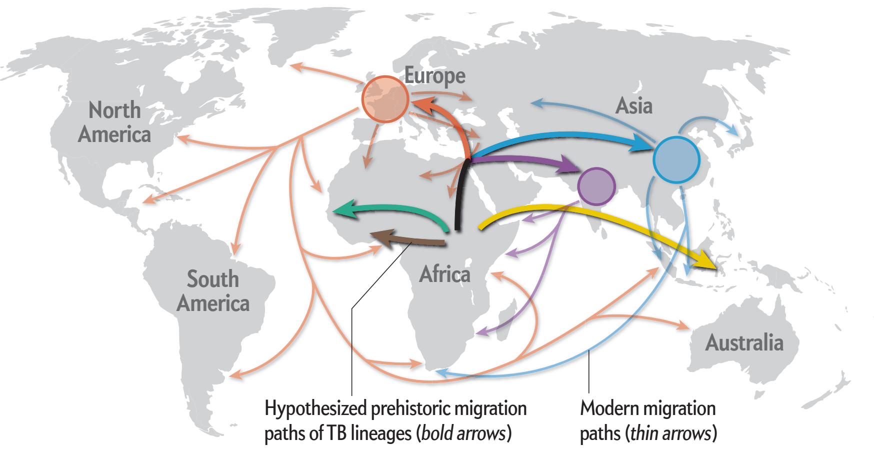
Designers of new treatments should take these latest findings into account if they do not want to make matters worse. Changing the host environment with improved housing, for example, may also prove key.

How TB Conquered the World

Scientists have long assumed that tuberculosis emerged around 10,000 years ago, when humans began domesticating cattle. Recent genetic analysis suggests, however, that the TB germ may in fact predate the first major human migration 60,000 to 70,000 years ago. As TB-infected people spread across the world, the pathogen eventually evolved into at least seven families, or lineages.

Out of Africa and Back Again

The two oldest families of TB germs began in West Africa, where they are still found. Four more lineages took hold around the Indian Ocean and in India, East Asia and Europe. Further migration and colonization led to a greater spread. Still unclear: why the slave trade did not establish the West African lineages in the Americas.



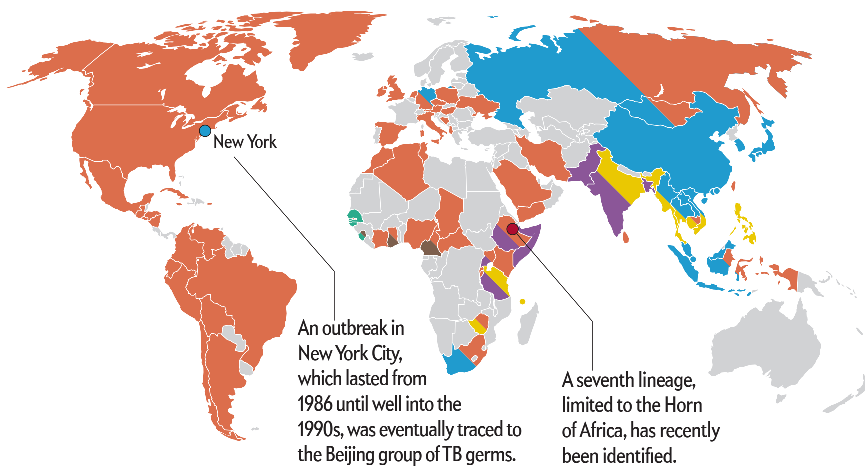
Major TB Lineages

Ancient
- West African 1
- West African 2
- Indo-Oceanic
- Hypothesized common ancestor of modern lineages

Modern
- Euro-American
- East African–Indian
- East Asian

Current Distribution

Different families of TB germs spread at different rates. Africa is the only continent where all the TB lineages that have so far been identified can still be found. A particularly dangerous member of the East Asian family of TB germs, known as the Beijing group, is now threatening the globe.



SOURCE: "HIGH FUNCTIONAL DIVERSITY IN *MYCOBACTERIUM TUBERCULOSIS* DRIVEN BY GENETIC DRIFT AND HUMAN DEMOGRAPHY," BY RUTH HERSHBERG ET AL. IN *PLOS BIOLOGY*, VOL. 6, NO. 12; DECEMBER 16, 2008 *(top)*; "VARIABLE HOST-PATHOGEN COMPATIBILITY IN *MYCOBACTERIUM TUBERCULOSIS*," BY SEBASTIEN GAGNEUX ET AL., IN *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES USA*, VOL. 103, NO. 8; FEBRUARY 21, 2006 *(bottom)*

initial infection, including in untreated cases. The body, mounting an immune response, walls off the bacteria into a cavity, and the two begin an uneasy truce that can last for decades.

Today researchers call the newly identified collection of TB microbes the Beijing group (because the greatest concentration of cases was later found in the Chinese capital). Eventually they learned that it is a subset of one of six large families of TB germs. (A seventh family, found so far only in the Horn of Africa, has been reported in the past six months.) Until the early 1990s, no one had realized that *M. tuberculosis* even had multiple families.

The first clues that TB strains fall into distinct groups came in 1991 in San Francisco, during an outbreak in a homeless shelter for people with HIV. Peter Small, now a senior program officer at the Bill & Melinda Gates Foundation, was then a resident at San Francisco General Hospital, where he worked with Philip Hopewell, a prominent tuberculosis expert. Small had just learned how to track the spread of individual TB strains using certain patterns that appeared in their DNA—a powerful new molecular biology technique that was then being developed. While public health servants took up the time-honored task of contacting everyone who had come into contact with an infected person, Small was given the job of identifying and tracing the TB germs involved.

The results were frightening: of the 14 people from the shelter who had fallen ill over four months, Small found that 11 shared the same strain of tuberculosis, which was identified by its unique DNA fingerprint, a pattern of code letters found only in that strain. Having the same strain meant that the illness in those 11 individuals stemmed from recent transmission of the infection, as opposed to reactivation of latent infections (which would have yielded dissimilar genetic profiles). Furthermore, the progression from initial infection to full-blown disease and transmission to another person was lightning-fast.

Maps by XNR Productions

"It was a huge wake-up call," Small says. Investigators had expected to find reactivated disease in individuals with compromised immune systems, not new infections. And they were stunned by how quickly the bacterium spread from one person to the next and by how rapidly the illness progressed. HIV and TB seemed to be acting synergistically in their attacks on people's immune systems. A germ that raced through its latent stages faster and that was more infectious would be especially tough to bring under control and to keep contained.

