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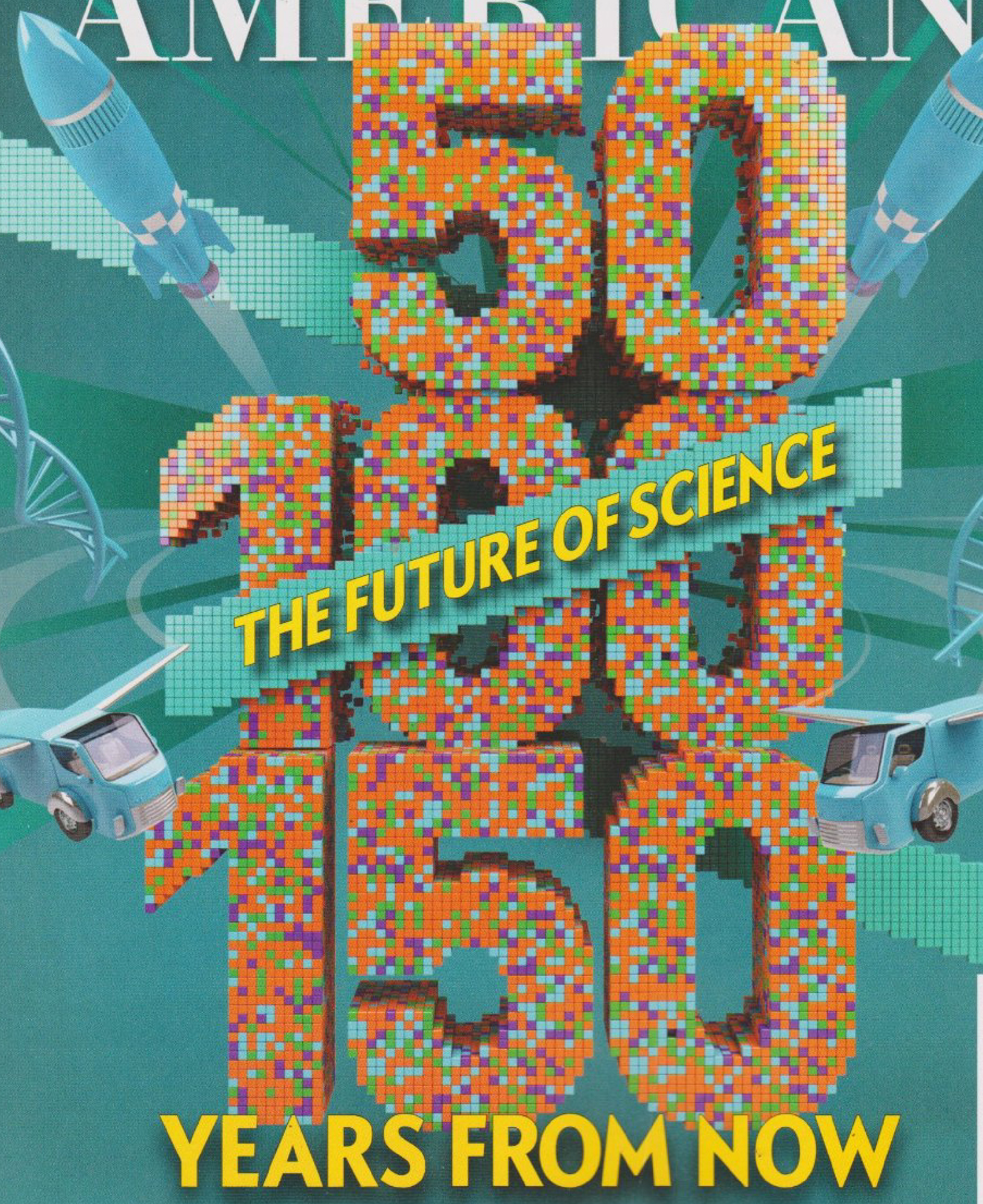

JANUARY 2013

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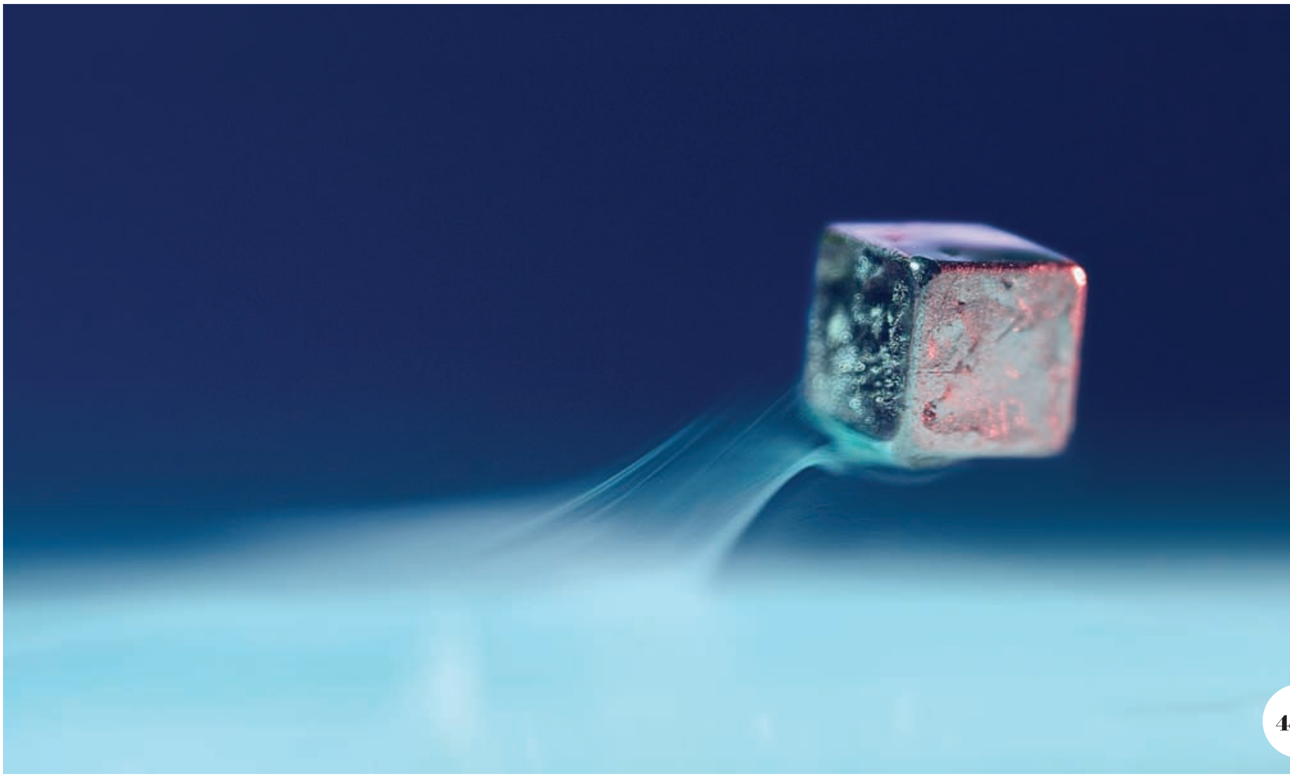
ON THE COVER

In a twist on our column 50, 100 & 150 Years Ago, which reprises excerpts from the archives of *Scientific American*, we asked leading scientists and science writers to look forward to what the world will be like in the years 2063, 2113 and 2163 and tell us what role science and technology will play in our future. Image by Chris Labrooy.

SCIENTIFIC AMERICAN

January 2013 Volume 308, Number 1



FEATURES

Photograph by Zachary Zavislak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SCIENTIFIC AMERICAN

DEPARTMENTS

ON THE WEB

The *Scientific American* Gift Guide
Need help with gift ideas for the science-minded folks on your list this year? Check out our editors' picks for the best gadgets, apps and other high-tech must-haves. Go to *www.ScientificAmerican.com/jan2013/gifts*

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

Living in the Future

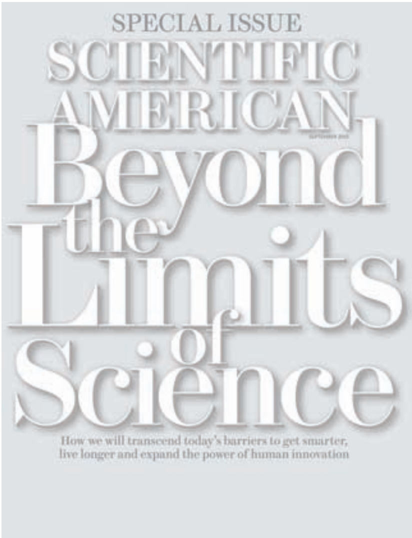
LARRY PAGE, CEO OF GOOGLE, has said that he gets excited about ideas that can change the world even though "it's easy to think they're crazy now." Take the company's self-driving cars project. Within 10 years, he told a rapt audience at the 2012 Google Zeitgeist meeting, the technology could eliminate a leading cause of death for 16-year-olds. They would have the illusion of driving, he explained: "They just can't kill themselves or anybody else." Or consider wearable computers such as Google's prototype Project Glass, which could add information to augment the reality you see: "Every time I use it, I feel like I'm living in the future," Page said. Soon even your smartphone will know when not to interrupt you or when to warn you if you will be late to a meeting based on an item in your calendar, where you are at that moment and that appointment's physical location.