When the team broadened its study to include immigrants, they found exactly the pattern that they had expected, which provided no comfort. This time genetic tests showed that the illness stemmed, as anticipated, mostly from latent infections that had been reactivated.

Not all the TB strains that the researchers found spread at the same rate, however, which was odd because they believed at the time that all strains behaved more or less alike. Small and his colleagues would find the TB fingerprint of one patient all over the city, whereas that of another, very similar patient would not show up in anyone else. "You couldn't help but think, 'Well, maybe the bacteria differ,' which was a pretty radical thought at the time," Small says.

Their findings had important implications for public health; clinicians needed to step up their efforts to reduce transmission and to ensure that patients completed their treatments. They also challenged researchers to rethink their understanding of the organism itself, including when tuberculosis might have first affected humans. If all TB strains belonged to one big family that caused illness in the same manner (as had long been assumed), chances were that *M. tuberculosis* had originated fairly recently, perhaps 10,000 years ago. If, on the other hand, separate families of TB microbes had evolved and were spreading at different rates, then the organism had probably been around much longer than anyone had suspected, giving it plenty of time to diversify. Indeed, in 2005 researchers at the Pasteur Institute in Paris performed a genetic analysis that suggested *M. tuberculosis* could have evolved from an ancestor species as early as three million years ago.

In the complex dialogue between the tuberculosis organism and the human body, some strains excel at inhibiting the immune system, whereas other strains boost it.

STARTLING EVIDENCE

THE SAN FRANCISCO BAY AREA turned out to be an ideal location to test the hypothesis that *M. tuberculosis* could be divided into distinct families of microbes associated with specific geographical regions. With immigrants from Africa, Latin America, Eastern Europe and multiple regions in Asia, it is, in many respects, a microcosm of the world. In the early 2000s a group of investigators—many of whom had worked with Small and Hopewell during the TB outbreak in San Francisco—began studying samples from various TB patients and comparing the molecular markers in their bacterial genomes.

Using 875 strains collected between 1991 and 2001 from individuals representing 80 countries, the group identified fragments of DNA present in some strains but not in others. Based on these differences, the scientists found that the strains sorted into six main families that had apparently originated in different regions of the world and, it also seemed, were still infecting people who had recently lived in those places. There were three ancient ones, including two found only in West Africa and another that arose in Africa, then migrated with humans along the Indian Ocean more than 60,000 years ago. Three more modern lineages developed in western Europe (traveling to the Americas at the end of the 19th century), northern India and East Asia (the Beijing group turned out to be a prominent member of this family). Africa was the only location that seemed to play host to all six lineages, although the Euro-American family was widespread, and the Beijing strains were rapidly gaining a foothold around the globe.

Working with population geneticist Marcus Feldman and others at Stanford University, Sebastian Gagneux, then at the Institute for Systems Biology in Seattle, traced each lineage's ancestral life story. By comparing the DNA sequences of 89 critical genes (most of which were vital to the bacterium's continued survival), Gagneux and his colleagues could estimate different lineages' ages and geographical movements. These so-called housekeeping genes are under tremendous evolutionary pressure to stay the same; any changes are more likely to harm rather than help the bug. So the more closely matched the strains, the more closely related they would be, and the most genetically diverse groups would belong to the oldest families.

The oldest TB lineages from Africa, the researchers theorized, may have taken root in small, scattered hunter-gatherer groups. At that time, limited opportunities for transmission may have produced TB's characteristic latency. It could, for instance, infect a child, wait a generation and reactivate in time to infect new family members. As ancient humans began to migrate over land, the group proposed, the organism tagged along, and the Indo-Oceanic lineage developed, taking advantage of an increasing population. Later migrations and population expansions provided fertile ground for the three more modern lineages to emerge and adapt to their hosts. As humans traveled, traded, crammed into crowded cities, went to war, and died, tuberculosis went along for the ride, causing increasingly frequent and more severe illness.

The genetic clustering among the lineages provided the evidence that the mycobacterium had evolved along with its hosts. Gagneux, emphasizing that it was all a careful guess, proposed an Out of and Back to Africa hypothesis. Modern lineages had emerged along early human migration routes out of Africa, he suggested, then had more recently gone back to the continent and out again. The Euro-American family of strains, for instance, followed colonization to Africa, Asia and the Middle East. The East Asian lineage moved to South Africa via Southeast Asian slaves in the 17th and 18th centuries, with another wave following via Chinese gold miners.

The diversification of the bacterial families and their dissemination around the globe pointed to a complex coevolution between host and pathogen that is probably still under way. Whenever people jammed into overcrowded living spaces, the more aggressive TB strains with shorter latency periods spread rapidly. Meanwhile the older, West African and Indo-Oceanic lineages, which tended to thrive in less populated areas, caused an illness that progressed more slowly. "If there are very few hosts, it doesn't pay to be very virulent, because you kill all your hosts, then you die out together with all your hosts," says Gagneux, who now heads up tuberculosis research at the Swiss Tropical and Public Health Institute in Basel. One two-year study in the Gambia seems to support this idea: patients exposed to the modern TB strains were nearly three times as likely to progress to active disease. In fact, the more aggressive strains of TB have begun overtaking the oldest pair of lineages even in Africa.

NOW WHAT?

ALL THE DATA GENERATED since the 1990s have consistently marked the Beijing group of strains as particularly worrisome. It seems to spread more easily and to cause more severe disease, and it may even be especially adept at becoming resistant to antibiotic drugs. In 1998 investigators determined that the aggressive strains that had spurred the outbreaks in New York City in the 1980s and 1990s fell within this group as well.

Just as important in fueling TB's continuing ravages around the globe are the environmental conditions under which people live. Small moved to India in 2011, where he still resides, to learn about the realities of living with TB in one of its most devastating breeding grounds. TB germs do not spread in a vacuum, he notes. People with tuberculosis might also be malnourished or alcoholic or might avoid taking medication. Not just HIV but also diabetes seems to interact synergistically with the organism to manipulate the immune response in ways that facilitate transmission and activation. Social conditions such as crowded housing, poor air quality, hunger and stigma tend to make matters worse.

The interplay of bacteria and human environments is worth noting, Small says. Investigators suspect that some strains of TB, for example, tend to provoke a brisk immune response, leading to the quick development of cavities in the lung and rapid progression from latency to illness. Other strains tend to suppress the immune system, making their home in different organs. In the complex dialogue between host and pathogen, Small says, "some of these strains seem to be really good at dialing down the immune system and others at dialing it up."

In a close examination of genetic molecules across a variety of strains, Small and Gagneux found that the bug did not follow the evolutionary pathway of most human pathogens. Instead of changing over time, the DNA that gave rise to the germ's outer proteins (the part that is recognized and targeted by the body's immune system) stayed the same. More typically, disease-causing bacteria are forced to change their protein coverings or risk being eliminated from the human population within a few generations. This bizarre finding has serious implications for some of the new vaccines that are now being developed against tuberculosis. Vaccines, by definition, are designed to boost the body's immune response to quash an infection. Yet for TB, this enhancement could perversely enhance transmission. A family of bacteria that has evolved to boost the immune response might be helped, not hurt, by a vaccine that has further activated the immune system of people who were inoculated.

"Again it's a bit complicated," Small explains. Once inside the body, the TB germ actually does not do very much. It is the body's own attempts to rid itself of the infection that causes the most damage. For example, the white blood cells of the immune system create the cavities in the lungs where TB gets walled off. "Thus, augmenting the host response could be helping the bug, not the host," he says. "This is just a theory, as a strong response could also prevent the bug from getting a foothold in the first place. But if true, it has important implications."

Evolutionary biologist Paul W. Ewald of the University of Louisville backs up Small's concerns. The vaccine in use today, which primarily protects children in high-risk areas from developing such severe complications as TB meningitis, is about 90 years old and has been given to about one billion people. Ewald suggests that the inoculation, which is based on a weakened strain of a closely related bacterium that infects cattle, may have inadvertently encouraged more deadly strains of *M. tuberculosis* to flourish. "It's dawning on people that this is a sophisticated organism that's evolving with humans," Ewald says.

This interaction implies that learning how to direct evolution of TB through the use of standard public health measures and more sophisticated therapies might help defeat it. Better housing that decreases crowding and enhances air ventilation, for example, might favor less powerful strains of TB. But improving living conditions for the one billion people who live in the world's slums is a lot harder than handing out pills. (On the other hand, the passage and enforcement of a law in 1901 that mandated greater access to air and light in tenement buildings helped to decrease TB infection rates in New York City in the years before antibiotics.) Gagneux, for his part, also foresees the need to bring together immunologists, ecologists, evolutionary biologists, population geneticists and social scientists to tackle all aspects of TB's ability to transmit itself, cause disease and adapt to different environments. Such cross-disciplinary partnerships often sound better on paper than they work in practice, he admits: "But ultimately, I think that's what we need."

Gagneux would like researchers who are developing new diagnostic tools, treatments and vaccines to at least consider testing them against various strains from different parts of the world. Right now most are checked solely against strains that were first grown in laboratories more than 60 years ago and may no longer be relevant. With some lineages potentially being naturally resistant to new drugs or predisposed to evade diagnostic tests, ignoring TB's family tree could prove to be a death sentence for millions more people around the world. SA

MORE TO EXPLORE

Worldwide Occurrence of Beijing/W Strains of *Mycobacterium tuberculosis:* A Systematic Review. Judith R. Glynn et al. in *Emerging Infectious Diseases,* Vol. 8, No. 8, pages 843–849; August 2002. **wwwnc.cdc.gov/eid/article/8/8/02-0002_article.htm**

Host-Pathogen Coevolution in Human Tuberculosis. Sebastien Gagneux in *Philosophical Transactions of the Royal Society B,* Vol. 367, No. 1590, pages 850–859; March 19, 2012. **http://rstb.royalsocietypublishing.org/content/367/1590/850.long**

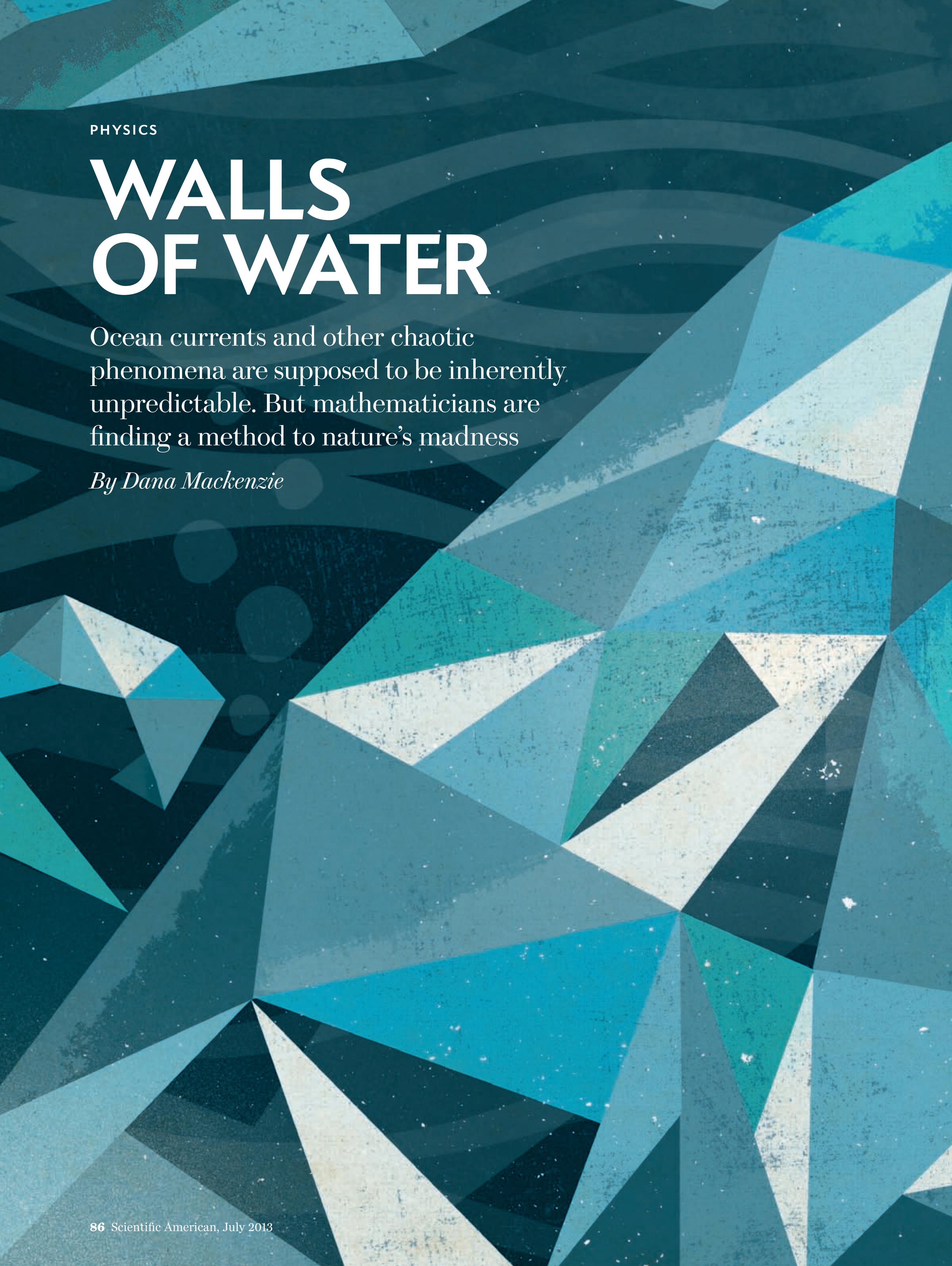
SCIENTIFIC AMERICAN ONLINE
View a slide show about the effort to fight tuberculosis that spans a century and several continents at **ScientificAmerican.com/jul2013/tuberculosis**