GOOGLE'S Larry Page, at a recent meeting, discussed advances due in a few years. In this issue, we look 50, 100 and 150 years out.

Page was just looking a few years ahead. How much more crazy—and world-changing—do things become when you look over larger spans of time? In this issue's cover story, you will find out. Riffing off *Scientific American*'s popular monthly column, 50, 100 & 150 Years Ago, we speculate about the future using those same time blocks, ultimately going up to a century and a half ahead. Among other things, you will learn about an airborne successor to those self-driving cars, three scenarios about what a century of climate change could bring and, 150 years from now, the possibility of mental interfaces with computers. Turn to page 26 for the start of the section. A companion feature by Cameron M. Smith, called "Starship Humanity," discusses our next steps for going beyond Earth as a species and how that could affect our evolution; the story starts on page 38.

In the category of science fiction that is here today, you can explore the feature article "Bionic Connections," by D. Kacy Cullen and Douglas H. Smith, on page 52. The authors describe efforts to connect prosthetic arms and legs directly to the nervous system. The technology would let the brain sense the limbs and control them—creating artificial limbs that would feel and move like real ones. At this point in development, the interface involves laboratory-grown nerve fibers and electricity-conducting polymers. But the potential for more is clear. In upcoming years, who knows? SA

Photograph by Mariette DiChristina; Illustration by Nick Higgins editors@sciam.com



September 2012

A QUESTION OF SCOPE

The title of the single-topic issue "Beyond the Limits of Science" left me scratching my head. To my eyes, the issue was packed with accounts of topics firmly within the limits of science. Science does have its limits, but I cannot understand why *Scientific American* would portray indisputably scientific endeavors as being beyond them.

Zachary Miller
Fleetwood, Pa.

SQUARE ROOT OF NOT

In "Beyond the Quantum Horizon," David Deutsch and Artur Ekert describe how a π/2-pulse—a pulse of light with the same frequency but half the duration or amplitude of a π-pulse that would change the state of an atom's electron from 0 to 1, or vice versa—works in the computation for finding the square root of NOT (a logic gate in which inputting 0 or 1 results in the opposite figure). The authors state that if you "start with an electron in state 0, send in a π/2 pulse, then send a second π/2 pulse," the electron will be in state 1. Yet how is this possible unless the superposition state retains a "memory" of where it came from? Wouldn't the second π/2 pulse have equal probability of bumping the superimposed state into either sharp state?

Robert Friefeld
Long Beach, Calif.

"When we find something that we can't calculate, it could be that we've found a limit to our mathematics, not the universe."

Ted Grinthal *Berkeley Heights, N.J.*

EKERT REPLIES: Two consecutive applications of the square root of NOT convert 0 to 1, or 1 to 0, but the intermediate superpositions of 0 and 1 are not the same in the two cases. Although both superpositions contain the same proportion of 0 and 1, they differ in the relative phase between the two. Thus, the superposition state indeed retains a "memory" of where it came from. The square root of NOT would be impossible if there were only one equally weighted superposition of the states representing 0 and 1.

MATH AND REALITY

"Machines of the Infinite," by John Pavlus, states that the "universe itself is beholden to the computational limits imposed by P versus NP," the question of whether tough problems whose solutions can be quickly verified can also be quickly solved.

This is a common misunderstanding. Nothing in the real world (whatever that is) is constrained in any way by our mathematics, physical laws or anything else we invented. Mathematics is merely a useful tool created to describe the universe. When we find something that we can't calculate or describe with our math, it may be that we've found a limit or constraint on the universe; it could also be that we've found a limit or constraint to our mathematics.

Ted Grinthal
Berkeley Heights, N.J.

ABSTRACT INTELLIGENCE

"Can We Keep Getting Smarter?" by Tim Folger, referred to researchers having attributed the Flynn effect, the fact that IQ scores have been steadily rising since the start of the 20th century, to the world perhaps becoming increasingly representational rather than actual. Yet that doesn't necessarily make us smarter. If an IQ test asked something like "How are fire and deer similar?" a modern person might answer that both words have four letters or one syllable. Most hunter-gatherers, however, would know about the concept of using fire to manage deer habitats. And even in the fairly recent past, people off the street knew how to make soap or to shoe a horse.

Because modern people interact with computers in a graphical user interface and have grown up playing video games, it is natural for us to quickly respond to simple geometric shapes. But a modern person in an unfamiliar environment can't respond to three-dimensional shapes in the same way.

"Smart" is a relative term. Our ancestors would marvel at how stupid we are that we can't even skin a rabbit or operate a printing press.

Tom Whitley
Seattle

I question using the abstract-reasoning sections of the Wechsler Intelligence Scale for Children (WISC) as proof of rising intelligence. Folger points out the paradox of these supposedly "culture-free components of intelligence" seeming to be altered by culture, but he doesn't mention that the tests themselves have altered the culture. After the tests were used, their concepts were everywhere, such as in books of puzzles and popular magazines. It is no wonder that each new class of children knew more correct answers.

Richard S. Blake
East Falmouth, Mass.

LIMITS OF LIFE SPAN

"How We All Will Live to Be 100," by Katherine Harmon, reports on different strategies proposed to further increase human life span beyond what appears to be an approaching limit.

A 2005 paper by S. Jay Olshanksy and his colleagues in the *New England Journal of Medicine* has argued, however, that the U.S. might face a decline in life expectancy this century because of an increase in obesity, diabetes, hypertension and accompanying comorbidities. Considering such factors, a separation of wealthy and less privileged countries might represent more informative projections.

Harmon also writes that advances in sanitation might continue to extend our life expectancy. If the hygiene hypothesis is true, above a certain threshold, however, increased sanitation might have an opposite effect by increasing the rate of autoimmune diseases.

Thomas Boehm
Medical University of Vienna

BIGGER DISASTERS

"Questions for the Next Million Years," by Davide Castelvecchi, explores environmental questions such as seismologist Thorne Lay's thoughts on the future commonness of large earthquakes, but several really big issues on the subject are overlooked. For instance, the biggest earthquake might topple every building in Los Angeles, but the atmospheric pollution generated by an eruption of the volcano in Yellowstone National Park would endanger everyone on the planet. How often do such supervolcano eruptions occur? The last was about 75,000 years ago, but Paleolithic scientists never published their observations.

Gerald Davidson
Red Lodge, Mont.

CLARIFICATION

"The Winters of Our Discontent," by Charles H. Greene [December 2012], referred to the National Climatic Data Center forecasting a mild 2010–2011 winter for the eastern U.S.; that forecast originally came from the National Oceanic and Atmospheric Administration's Climate Prediction Center. The article also described La Niña as bringing warmer, mild winters and El Niño bringing colder, harsher ones; La Niña should have been described as bringing drier, mild winters and El Niño as bringing wetter ones.

Further, the article stated that by early March 2012, a strong and persistent atmospheric high-pressure system developed in the eastern Pacific; it should have said that the already existing high-pressure system in that region strengthened. The article also indicated that in certain circumstances El Niño and La Niña steer the trajectory of the jet stream; they do not steer it but are associated with climate conditions that can affect the jet stream's path.

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New York, NY 10013-1917
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A To-Do List for Washington

Energy, free speech and health care lead the list of urgent policy decisions for the next four years

The president and the newly inaugurated 113th Congress are about to face a number of science- and technology-related decisions that will determine the country's trajectory. We urge dramatic action on the science policy issues that matter most:

ENSURE A CLEAN, SECURE ENERGY SUPPLY

U.S. ENERGY POLICY must be guided by two intertwined goals: guaranteeing the security of the nation's energy supply and limiting runaway climate change. A tax on the carbon dioxide emissions of fuels is key to achieving both. A firm carbon price would encourage individuals and businesses to shift away from carbon-heavy fuels such as petroleum and coal. It would also encourage the development of next-generation energy sources that we will need if we are to secure the country's energy supply for the coming decades. The president and Congress must also end the market-distorting subsidies given out like Halloween candy to industries across the energy spectrum—from coal and oil to wind and solar. Without a level playing field and a steady price on carbon, companies cannot assess whether advanced technologies such as "clean coal" power plants or electric vehicles will ever make economic sense.

PROTECT FREE SPEECH ONLINE

IN THE 21ST CENTURY the Internet has become our public square and printing press—a place where citizens have their voices heard. That freedom to speak must be protected. Network neutrality—the idea that all data on the Internet should be treated equally regardless of creator or content—is often considered to be a technical business matter. At its core, however, net neutrality guarantees the right to speak freely on the Internet without fear of gatekeepers who would block content with which they disagree. The Federal Communications Commission must enforce policies that would protect free speech on the Internet. The most powerful method at the commission's disposal is to reverse policies enacted a decade ago by the FCC and reclassify broadband Internet service as a telecommunications service. Just as the telephone companies cannot now referee your phone conversations, the owners of broadband Internet lines should not be allowed to interfere with what online content citizens have access to.

MAKE HEALTH CARE SMARTER

THE 2010 AFFORDABLE CARE ACT, or Obamacare, was never supposed to be the last word in health care reform. The president and Congress must reach at least three additional objectives for the U.S. to rehabilitate its alarmingly dysfunctional health care system: 1) figure out a way to lower medical costs, which threaten to bankrupt the country if they continue spiraling upward; 2) improve the health outcomes of its patients; and 3) make health care affordable for businesses and individuals.

These are massive challenges that demand systemic changes to our health care system. But as a start, we might begin with small steps such as rewarding primary care physicians and nurse practitioners with financial bonuses if they keep their patients healthy and out of the hospital. And we should target individuals who have asthma, heart disease or diabetes for more attentive care, given that complications from these conditions can be very expensive to treat but are often preventable.

Other science- and technology-related policy issues will arise in the next four years. Congress will soon renew a comprehensive "farm bill." Because the bill also serves as the nation's de facto food and nutrition policy, Congress should craft the bill to support a healthy nation, not just agribusiness. Both presidential campaigns wisely acknowledged the need to award more immigrant visas to the highly skilled workers required by high-tech industries. And we must continue to overhaul our science, technology, mathematics and engineering education strategies to ensure that the U.S. will be supplying the world with highly skilled workers in the coming decades, not the other way around. The future of the nation depends on it. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/jan2013

Illustration by Liz Meyer

Jacob Tanenbaum teaches fourth and fifth grade science in Cottage Lane Elementary School in Blauvelt, N.Y.

Creation, Evolution and Indisputable Facts

A science teacher asks if scientists and biblical literalists can get along

As a science teacher, I am always curious about people's attitudes toward what I teach. Since more than 40 percent of U.S. adults believe literally what is written in the Book of Genesis—that Earth and the universe were created in six days about 6,000 years ago—and since I was in the neighborhood recently, I decided to visit the Creation Museum in Petersburg, Ky., run by the Answers in Genesis (AiG) Ministry.

The museum has a brand-new planetarium and 70,000 square feet of exhibits claiming that the story of Genesis happened exactly as written. In the main lobby, a large display depicts life just after creation. Richly detailed with plants and rocks, it features a small boy playing, while two dinosaurs graze nearby. According to the exhibits, the stars are younger than Earth (they were created on Day 4), and Noah saved all animal species that we see today from the Flood. Earth had its one and only ice age, lasting a few hundred years.

What disturbed me most about my time spent at the museum was the theme, repeated from one exhibit to the next, that the differences between biblical literalists and mainstream scientists are minor. They are not minor; they are poles apart. This is not to say that science and religion are incompatible; many scientists believe in some kind of higher power, and many religious people accept the idea of evolution. Still, a literal interpretation of Genesis cannot be reconciled with modern science.

Scientists tell us we live in a remote corner of a vast universe that existed billions of years before humans arrived. The universe and Earth could continue just fine without us. We are one species of many on a little planet with an ancient fossil record that shows that more than 99 percent of the species that once lived are now extinct. This speaks to a tenuousness of our existence as a species—an existence we need to protect vigorously.

AiG's biblical literalists, on the other hand, hold that we are God's favorites. We live at the universe's center on a planet God made and maintains for us to use. Earth's resources are here for us to exploit. God protects us and promised he would not destroy Earth again until the end of days. In that scenario, we have little reason to safeguard our existence.

Creationists begin with answers and work to prove that those answers are right. This is antithetical to the scientific process. Scientists who formed the idea of human evolution did not invent the idea and go looking for fossils. Well before Charles Darwin published his treatise in 1859 and well before workers in a limestone quarry in 1856 found strange bones that would later be called Neandertal, scientists struggled to explain what they saw in the natural world and in the fossil record. The theory of evolution was the product of that analysis. That is how science works.

The danger is that 40 percent of the American electorate seems to have forgotten what science is. Considering that our nation put a man on the moon and invented the airplane and the Internet, this development is extraordinary. Yet when much of the electorate faces the complex scientific questions of our day, they do not reject science wholesale, they cherry-pick it. Few if any of them live without the benefits of fossil fuels and electricity. Most are happy to fly in airplanes, take hot showers, heat their homes, drive their cars, watch their televisions and text their friends. They reject science *only* if it conflicts with their beliefs or asks them to change their way of life.

When Americans selectively reject science, it handicaps us, as a nation, in a knowledge-based global economy. We need to be open when scientific discoveries tell us our actions have consequences, raise doubts about our future and ask us to change. So I'll keep teaching science, not belief. Because if students do not understand how science works, we can destroy our country's future or even threaten our existence on this old Earth. SA

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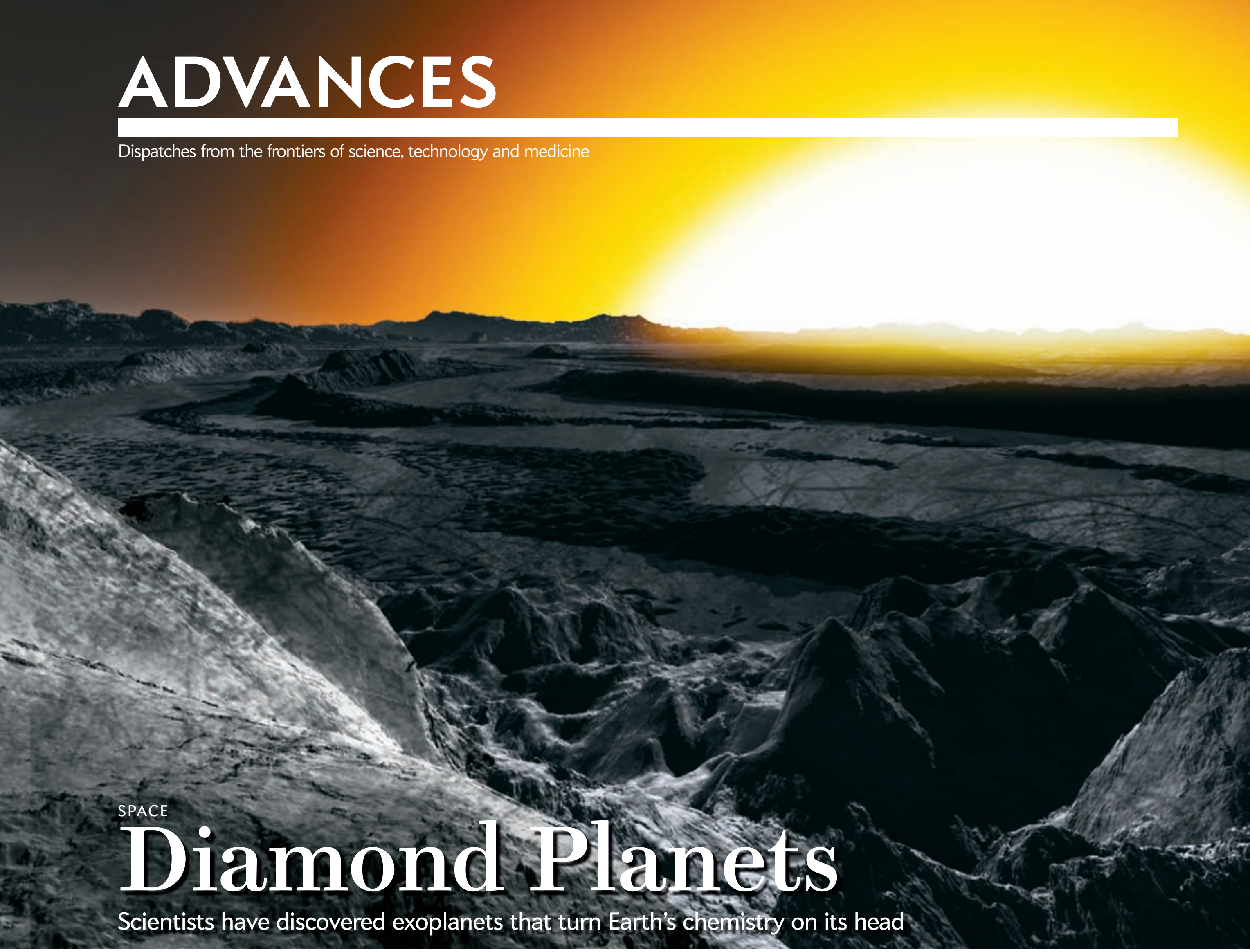
SOURCE: ANDREA L. SIEGEL (*Tanenbaum*)