PHYSICS

WALLS OF WATER

Ocean currents and other chaotic phenomena are supposed to be inherently unpredictable. But mathematicians are finding a method to nature's madness

By Dana Mackenzie



ALL ALONG THE GULF OF MEXICO, 2010 WAS THE SUMMER OF THE Oil Spill. As BP's uncapped Deepwater Horizon oil well gushed away off of Louisiana, tourists stayed away from the Gulf Coast in droves, convinced by news reports that oil was coming ashore or would do so imminently. As far away as Fort Myers and Key Largo in Florida, beaches were deserted and hotel occupancy rates were down.

In reality, the situation was never so dire—especially on the western coast of Florida. This part of the Gulf Coast was protected for the duration of the oil spill by a persistent, invisible divide. Lying above the continental shelf off of Florida was an unseen line that directed the oil and prevented it from spreading farther east. It was not a solid object, but a wall of water that moved around as ocean currents shifted. Nevertheless, this wall was just as effective as any seawall or containment boom.

Scientists call these invisible walls "transport barriers," and they are the maritime equivalent of continental divides. They separate water flowing in one direction from water flowing in another. In a chaotic ocean, they provide a road map to tell you where the traffic is going. Although water currents often appear to be almost completely unpredictable, transport barriers restore a measure of order and structure to their chaotic flow.

The study of these structures has blossomed in recent years, and their importance is still not fully appreciated by the scientific community. But already researchers have shown how their study may help explain why the surface oil from the Gulf spill disappeared more rapidly than expected and why none of it escaped through the Strait of Florida into the Atlantic. During future disasters, understanding these flows could make cleanup efforts more efficient. The research could also elucidate how blood flow affects the formation of plaques in arteries and help to predict how allergy-causing spores migrate in the atmosphere.

The study of chaos came of age in the 1970s, when scientists discovered that in certain natural phenomena, even tiny perturbations could lead to profound changes. The proverbial refrain is that the flutter

Illustration by Andrew Bannecker

Dana Mackenzie is a freelance mathematics and science writer who lives in Santa Cruz, Calif. He received his Ph.D. in mathematics at Princeton University and is a U.S. Life Master at chess. His most recent book is *The Universe in Zero Words* (Princeton University Press, 2012).

of a butterfly's wing on one side of the globe could make subtle changes in air currents that cascaded, to the point of causing a tornado on the other side weeks later.

Flowing fluids—which include gases such as air and liquids such as seawater—are in fact the quintessential example of chaotic systems and one of the most ubiquitous: the dynamics of fluids govern phenomena from the Gulf Stream to the flow of air through a wind turbine to curving penalty kicks in soccer. The mathematical equations describing fluid flow were unveiled nearly 200 years ago, by Claude-Louis Navier (in 1822) and George Stokes (in 1842). Yet knowing the equations is not the same thing as solving them, and the Navier-Stokes equations remain among the most challenging problems in mathematics.

In principle, an exact solution of the Navier-Stokes equations would yield a detailed prediction of the future behavior of a fluid. But the precision of the answer would depend on exact knowledge of the present—or what scientists call the initial conditions. In reality, you can never know where every molecule of water in the ocean is going, and in a chaotic system any uncertainties—like the effects of a butterfly's motions—grow exponentially over time. Your exact solution to the Navier-Stokes equations will rapidly become moot.

And yet "chaotic" does not mean "random" or "unpredictable," at least in principle. In the past decade or so mathematicians have created a theoretical framework for understanding the persistent structures such as transport barriers that are hidden in chaotic fluids. In 2001 George Haller, a mathematician now at McGill University, gave these structures the rather unwieldy name "Lagrangian coherent structures." More poetically, Haller calls the intricate structure of transport barriers "the skeleton of turbulence." Once you have identified these structures in a body of fluid, you can make useful short- to medium-term predictions of where the fluid flow will carry an object, for instance, even without a perfect, precise solution of the Navier-Stokes equations.

What does a transport barrier look like? You are looking at one every time you see a smoke ring. At its core lies an *attracting* Lagrangian coherent structure—a curve toward which particles flow, as if they were attracted by a magnet. Ordinarily you cannot see such a structure, but if you blow smoke into the air, the smoke particles will concentrate around it and make it visible.

Much harder to visualize are the *repelling* Lagrangian coherent structures—curves that, if they were visible, would appear as if they were pushing particles away. If you could run time backward, they would be easier to see (because they would attract particles); failing that, the only way to find them is to tease them out by computer analysis. Though difficult to observe, repelling structures are particularly important because, as Haller has proved mathematically, they tend to form transport barriers.

An experiment conducted in the summer of 2003 in Monterey Bay off the coast of California showed that Lagrangian coherent structures could be computed in real time and in real bodies of water. Mathematician Shawn C. Shadden of the Illinois Institute of Technology and his collaborators monitored surface currents in the bay using four high-frequency radar stations deployed around the bay.

Analyzing the radar data, the researchers discovered that most of the time a long transport barrier snakes across the bay from Point Pinos, at the southern edge, almost all the way to the northern side. Waters to the east of the barrier circulate back into the bay, whereas those on the western side go out to sea. (Occasionally the barrier detaches from Point Pinos and drifts farther out to sea.) Such information could be vital in case of a pollutant spill.

To confirm that the computed structures did actually behave as advertised, Shadden's team tracked the motion of four drifting buoys they deployed in collaboration with the Monterey Bay Aquarium Research Institute. When they placed drifters on opposite sides of the transport barrier, one drifter would follow the water circulating back into the bay, and the other one would hitch a ride on the currents heading southward along the coast. They also showed that a drifter placed on the recirculating side of the structure would stay in the bay for 16 days—even though they had used only three days of data to compute it. This robustness of their results testified to the strength and persistence of the transport barrier. For 16 days, it really was like an invisible wall in the water.