Illustration by Viktor Koen



SPACE

Diamond Planets

Scientists have discovered exoplanets that turn Earth's chemistry on its head

The study of exoplanets— worlds orbiting distant stars—is still in its early days. Yet already researchers have found hundreds of worlds with no nearby analogue: giants that could steamroll Jupiter; tiny pebbles broiling under stellar furnaces; puffy oddballs with the density of peat moss. Still other exoplanets might look familiar in broad-brush, only to reveal a topsy-turvy realm where rare substances are ordinary, and vice versa.

Take carbon, for instance: the key constituent of organic matter accounts for some of humankind's most precious materials, from diamonds to oil. Despite its outsize importance, carbon is uncommon—it makes up less than 0.1 percent of Earth's bulk.

On other worlds, though, carbon might be as common as dirt. In fact, carbon and dirt might be one and the same. An exoplanet 40 light-years away was recently identified as a promising candidate for just such a place—where carbon dominates and where the pressures in the planet's interior crushes vast amounts of the element into diamond.

The planet, known as 55 Cancri e, might have a crust of graphite several hundred kilometers thick. "As you go beneath that, you see a thick layer of diamond," says astrophysicist Nikku Madhusudhan, a postdoctoral fellow at Yale University. The crystalline diamond could account for a third of the planet's thickness.

Carbon-based worlds would owe their distinct makeup to a planet-formation process very different from our own. If the composition of the sun is any indication, the cloud of dust and gas that coalesced into the planets of our solar system ought to have contained about twice as much oxygen as carbon. Indeed, Earth's rocks are mostly based on oxygen-rich minerals called silicates. Astronomers have determined that 55 Cancri e's host star, however, contains slightly more carbon than oxygen, which may reflect a very different planet-forming environment. And Madhusudhan and his colleagues calculated that the planet's bulk properties—denser than a water world but less dense than a world made of Earth-like minerals—match those predicted for a carbon planet. The researchers published their findings in the November 10, 2012, *Astrophysical Journal Letters*.

Life-forms on a carbon planet—if they exist—would little resemble the oxygen-dependent organisms of Earth. Precious oxygen would prove valuable as a fuel in much the same way that humans covet hydrocarbon fuels on Earth, says Marc Kuchner of the NASA Goddard Space Flight Center. Even courtship customs would be worlds apart from ours. "You would not be impressed if someone gave you a diamond ring," Kuchner muses. "If your suitor showed up with a glass of water, that would be really exciting." *—John Matson*

Illustration by Ron Miller

HEALTH

Safe from Scorpions

Antivenoms for snake and spider bites get a much needed makeover

Over the past few years researchers in Mexico have become global leaders in developing drugs to treat bites from poisonous spiders and snakes. Several of their remedies are clearing the hurdles of the U.S. Food and Drug Administration, including the scorpion antivenom Anascorp, which was approved by the FDA in 2011, and black widow drugs that are in advanced clinical trials.

Antivenoms are among the oldest drugs in the medical arsenal. They were first produced in the late 1800s at France's Pasteur Institute, and since the 1930s pharmaceutical company Merck has been manufacturing antivenom for black widow bites. But Merck limited distribution in 2009 because of side effects and poor drug sales, and compounds that counteract venom from scorpions and snakes have also been in short supply. The team at the National Autonomous University of Mexico, led by molecular biologist Alejandro Alagón, has introduced a new generation of antivenoms that are safer and less expensive to produce.

The method is based on the one scientists used in the 1800s: they inject venom into animals that have powerful natural defenses against the toxin. They then harvest and purify the antibodies, which are Y-shaped molecules that attach their forked end to the venom and neutralize it. In the case of antibodies directed against black widow bites, the molecule's tail (the bottom of the Y) can interact with the human body and occasionally cause a negative reaction—in a few cases, with fatal results. Although such side effects are rare, many physicians preferred not to use Merck's aging recipe. Black widow bites cause two days of crippling pain, but they do not usually kill, so doctors often treat just the symptoms.

Alagón and his team came up with a twist on the old formula: they chemically cut off the tail of the antivenom antibody, making the Y into a V to lower the risk of side effects. Alagón says the updated formula for black widow bites is safer than the old one and cheaper than a hospital stay—it can eliminate symptoms in 30 minutes.

Because the new antivenoms are relatively inexpensive to produce, Alagón's lab thinks the drugs may be affordable in Africa, where many pharmaceutical companies simply don't see a market for such products. *—Erik Vance*

NEUROLOGY

Linking Immunity and Mental Health

New uses may put an immune treatment in short supply

A once obscure medical treatment is seeing new popularity thanks to an improved understanding of the role the immune system plays in conditions as varied as obsessive-compulsive disorder (OCD) and Alzheimer's disease. Some worry that supplies of intravenous immunoglobulin (IVIG), which is made of blood plasma from donors, may run short if a clinical trial confirms its effectiveness at slowing the progress of Alzheimer's.

IVIG contains an antibody known as IgG that helps to ward off infection, modulates the immune system and reduces inflammation, although the full extent of how IVIG works remains unknown. When IVIG was first approved commercially in the early 1980s—it was prescribed to replace antibodies in patients with primary immunodeficiency disease (PIDD) and, later, was used to regulate the immune system in autoimmune conditions such as multiple sclerosis. Today IVIG has over 100 off-label indications, which represent the fastest-growing sector of its market.

Among these are an emerging crop of psychiatric illnesses, including some forms of schizophrenia and OCD, that may have autoimmune causes. IVIG is now often prescribed to patients with autoimmune encephalitis, a group of rare conditions in which antibodies attack the brain, causing such symptoms as psychosis and catatonia. And there are clinical trials, due to be completed in 2016, studying the effects of IVIG on children with sudden-onset OCD, which some researchers believe can be caused by antibodies to *Streptococcus* bacteria crossing the blood-brain barrier.

Researchers are also hoping that IVIG may be able to slow the progression of Alzheimer's. A recent study at Weill Cornell Medical College suggested that IVIG might reduce the buildup of aberrant proteins in the brain and quell the damage caused by inflammation. Although IVIG's Alzheimer's application is still in late-stage trials, the market is bracing itself for a surge in demand—up from 7 to 12 percent a year—if approval is met. "It's a real concern because [IVIG] is not just a pill that you make. It's not an unlimited resource," says Jordan Orange, professor of pediatrics, pathology and immunology at the Baylor College of Medicine. Doctors are urging one another to reexamine how they prescribe IVIG treatments and to seek alternatives in cases where the benefits are less clear. *—Susannah Cahalan*

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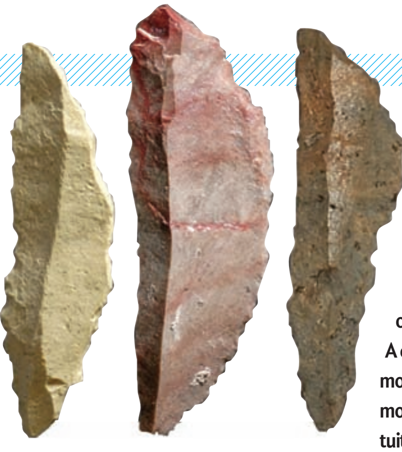
ARCHAEOLOGY

A Prehistoric Arms Race

Arrowheads hint at how modern humans overtook Neandertals



Archaeologists excavating a South African cave have recovered remains of the oldest known complex projectile weapons. The tiny stone blades, which were probably affixed to wood shafts for use as arrows, date to 71,000 years ago and represent a sophisticated technological tradition that endured for thousands of years. The discovery bears on an abiding question about when and how modern human cognition emerged.