CLOSE CALL IN THE GULF

THE MOST DRAMATIC demonstration of the transport barrier concept came in the aftermath of the 2010 Gulf oil spill. Oceanographers and mathematicians have analyzed the huge volumes of data on the spill and shown how the information could have enabled scientists to better predict where the oil would go.

Lagrangian coherent structures might help explain why the surface oil disappeared more rapidly than anyone expected—much faster, for example, than the oil from the *Exxon Valdez* spill in 1989 in Prince William Sound in Alaska. (The fate of the subsurface oil has been more controversial, and much of it may still remain at the bottom of the Gulf.) The warm Gulf of Mexico, it turned out, is home to hordes of microorganisms that feed on hydrocarbons that naturally seep into the Gulf waters. Giv-

IN BRIEF

Invisible dividing lines often form in the flow of fluids, including winds and oceanic currents.

Such "transport barriers," so-called Lagrangian coherent structures, make these chaotic phenomena more predictable.

Understanding these structures could aid in search operations at sea and improve cleanup after an oil spill. It could also help in any problem involving turbulent fluid motion, such as modeling blood flow or weather.

en a much more abundant supply of hydrocarbons than usual, these microorganisms flourished. Microbiologist Dave Valentine and mathematician Igor Mezic, both at the University of California, Santa Barbara, showed that the bacteria tended to congregate in coherent regions defined by transport barriers. Clearly, the long-term stability of those regions helped the oil degrade. Valentine notes that it would have been a different story if the blowout had happened off the coast of Brazil, another region where vast deepwater oil reserves have been discovered. There the currents lead out to sea, where a captive supply of bacteria does not exist to chow down on the hydrocarbons.

Transport barriers may also explain why the oil from Deepwater Horizon avoided flowing into the Loop Current, a persistent jet that leads through the Florida Straits and into the Atlantic, where it could have polluted beaches along the East Coast. As late as July 2, the National Oceanic and Atmospheric Administration was predicting a 61 to 80 percent chance some oil would make it to the Loop Current. The prediction was based on 15 years of historical ocean current data from the Gulf of Mexico.

In 2010 we apparently got lucky. First, unusually strong winds from the Southwest pushed the oil slick to the north, away from the Loop Current. In addition, a giant eddy, called Eddy Franklin, detached from the Loop Current and pushed it farther south than usual, forming a barrier between the oil and the current. It remains to be seen whether any of these phenomena could have been anticipated. Haller, however, with oceanographer Maria Olascoaga of the University of Miami, has shown that other seemingly capricious changes in the oil slick were predictable. On May 17, for instance, a giant "tiger tail" (named after its shape) of oil suddenly traveled more than 160 kilometers southeast in one day. According to their computer analysis, the tiger tail traveled along an attracting Lagrangian coherent structure, and the impending instability was presaged seven days earlier by the formation of a strong attracting "core" on that structure. Likewise, an abrupt westward retreat of the oil slick's leading edge on June 16 was anticipated nine days earlier by the formation of an exceptionally strong repelling core to the east of the slick. Had surveillance been in place that could identify transport barriers, cleanup boats could have been sent to the right locations.

Beyond the study of oceanic currents, applications of the transport barrier concept have proliferated in recent years. For example, Shane Ross of Virginia Polytechnic Institute has studied the effect of transport barriers in the atmosphere on airborne pathogens. He and plant biologist David Schmale, also at Virginia Tech, used a small drone airplane to collect air samples at an altitude between tens and hundreds of meters above Blacksburg. When an attracting structure passed by or when two repelling structures passed in rapid succession, the researchers detected a spike in the number of spores of a fungus called *Fusarium*. Ross hypothesizes that in the first case the spores had been pulled toward the coherent structures, whereas in the second they had become trapped between the two repelling barriers, like cattle herded into a small region by prods. Some of the spores were of a species that does not usually occur in Virginia, which suggests that the structures remained intact long enough for the spores to be transported several hundred kilometers.

Shadden is now studying the role of Lagrangian coherent structures in blood flow. For example, he has used these structures to reveal the boundaries between blood ejected on one heartbeat and blood ejected on the next. He showed that most of the blood in a normal ventricle remains there for at most two heartbeats. But in six patients with enlarged hearts, regions of blood recirculated for much longer—"a widely recognized risk factor for thrombosis," he wrote in a draft of his study.

More than a decade after Haller named them, Lagrangian coherent structures are still far from being a mainstream tool in oceanography or atmospheric science. One objection raised about their usefulness is that if there are errors in the measurement of the flow field, they will surely propagate and produce errors in the predictions of the transport barrier as well. But the Monterey Bay experiment found that the location of the transport barriers was relatively insensitive to measurement errors.

Another objection is that to compute the structures, you need to know the entire flow field, meaning the velocity of water flowing at each point. But if you know that, you can forecast the oil slick using existing computer models. So what are calculations of Lagrangian coherent structures good for?

As it turns out, forecasting is not the only game in town. "Hindcasting" may turn out to be important in finding the source of "mystery oil spills" that wash ashore from unknown sources—often from sunken ships. For example, the *SS Jacob Luckenbach,* which sank off San Francisco in 1953, polluted the California coast every year beginning around 1991, but the source of the spill was not discovered until 2002. Plane crashes and shipwrecks have also produced "debris spills" and "body spills." Because conventional ocean models cannot be reversed in time, rescuers cannot extrapolate backward from the observed debris field to find the source. Oceanographer C. J. Beegle-Krause and mathematician Thomas Peacock of the Massachusetts Institute of Technology are now working on using Lagrangian coherent structures to forecast where shipwreck survivors will drift in the currents, which would help narrow down the search area. In such situations, as Peacock notes, "even a few minutes might be a matter of life and death."

Finally, Lagrangian coherent structures provide more than mere forecasts or hindcasts; they provide understanding. Knowing about the structures enables scientists to better interpret the predictions of computer models. If a model predicts that a filament of oil will move toward Pensacola and we can see a structure pushing it or pulling it that way, we can be reasonably confident in the prediction. If there is no corresponding structure, we might treat the model with more skepticism.

Mathematicians are now broadening their research into different types of organized structures in turbulent fluids, such as eddies and jets. With deeper understanding, we may be able to answer questions about chaotic phenomena that now elude us. SA

MORE TO EXPLORE

The Correlation between Surface Drifters and Coherent Structures Based on High-Frequency Radar Data in Monterey Bay. Shawn C. Shadden et al. in *Deep-Sea Research, Part II: Topical Studies in Oceanography,* Vol. 56, Nos. 3–5, pages 161–172; February 2009.