Fossils show that humans who basically looked like us had evolved by 200,000 years ago. Yet based on the cultural stuff they left behind, it looked as though anatomically modern humans did not begin reliably thinking like us until little more than 40,000 years ago. The new finds, which come from a site called Pinnacle Point 5-6 (PP5-6), indicate otherwise.

Kyle S. Brown of the University of Cape Town and his colleagues argue that the tiny points they found, which the ancient people at PP5-6 made by carefully heating and shaping stone, are a proxy for complex cognition and that the 11,000-year duration of the tradition indicates it was transmitted verbally from generation to generation.

The findings, published online November 7, 2012, by *Nature*, add to mounting evidence that modern cognitive capacity evolved at the same time as modern anatomy, with various elements of modern behavior emerging gradually over the subsequent millennia. (*Scientific American* is part of Nature Publishing Group.) A competing hypothesis holds that modern human behavior arose far more recently as the result of a fortuitous genetic mutation.

Brown and his collaborators conclude their paper by noting that this projectile technology, which allows one to attack from a safe distance, would have given modern humans a significant edge during hunting and interpersonal conflict as they spread out of Africa into Europe and encountered the resident Neandertals equipped with handheld spears. —*Kate Wong*

SCIENTIST IN THE FIELD

How to Survive the Next Big Storm

The scientist who predicted the damage from Hurricane Sandy explains how to protect coastal cities

PROFILE

NAME
Klaus Jacob

TITLE
Special research scientist

LOCATION
Lamont-Doherty Earth Observatory, Columbia University

City and state leaders on the U.S. East Coast are talking about putting barriers outside of New York City and other places. Will those work?

Barriers are not sustainable structures for more than 100 years, so they will not be sufficient for, say, 500 years of sea-level rise. Barriers can work, but you should only build them if you have [a plan to update them]. Hurricane Katrina in New Orleans overcame man-made barriers because the city kept [sinking] and the sea had risen after the levies and walls went up. You have to take action behind the barriers to prepare for their obsolescence—before you design and build them.

Would it be better for cities to alter their building and transportation infrastructure instead?

They need to do both. Even better, focus on land use and municipal planning. Most immediately, buildings on low ground should pull all their systems out of basements and put them on higher floors. Tall buildings should put their systems on the 10th floor—let the lower level be a parking garage or something. Then waterproof the basement and low floors. In New York City, transportation systems such as subways have to close all ventilation grates at the street level and find other ways to vent. Gates are needed for subway entrances, or the entrances should be redesigned. In Taipei, for example, at some stations you have to walk up from street level to enter before you can walk down below street level into the subway.

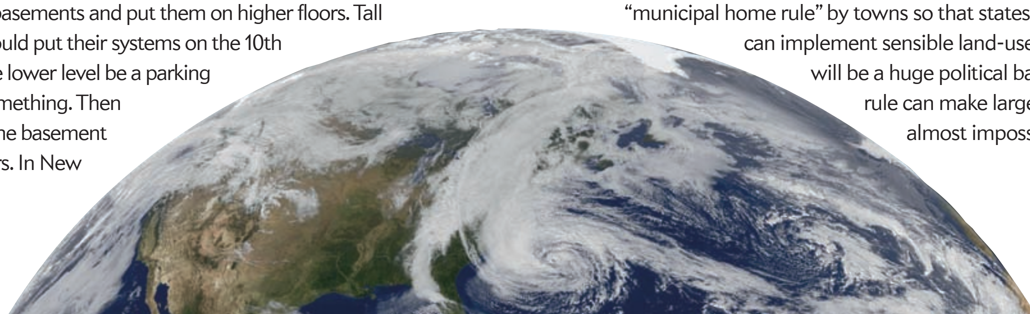
What about retreating from the coast?

Yes, we should retreat in certain low-lying areas. Insurance companies will not insure any property that is at a dangerous elevation. National flood insurance should also be revised; it is almost a hoax right now.

Can cities perhaps share solutions?

Every location needs a customized plan. But we also need to change land use up and down the U.S. East Coast. We must overcome "municipal home rule" by towns so that states or regions can implement sensible land-use policies. That will be a huge political battle, but home rule can make larger solutions almost impossible.

—*Mark Fischetti*



COURTESY OF TOVË RUTH SMITH AND SIMEN OESTMO *Arizona State University* (*top*); NASA EARTH OBSERVATORY IMAGE BY ROBERT SIMMON, WITH DATA COURTESY OF NASA/NOAA GOES PROJECT SCIENCE TEAM (*bottom*)

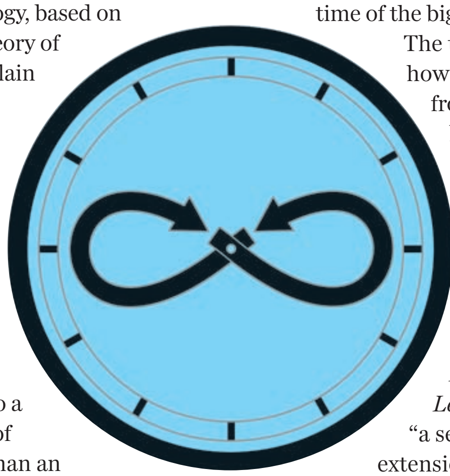
PHYSICS

The Missing Epoch

New calculations extend Einstein's general theory of relativity into the universe's first few moments

Instants after the big bang, the universe underwent a burst of rapid expansion known as inflation. In this period, according to standard cosmology, tiny ripples of energy seeded galaxies and the other large-scale structures we see today. But no one can explain how the ripples formed in the first place. Three physicists now say the key to this riddle lies in quantum gravity, a still tentative theory in which gravity would display the same fuzzy "uncertainty" typical of subatomic physics.

Standard cosmology, based on Einstein's general theory of relativity, cannot explain the origin of the ripples, because it breaks down at very small scales. During the infinitesimally brief period before the start of inflation, called the Planck era, the entire known universe was stuffed into a region many orders of magnitude smaller than an atom. If pushed that far back, relativity makes nonsensical predictions such as infinite energy densities.



To extend the reach of Albert Einstein's theory to such extreme regimes, researchers have developed a theory called loop quantum gravity. Beginning in the 1980s, Abhay Ashtekar, now at Pennsylvania State University, rejiggered Einstein's equations to make them quantum-friendly. Among the consequences are that space itself, instead of being a smooth backdrop, would consist of discrete units called loops and that its microscopic structure could fluctuate among multiple simultaneous states. In recent years physicists have also found that if loop quantum gravity is correct—a big if because experimental evidence is still lacking—then the big bang would really have been a "big bounce" from an earlier collapsing universe.

Ashtekar's team now says that by extending loop quantum gravity techniques it has bridged the gap between the big bounce—which is in the Planck regime—and the onset of inflation and that it can explain those all-important ripples without which you and I would not be here. The ripples, the researchers calculate, would be the natural outcome of quantum fluctuations existing at the time of the big bounce.

The team's predictions, however, differ slightly from those of "vanilla" inflation in a way that could be tested in future surveys of cosmic structure, Ashtekar says.

These results, to appear in *Physical Review Letters*, provide "a self-consistent extension of inflation all the way to the Planck scale," Ashtekar says.

The conclusion that quantum gravity might have left an imprint on today's large-scale cosmic structures is "quite surprising and beautiful," says Jorge Pullin of Louisiana State University, an expert on loop quantum gravity who was not involved in the research.

Neil Turok, director of the Perimeter Institute for Theoretical Physics in Ontario, says that the team still needs "artificial assumptions," which it pushes back from the onset of inflation to an earlier time. Loop quantum gravity "has many interesting ideas," Turok says, "but it is not yet a theory one should take too seriously as making predictions." —*Davide Castelvecchi*

Illustrations by Thomas Fuchs

TECHNOLOGY

Crunch Time

The U.S. Energy Department unleashes Titan, the world's fastest supercomputer

In 2005 engineers at the U.S. Department of Energy's Oak Ridge National Laboratory unveiled Jaguar, a system that would later be upgraded into a world-beating supercomputer. By 2011 it had swelled to a room-size system that used seven megawatts of energy, ran nearly 225,000 processor cores and had a peak performance of 2.3 quadrillion calculations per second. Still, to keep up with ever more sophisticated problems in energy research, the engineers had to scale Jaguar's processing power 10-fold. Simply adding more CPUs would have required a ridiculous amount of power—enough for 60,000 homes. Brute force wasn't going to do the trick.