Forecasting Sudden Changes in Environmental Pollution Patterns. María J. Olascoaga and George Haller in *Proceedings of the National Academy of Sciences USA,* Vol. 109, No. 13, pages 4738–4743; March 27, 2012.

Lagrangian Coherent Structures: The Hidden Skeleton of Fluid Flows. Thomas Peacock and George Haller in *Physics Today,* Vol. 66, No. 2, pages 41–47; February 2013.

SCIENTIFIC AMERICAN ONLINE
See videos of fluid barriers at **ScientificAmerican.com/jul2013/chaos**

Viewing the world with a rational eye

Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com). His book *The Believing Brain* is now out in paperback. Follow him on Twitter @michaelshermer

Gods of the Gaps

Arguments of divine intervention—alien or otherwise—start with ignorance

According to the popular series *Ancient Aliens,* on H2 (a spinoff of the History channel), extraterrestrial intelligences visited Earth in the distant past, as evidenced by numerous archaeological artifacts whose scientific explanations prove unsatisfactory for alien enthusiasts. The series is the latest in a genre launched in 1968 by Erich von Däniken, whose book *Chariots of the Gods?* became an international best seller. It spawned several sequels, including *Gods from Outer Space, The Gods Were Astronauts* and, just in time for the December 21, 2012, doomsday palooza, *Twilight of the Gods: The Mayan Calendar and the Return of the Extraterrestrials* (the ones who failed to materialize).

Ancient aliens theory is grounded in a logical fallacy called *argumentum ad ignorantiam,* or "argument from ignorance." The illogical reasoning goes like this: if there is no satisfactory terrestrial explanation for, say, the Nazca lines of Peru, the Easter Island statues or the Egyptian pyramids, then the theory that they were built by aliens from outer space must be true.

Whereas the talking heads of *Ancient Aliens* conjecture that ETs used "acoustic stone levitation" to build the pyramids, for example, archaeologists have discovered images demonstrating how tens of thousands of Egyptian workers employed wood sleds to move the stones along roads from the quarry to the site and then hauled them up gently sloping dirt ramps of an ever growing pyramid. Copper drills, chisels, saws and awls have been found in the rubble around the Great Pyramid of Giza, and the quarries are filled with half-finished blocks and broken tools that show how the Egyptians worked the stone. Conspicuously absent from the archaeological record are any artifacts more advanced than those known to be used in the third millennium B.C.

Another alleged aliens artifact is a symbol found in the Egyptian Dendera Temple complex that vaguely resembles a modern lightbulb, with a squiggly filament inside and a plug at the bottom. Instead of featuring archaeologists who would explain that the symbol depicts a creation myth of the time (the "plug" is a lotus flower that represents life arising from the primordial waters, and the "filament" signifies a snake), ancient aliens fantasists speculate that the Egyptians were given the power of electricity by the gods. In this "if this were true, what else would be true?" line of inquiry, it is telling that no electrical wires, glass bulbs, metal filaments or electric power stations have ever been excavated.

On the lid of the sarcophagus of the Mayan king Pakal in Mexico is a "rocketlike" image that *Ancient Aliens* consulting producer Giorgio Tsoukalos claims depicts the ruler in a spaceship: "He is at an angle like modern-day astronauts upon liftoff. He is manipulating some controls. He has some type of breathing apparatus or some type of a telescope in front of his face. His feet are on some type of a pedal. And you have something that looks like an exhaust—with flames." According to Mayan archaeologists, however, this depiction shows King Pakal sitting atop the sun monster and descending into the underworld (where the sun goes at night) within a "world tree"—a classic mythological symbol, with branches stretched into the heavens and roots dug into the underworld.

Ancient aliens arguments from ignorance resemble intelligent design "God of the gaps" arguments: wherever a gap in scientific knowledge exists, there is evidence of divine design. In this way, ancient aliens serve as small "g" gods of the archaeological gaps, with the same shortcoming as the gods of the evolutionary gaps—the holes are already filled or soon will be, and then whence goes your theory? In science, for a new theory to be accepted, it is not enough to identify only the gaps in the prevailing theory (negative evidence). Proponents must provide positive evidence in favor of their new theory. And as skeptics like to say, before you say something is out of this world, first make sure that it is not in this world.

Tellingly, in subsequent printings of *Chariots of the Gods?* the question mark was quietly dropped, and this disqualifier was added on the copyright page: "This is a work of fiction. Names, characters, places, and incidents are either the product of the author's imagination or are used fictitiously." Gap closed.

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/jul2013

Illustration by Izhar Cohen

The ongoing search for fundamental farces

Steve Mirsky has been writing the Anti Gravity column since a typical tectonic plate was about 33 inches from its current location. He also hosts the *Scientific American* podcast Science Talk.

Bingo Was Not His Name-O

A certain word game sometimes leaves the author drawing a blank

Chess never moved me. I played a little bit of poker and pool, but not enough to earn a nickname like Slim or Fats. No, my game was always Scrabble, almost going back to my days as a zygote, which, when pluralized to zygotes and placed propitiously, can score enough points to please a tsar or, better, a czar. Or, best, a cazique.

Anyhoo, before the Internet, we played Scrabble huddled in small groups, hunched over the board. We placed tiles by hand, then reached into a little bag for new ones to bring our total back to the ordained seven. We counted the points for each play, then added that number to our previous sums, and wrote it all on scraps of paper. Like animals.

But today, with the Web, wireless and smartphones, we Scrabblers can play our fellow afflicted anywhere, anytime: you can drop a quetzal on your pal at 4:00 A.M. for him or her to choke on over breakfast 1,000 miles away.

High-tech Scrabble, however, comes with a psychic danger unknown in the old days. After each move, a widget on the screen now offers to reveal the best play you could have made with the letters in your virtual rack. A game today thus affords competitors a plethora of regrets. And the worst come from not seeing a potential "bingo"—a rack-emptying play that earns a 50-point bonus. For purposes of public self-flagellation, I therefore recorded science-related bingos I missed over a few weeks in the early spring.

For example, how could I have not played CAMPHENE (73 points), when decades past I probably almost destroyed an undergraduate organic chem lab doing something with it? Or EPOXIES (96)? Or those important dyes, the EOSINES (61)?

I felt like a silly goose upon being introduced to ANSEROUS (131). I ran to the little boys' room after learning ENURETIC (61). And I was embarrassed to not know AMBARIS (77), especially because the fibers yield a hemp similar to jute, a word I play often.

Indeed, the list of plant words I failed to play positively bloomed. ORRICES (76), SEGETAL (76), INDUSIA (64), FERULAS (75) and the non-sea kind of ANEMONES (77) made me think that botanists might have a big advantage at this game.

As someone who really enjoys mushrooms, I should have gotten PORCINI (72). And as a bird-watcher who has seen his fair share of spoonbills, I should have realized that I had the letters to play ROSEATE (73).

In the physics world, NEGATON (77) is just another word for electron. If you can get the coefficient of friction down to zero, you have yourself a surface that's NONSKID (74). I was shaken not to notice GYRATORS (68). But if you want the power to FOREKNOW (104), well, that's metaphysics.

A choking victim hoping for a Heimlich would have been in trouble when I failed to play MANEUVER (84). If you're going to miss VIROLOGY (68), what are the odds you'll notice VARIOLES (71), unless your skin has been scarred by a pox? Geologists also use the word "varioles" to describe pockmarks on rock surfaces, perhaps the result of debris thrown up by BOLIDES (95) finishing their journeys through outer space. And if you're going to climb any rocks, a REVERSO (68) comes in handy.

How could I have not seen CAESAREAN (68), when almost a third of U.S. births nowadays are C-sections? And although I knew of the existence of the pregnancy hormone estriol, I did not know it was also sometimes called THEELOL (81). And for many mammals, pregnancy, a result of ALLOGAMY (86), begins before DIESTRUM (70).

The whole thing makes me want to find a few DEKARES (90) of land with a nice view and curl up under six feet of SOLONETZ (101). Perhaps after the burial, the assembled will say kind things about me as they exchange many words with friends. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/jul2013

Illustration by Matt Collins

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

Innovation and discovery as chronicled in *Scientific American*

July 1963

Laser Bloom

"The latest device to fascinate the technical community is the optical maser, or, as it is now often called, the laser. By conservative estimate about 500 research groups are engaged in laser development and exploitation in the U.S. alone. Much of this effort is directed toward the use of laser beams in communication systems. The amount of information that can be carried by a communication channel is proportional to its frequency, and in principle the visible region of the spectrum between the wavelengths of 4,000 and 7,000 angstrom units could accommodate 80 million television channels. —Arthur L. Schawlow"
The author shared the 1981 Nobel Prize in Physics.

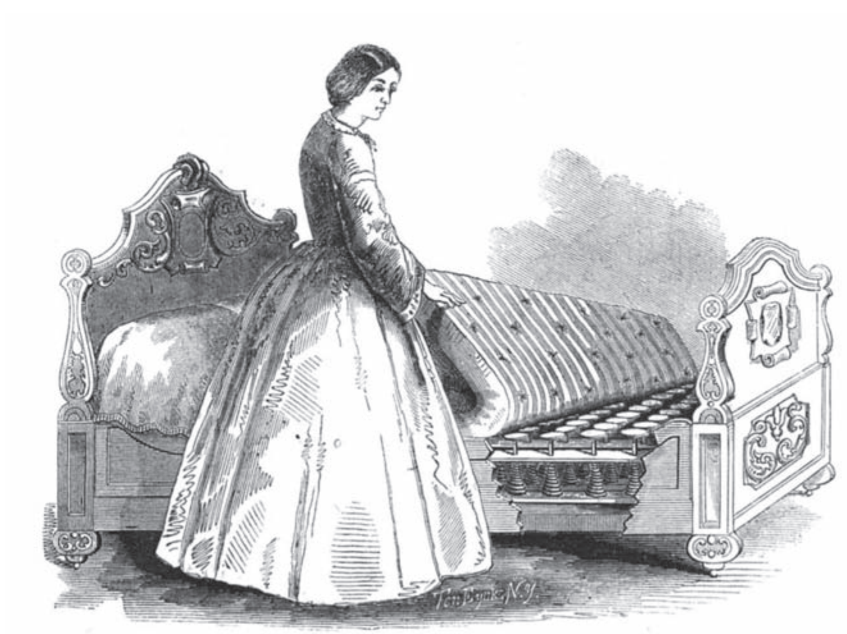
True or False?

"A warning against the increasing and largely unrestricted application of lie-detector techniques in business and industry has been issued by a psychiatrist and a psychologist at the University of Virginia. The polygraph merely measures involuntary responses. It cannot determine whether the response was stimulated by conscious deception or by a factor which might be unconsciously motivated. Yet an examiner usually seeks to impress the subject with the idea that the machine 'can't be beat' and so to encourage confessions, he 'uses deception in his effort to detect deception.' The authors conclude that lie-detector tests 'should be carefully and continually scrutinized, lest we find that George Orwell's *1984* is upon us.'"

July 1913

Eve of War

"Germany has devoted most time, money, and skilled research to the development of the various types of the dirigible; France, to that of the aeroplane, or *avion,* in all its forms. A similar comparison as to aeroplanes and trained pilots shows France to be much superior to Germany; and it is also stated that though the French machines are frailer looking, they are much better constructed than the German ones, which are still too heavy. Obviously, then, in case of war there would be a contest between German dirigibles and French aeroplanes—



THE ELEGANT, SCIENTIFIC HOME, with all the most advanced furniture, 1863

SCIENTIFIC AMERICAN, VOL. IX, NO. 1; JULY 4, 1863

like battleships and torpedo boats.”
For a slide show on weapons and warfare from our archives of 1913, see www.ScientificAmerican.com/jul2013/warfare

July 1863

Salt Mine

“It appears from scientific investigation that the salt deposit at New Iberia, Louisiana, is of the most extensive and wonderful description. For vastness and purity it is unequaled on the globe. One account says: ‘Imagine, if you can, the granite quarry of Massachusetts or the marble quarry of Vermont to be solid deposits of pure rock salt, clean and transparent as so much clear white ice, in one solid, inexhaustible mass, underlying the earth.’”
The rock salt mine on Avery Island, Louisiana, yielded more than 10,000 tons of salt for the Confederacy.

Sleep Technology

“The engraving represents an improved mode of constructing spring beds; Letters Patent have been granted. In point of economy, ease, and durability these beds are unsurpassed. It is confidently asserted that they will last fifty years.”