Oak Ridge engineers instead turned to video games—or more precisely, to the graphics processors used in Microsoft Xboxes, Nintendo Wiis and other video-game systems. In late October 2012 Jaguar became Titan, a supercomputer that leverages both CPU and GPU (graphics processing unit) accelerators to deliver 10 times the performance of Jaguar while consuming five times less power. It has become the world's most powerful supercomputer, beating the DOE's Sequoia, which had held the title since last June. Titan's performance comes at a price, however. Because Jaguar used only CPUs, its computer architecture was simpler, which made it easier to write its software. "The algorithmic complexity to write that code for a machine like Titan is momentous," says Tom Evans, an Oak Ridge computational scientist.

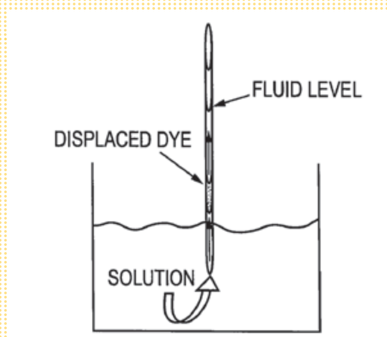
Titan will initially support a handful of key projects at Oak Ridge, including Denovo, software that simulates the behavior of neutrons in a nuclear power reactor. Oak Ridge's engineers designed Denovo for Jaguar as a way to help extend the life of the U.S.'s aging nuclear power plants, which provide about a fifth of the country's electricity. Running Denovo, Titan will take 13 hours to model the complete state of a reactor core at a specified point in time, a job that took Jaguar 60 hours to perform. "The ability to burn nuclear fuel uniformly is very much dependent on knowing and being able to predict the distribution of neutrons in the core," says Evans, who helped to create Denovo. The DOE will also make Titan available to researchers in academe, government and industry. *—Larry Greenemeier*

PATENT WATCH

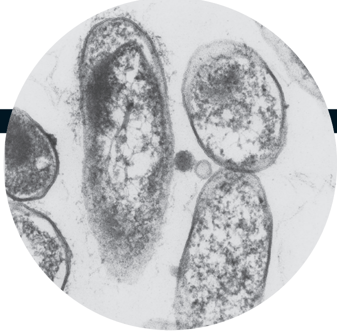
Molecularly imprinted polymer sensor device: Ketamine, Rohypnol and gamma-hydroxybutyrate (GHB) are so-called date-rape drugs that render victims compliant and vulnerable to sexual assault. To easily detect such drugs in a drink, George Murray, now chief scientist for Raptor Detection Technologies, and his colleagues turned to polymer chemistry.

Patent no. 8,241,575 details a thin, hollow device lined with polymer molecules cradling dye-tagged versions of the drugs. When the tube is placed in a spiked drink, capillary action draws liquid up, and the dye-tagged molecules swap places with those in the drink. In a positive sample, the drink inside the straw will quickly change color and creep up the length of the tube, alerting the would-be drinker. Murray's method builds each unit of the polymer piece by piece, giving him precise control over the number of chemical binding sites inside the device. Solutions with more drug molecules will displace dye farther up the tube, and how high the color change appears corresponds to concentration.

The method can also be used to detect other chemicals—the designer simply embeds the desired target molecule in the plastic matrix. Murray's employer already markets molecularly imprinted polymers as explosive detectors and holds the license to the date-rape prevention device. *—Marissa Fessenden*



COMMENT AT ScientificAmerican.com/jan2013



COURTESY OF RICARDO MAGGI North Carolina State University, *College of Veterinary Medicine Laboratory for Advanced Electron and Light Optical Methods*

MICROBIOLOGY

Stealth Pathogen

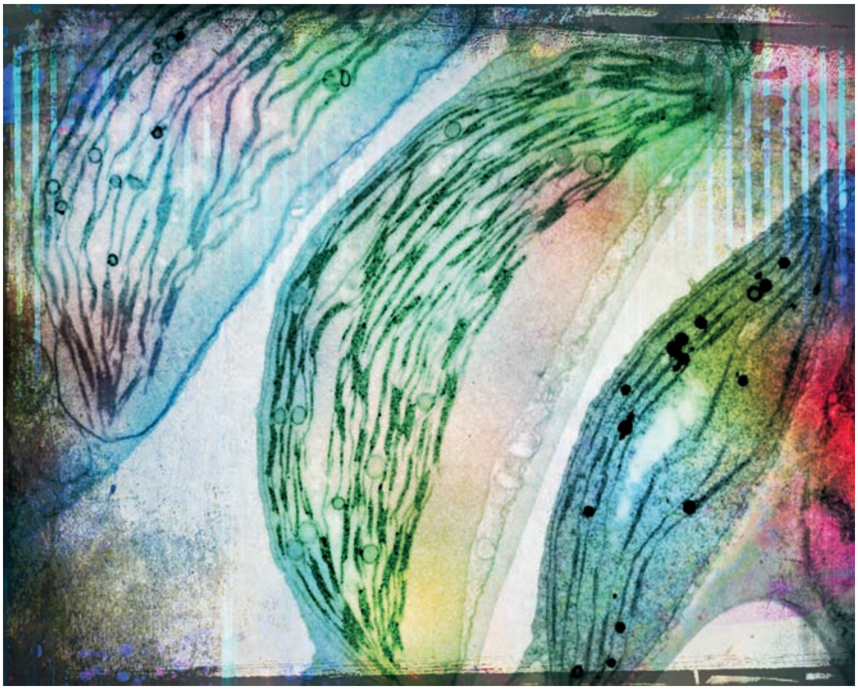
The bacteria behind cat scratch fever remain cloaked in mystery

A question that has been simmering for years in the veterinarian community is now attracting the interest of physicians as well: Do the bacteria that cause cat scratch disease—a typically mild illness with flulike symptoms—also cause chronic fatigue syndrome? Decades of case reports hint at associations between fatigue, chronic headaches, numbness, pain and cognitive impairment and infection with *Bartonella.* Yet researchers still do not have clear answers.

Recent research found fragments of *Bartonella* species' DNA in 41 percent of 296 patients examined by a rheumatologist. Many of them had visited multiple specialists without finding relief from their symptoms. The findings, published in May 2012 in *Emerging Infectious Diseases,* drew criticism in two letters to the editor, published last November, which expressed concerns with patient inclusion criteria and a low threshold cited as evidence of infection. "We must be cautious before attributing illnesses X, Y and Z to *Bartonella* infection without solid evidence," says Christina Nelson, a medical epidemiologist at the U.S. Centers for Disease Control and Prevention, who adds that the study results were difficult to interpret.

Complicating matters is the pathogen's elusive biology: it evades detection within hosts by changing proteins on its surface and by hiding inside blood vessels. In addition, the organism can shift strategies depending on whether it is in a mammalian host, such as a cat or dog, or an insect vector, such as a flea or tick. "We are not even at the tip of the iceberg" when it comes to understanding *Bartonella,* says Jane Koehler, a professor of medicine at the University of California, San Francisco.

—Marissa Fessenden



WHAT IS IT?

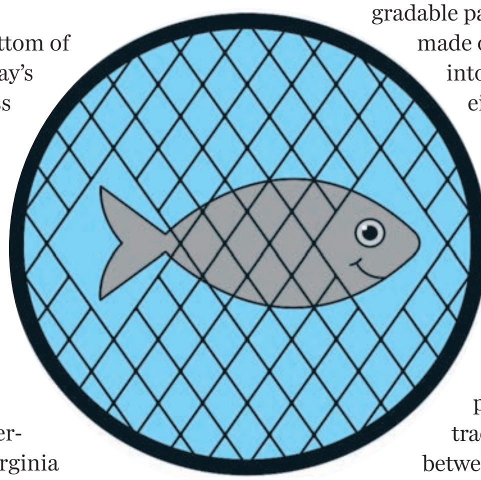
Seasoned cells: Researchers at the University of Leicester in England have discovered a new way to regulate plant development. R. Paul Jarvis and his team screened thale-cress (*Arabidopsis thaliana*) plants, model organisms in the mustard family, for genes affecting chloroplasts, the structures within plant cells where photosynthesis occurs.

A healthy chloroplast (*middle*) is made up of thousands of proteins, one of which acts to sort the others; when chloroplasts lack this guide, they become small and underdeveloped (*right*). In the November 2, 2012, *Science,* however, the scientists identified the *SP1* gene, which, when altered, can counteract the loss of this missing sorting factor (*left*). Jarvis says this gene is important in controlling plant development, particularly when chloroplasts "undergo major changes—for example, during fruit ripening." He and his group are currently testing this finding in tomatoes, and, if successful, they will begin to explore more carefully how it might be used to benefit farmers and consumers, Jarvis says. —*Ann Chin*

BIOLOGY

The Escape Hatch

A biodegradable trap may snare fewer sea creatures



In 2006 scientists were mapping the bottom of the York River, one of the Chesapeake Bay's many tributaries, when they came across something odd. "We started to see these little squares all over the place," says Donna Bilkovic, a biologist at the Virginia Institute of Marine Science. "They were clearly man-made."