Letter from Mr. Fix-It

“Messrs. Editors: All machinery requires attention, and occasional ‘fixing’; and the women are not good at such work. Every now and then it is: ‘John, I wish you would look at that sewing machine’; or ‘John, that wringer has something wrong about it’; and so on. Well, the only way to meet that is to buy the very best machinery; you will then have little trouble. Some churls may say: ‘I won’t buy so-and-so; what else have the women got to do? Let them work!’ All I have to say to such is that I hate to see the women of the family borne down with the fatigue of severe labor; and if it is a little troublesome to fix machinery for them, I for one am content to endure that trouble. —John Gray”

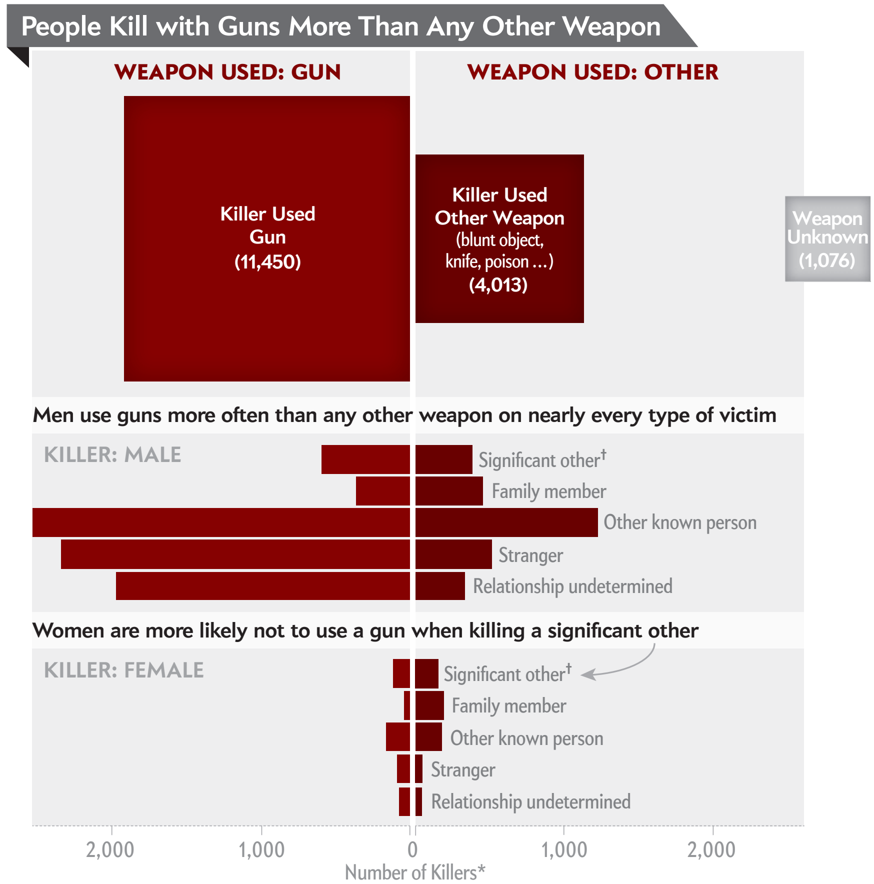
Family, Friends and Gunshot

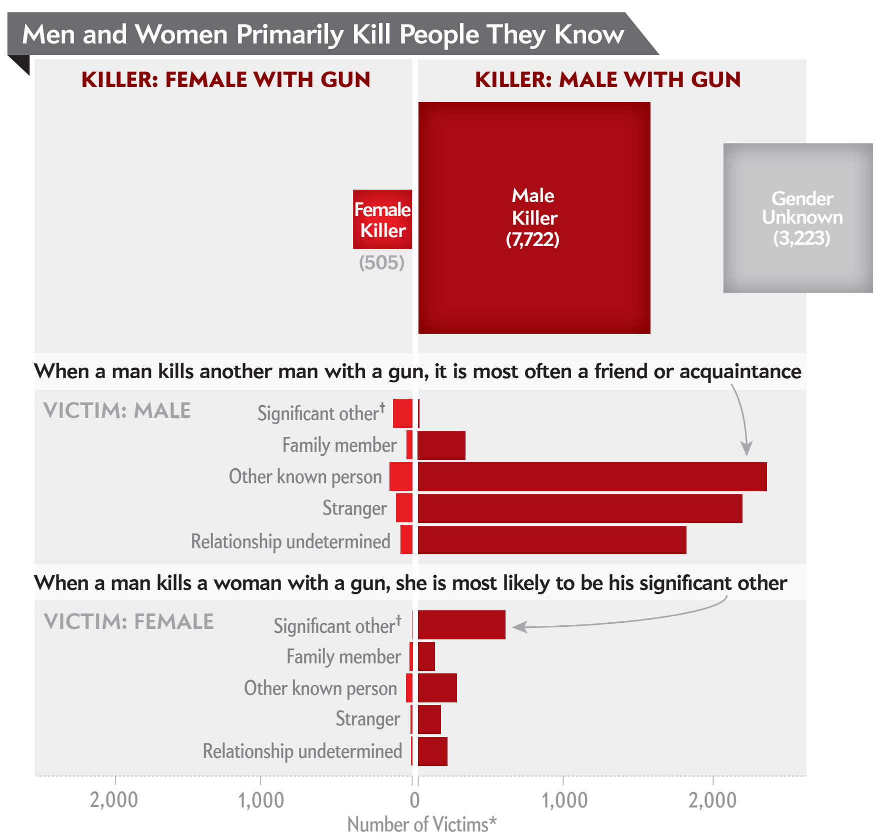
Who kills whom with what

The statistics of who kills and how they do it often get lost in the arguments over gun control. In the U.S., where guns are plentiful, men commit more than 90 percent of killings. Their weapon of choice is overwhelmingly a gun. Men kill significant others, individuals they know and strangers more often with guns than any other weapon (*top*). Women also more frequently use guns to kill strangers. Perhaps counterintuitively, women are more likely to kill a significant other or family member using a blunt object, knife, poison or other method. (The numbers here, from FBI data on more than 13,000 killing incidents in the U.S. in 2010, include murders, negligent manslaughters and acts of self-defense but not suicides.)

Although we tend to think of murderers as crooks or assassins, they are more likely to be someone familiar (*bottom*). Both men and women kill many more significant others, family members, acquaintances and co-workers combined than strangers. —*Mark Fischetti*

SCIENTIFIC AMERICAN ONLINE
For details on children, teenagers and adults killed by guns, see ScientificAmerican.com/jul2013/graphic-science





SOURCE: PERISCOPIC (*data from FBI's Uniform Crime Reports, Supplementary Homicide Report, 2010*)

**Numbers may not correlate exactly because some incidents may involve multiple offenders or victims*

†Spouses, partners, girlfriends or boyfriends

Graphic by Scientific American