The squares turned out to be hundreds of loose crab traps, escapees from the bay's large blue crab fishery. Every year crabbers around the world set millions of these cagelike traps, known as pots, and sometimes a high percentage go missing. In Maryland and Virginia alone, crabbers set out around 800,000 pots annually, and as many as 30 percent break free of their lines and drift away only to stick in the mud, sometimes for years. But just because the pots are derelict does not mean they no longer work: each one can catch more than 50 crabs a year, as well as several other species, including the diamondback terrapin, a threatened species.

The task of recovering so many pots spread over so large an area is impractical, so Bilkovic and her colleague Kirk Havens devised a simple way of disarming a wayward trap: a biodegradable panel. If a pot is lost, the panel, which is made of plant-based materials and incorporated into the pot's side, dissolves over a period of eight to 12 months. Once the panel is gone, anything that swims in can swim out.

Bilkovic was concerned, however, that if the panel also affected the blue crab catch in working pots, then crabbers would be reluctant to use it. That does not appear to be an issue, however. In a study last December in *Conservation Biology,* Bilkovic and Havens had crabbers in the Chesapeake Bay test the pots with biodegradable panels against the traditional variety. They found no difference between the number or the size of crabs caught.

"It's an ingenious solution," says John Bull, a spokesperson for the Virginia Marine Resources Commission. Yet even though each panel costs only around $1, that may still be too much: "It would add another $750,000 to $1.5 million to an industry that doesn't have the money right now." —*Eric Wagner*

COMMENT AT ScientificAmerican.com/jan2013

TECHNOLOGY

Super Long-Term Storage

Data saved in quartz glass might last 300 million years

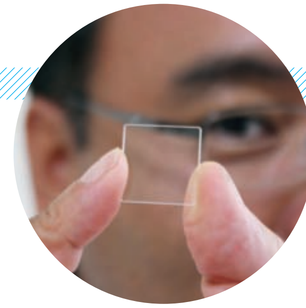
Most cultural institutions and research laboratories still rely on magnetic tape to archive their collections. Hitachi recently announced that it has developed a medium that can outlast not only this old-school format but also CDs, DVDs, hard drives and MP3s.

The electronics giant partnered with Kyoto University's Kiyotaka Miura to develop "semiperpetual" slivers of quartz glass that Hitachi says can preserve information for hundreds of millions of years with virtually no degradation.

The prototype is made of a square of quartz two centimeters wide and two millimeters thick. It houses four layers of dots that are created with a femtosecond laser, which produces extremely short pulses of light. The dots represent information in binary form, a standard that should be comprehensible even in the distant future and can be read with a basic optical microscope. Because the layers are embedded, surface erosion would not affect them.

The medium has a storage density slightly better than that of a CD. Additional layers could be added, which would increase the density. But the medium is more remarkable for its durability. It is waterproof and resistant to chemicals and weathering, and it was undamaged when exposed to 1,000-degree heat for two hours in a test. The results of that experiment led Hitachi to conclude that the quartz data could last hundreds of eons.

"If both readers and writers can be produced at a reasonable price, this has the potential to greatly change archival storage systems," says Ethan Miller, director for the Center for Research in Intelligent Storage at the University of California, Santa Cruz. The medium could be ideal for safekeeping a civilization's most vital information, museum holdings or sacred texts. The question is whether the world as we know it would even last that long. "Pangaea broke up less than several hundred million years ago," Miller adds. "Many quartz-based rocks from that time are now sand on our beaches—how would this quartz medium fare any differently?" —*Timothy Hornyak*



Hitachi's new storage device

FOOD

Healthier Ice Cream?

Scientists are experimenting with unsaturated fats for a rich but less artery-clogging dessert

Ice cream is a complex, three-phase food system in which ice (solid), air (gas) and unfrozen water (liquid) coexist. Much that makes ice cream an indulgence derives from its relatively high fat content, which can range from 10 to 18 percent in premium varieties. In addition to its role in taste and flavor development, fat is crucial to ice cream's texture. No wonder, then, that most low-fat varieties fail to offer the same taste sensation.

Lately food scientists have found clever ways to experiment with unsaturated fats aiming to bring consumers the full satisfaction of ice cream with fewer of the health consequences associated with saturated fats. Solid fat builds structure in ice cream via partial coalescence, which occurs when two fat droplets collide and fuse only "at their hip," remaining distinguishable from each other. The fusion is mediated by crystals that protrude from the surface of the spherical droplets—imagine the thorns of a prickly pear—that pierce neighboring droplets as they collide. These droplets then aggregate and deposit onto the surface of air bubbles and stabilize the frozen foam. In this way, partial coalescence enables ice cream to taste creamier, hold its shape and melt more slowly.

Given that unsaturated fats are liquid, the original thought was that they would not be good candidates to make ice cream less of a sin. Recent research, however, has the skeptics thinking twice. New studies led by Douglas Goff of the University of Guelph in Ontario suggest that plateletlike or needlelike droplets (as opposed to spheres) that contain 40 to 60 percent unsaturated fats are very effective at building structure in ice cream. Such fats can be blends of any highly unsaturated oil (such as high-oleic sunflower or canola oil) and saturated fats such as coconut oil or cocoa butter. Platelets formed only when Goff's team added commonly used unsaturated emulsifiers, such as glycerol monooleate, which are thought to force the fat crystals to grow preferentially in one dimension, hence generating the needlelike profile. Because of their shape, the amount of fat needed to create a stable frozen foam (via partial coalescence) decreases. This opens up the possibility for low(er) fat, creamy, slow-melting ice cream.

—*Cesar Vega*

Vega is a research manager at Mars Botanical, a division of Mars, Inc. His opinions are his own.

COURTESY OF PLANNING OFFICE OF THE CENTRAL RESEARCH LABORATORY, HITACHI, LTD. *(top);* ADRIANNA WILLIAMS *Corbis (bottom)*

Best of the Blogs

BIOLOGY

A Feathered Innovator

In a first for its species, a captive cockatoo creates a tool

Since the early 1960s membership in the club of tool users has expanded from humans to chimpanzees and beyond. To date, it includes elephants, dolphins, octopuses, crows, ravens, rooks, jays, dingoes and dogs (sort of). Among birds, tool use has been well documented in corvids (crows, rooks, jays, ravens), but evidence is scant in other bird families.

Now a parrot named Figaro may pave the way for admission into the tool-use club for his species, Goffin's cockatoo, also known as the Tanimbar corella or Goffin's corella (*Cacatua goffini*). Figaro is part of a captive colony of cockatoos in the department of cognitive biology at the University of Vienna. One day the male parrot dropped a pebble through an opening in the wire mesh surrounding the aviary in which he was housed, where it fell onto a wood beam. Figaro tried in vain to retrieve the pebble with his claw. Frustrated, he flew away, retrieved a small piece of bamboo and, holding it in his beak, attempted to use it to nudge the pebble back into his enclosure. He was unsuccessful. Luckily, a student observer noticed the exciting behavior and reported it to the researchers. No Goffin's cockatoo in the wild had ever been recorded using a tool, so the behavior was remarkable.

Yet was it a fluke? To find out, the researchers embarked on a series of experiments. In 10 different trials over the course of three days, they placed small cashews on the wood beam outside the aviary, just as the pebble was in the initial observation. In the first test, Figaro started by trying a stick that had been lying on the floor of the enclosure, but it was too short. He then broke a splinter off of a wood beam and, holding it in his beak, successfully retrieved the nut. In all, it took him 25 minutes to get his snack. Not only was he able to use a preexisting tool, he also spontaneously manufactured one. In the second through 10th trials, his performance was significantly faster. Ten times in a row, Figaro successfully found or fabricated tools to retrieve a cashew.

Tool-using Figaro

What makes this particularly exciting is that Figaro is a parrot, not a corvid. Corvids routinely use their beaks to modify twigs and sticks for nest building, so the cognitive leap to tool manufacture makes anatomical and ecological sense. Parrots, however, nest in naturally occurring cavities found in trees. Figaro's example shows that tool use can spontaneously develop in an individual whose intelligence had not been explicitly shaped by evolution for tool use.

As vocal-learning birds, parrots have long been studied for insights into language, but it seems as if the ability to use tools for solving problems also exists within their cognitive tool kit—at least under certain conditions. Identifying just what those conditions are now falls to the researchers, who are planning to see how different experiences throughout a cockatoo's development could contribute to tool-related abilities, as well as the extent to which tool use could spread to other cockatoos through social learning. —*Jason G. Goldman*

Adapted from The Thoughtful Animal at **blogs.ScientificAmerican.com/*thoughtful-animal***

MARINE BIOLOGY

Clever Coral

Reefs recruit fish as bodyguards

Just below the ocean's surface, coral reefs are under constant assault by seaweeds that seek to take control by stealing the corals' prime sunlit location for themselves. Many of these plant invaders come equipped with deadly chemical weapons that knock down the corals' metabolism, which might come off as an unfair fight against a seemingly unarmed foe. But corals are not defenseless: as a recent paper in *Science* shows, they have fish bodyguards at the ready to mount a defense.

Study co-author Mark Hay, a biology professor at the Georgia Institute of Technology, and his postdoctoral student Danielle Dixson were studying coral-seaweed interactions in Fiji. The scientists noted that when they introduced the toxic seaweed *Chlorodesmis fastigiata* to the reef-building coral *Acropora nasuta,* small gobies would emerge within seconds from their hiding places to pick at and eat the seaweed.

To really understand what was going on, the scientists took a variety of water samples and exposed the fish to them in the lab. They found that gobies were drawn only to water from corals that had been damaged by seaweed but not to the chemical signature of an alga by itself. "We found that the gobies were being 'called to' the area damaged by the algae and that the 'call' was coming from the damaged coral, not from the seaweed," Hay says. The gobies are not being entirely selfless. Gobies don't just eat seaweed—they also eat mucus from the coral itself. "The fish are getting a safe place to live and food from the coral," Hay notes. "The coral gets a bodyguard in exchange for a small amount of food. It's kind of like paying taxes in exchange for police protection." —*Christie Wilcox*

Adapted from Science Sushi at blogs.ScientificAmerican.com/science-sushi

COURTESY OF ALICE AUERSPERG *University of Vienna*

COMMENT AT ScientificAmerican.com/jan2013

David Stipp is a Boston-based science writer who focuses on aging research. He is author of *The Youth Pill: Scientists at the Brink of an Anti-Aging Revolution* (Current, 2010).

Is Fasting Good for You?

Intermittent fasting might improve health, but clinical data are thin

In E. B White's beloved novel *Charlotte's Web,* an old sheep advises the gluttonous rat Templeton that he would live longer if he ate less. "Who wants to live forever?" Templeton sneers. "I get untold satisfaction from the pleasures of the feast."

It is easy to empathize with Templeton, but the sheep's claim has some merit. Studies have shown that reducing typical calorie consumption, usually by 30 to 40 percent, extends life span by a third or more in many animals, including nematodes, fruit flies and rodents. When it comes to calorie restriction in primates and people, however, the jury is still out. Although some studies have suggested that monkeys that eat less live longer, a new 25-year-long primate study concluded that calorie restriction does not extend average life span in rhesus monkeys. Even if calorie restriction does not help anyone live longer, a large portion of the data supports the idea that limiting food intake reduces the risks of diseases common in old age and lengthens the period of life spent in good health.

If only one could claim those benefits without being hungry all the time. There might be a way. In recent years researchers have focused on a strategy known as intermittent fasting as a promising alternative to continuous calorie restriction.

Intermittent fasting, which includes everything from periodic multiday fasts to skipping a meal or two on certain days of the week, may promote some of the same health benefits that uninterrupted calorie restriction promises. The idea of intermittent fasting is more palatable to most people because, as Templeton would be happy to hear, one does not have to renounce the pleasures of the feast. Studies indicate that rodents that feast one day and fast the next often consume fewer calories overall than they would normally and live just as long as rats eating calorie-restricted meals every single day.

In a 2003 mouse study overseen by Mark Mattson, head of the National Institute on Aging's neuroscience laboratory, mice that fasted regularly were healthier by some measures than mice subjected to continuous calorie restriction; they had lower levels of insulin and glucose in their blood, for example, which signified increased sensitivity to insulin and a reduced risk of diabetes.

THE FIRST FASTS

Religions have long maintained that fasting is good for the soul, but its bodily benefits were not widely recognized until the early 1900s, when doctors began recommending it to treat various disorders—such as diabetes, obesity and epilepsy.

Related research on calorie restriction took off in the 1930s, after Cornell University nutritionist Clive McCay discovered that rats subjected to stringent daily dieting from an early age lived longer and were less likely to develop cancer and other diseases as they aged, compared with animals that ate at will. Research on calorie restriction and periodic fasting intersected in 1945, when University of Chicago scientists reported that alternate-day feeding extended the life span of rats as much as daily dieting in McCay's earlier experiments. Moreover, intermittent fasting "seems to delay the development of the disorders that lead to death," the Chicago researchers wrote.

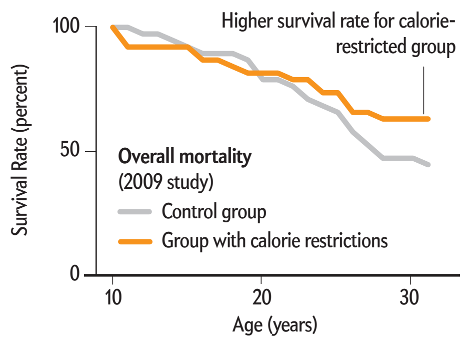
In the next decades research into antiaging diets took a backseat to more influential medical advances, such as the continued development of antibiotics and coronary artery bypass surgery. More recently, however, Mattson and other researchers have championed the idea that intermittent fasting probably lowers the risks of degenerative brain diseases in later life. Mattson and his colleagues have shown that periodic fasting protects neurons against various kinds of damaging stress, at least in rodents. One of his earliest studies revealed that alternate-day

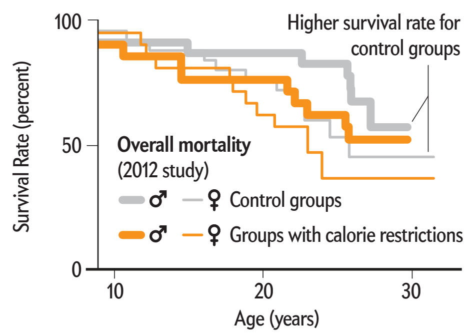
Photoillustration by Kelly Blair

feeding made the rats' brains resistant to toxins that induce cellular damage akin to the kind cells endure as they age. In follow-up rodent studies, his group found that intermittent fasting protects against stroke damage, suppresses motor deficits in a mouse model of Parkinson's disease and slows cognitive decline in mice genetically engineered to mimic the symptoms of Alzheimer's. A decidedly slender man, Mattson has long skipped breakfast and lunch except on weekends. "It makes me more productive," he says. The 55-year-old researcher, who has a Ph.D. in biology but not a medical degree, has written or co-authored more than 700 articles.

Mattson thinks that intermittent fasting acts in part as a form of mild stress that continually revs up cellular defenses against molecular damage. For instance, occasional fasting increases the levels of "chaperone proteins," which prevent the incorrect assembly of other molecules in the cell. Additionally, fasting mice have higher levels of brain-derived neurotrophic factor (BDNF), a protein that prevents stressed neurons from dying. Low levels of BDNF have been linked to everything from depression to Alzheimer's, although it is still unclear whether these findings reflect cause and effect. Fasting also ramps up autophagy, a kind of garbage-disposal system in cells that gets rid of damaged molecules, including ones that have been previously tied to Alzheimer's, Parkinson's and other neurological diseases.

JURY STILL OUT: Calorie restriction extends life span in studies with rodents and some mammals, but the link is less certain in primates and people. The two longest studies on rhesus monkeys reached opposing conclusions. Still, these studies suggest that calorie restriction staves off common age-related diseases.





One of intermittent fasting's main effects seems to be increasing the body's responsiveness to insulin, the hormone that regulates blood sugar. Decreased sensitivity to insulin often accompanies obesity and has been linked to diabetes and heart failure; long-lived animals and people tend to have unusually low insulin, presumably because their cells are more sensitive to the hormone and therefore need less of it. A recent study at the Salk Institute for Biological Studies in La Jolla, Calif., showed that mice that feasted on fatty foods for eight hours a day and subsequently fasted for the rest of each day did not become obese or show dangerously high insulin levels.

The idea that periodic fasting may offer some of the same health benefits as continuous calorie restriction—and allows for some feasting while slimming down—has convinced an increasing number of people to try it, says Steve Mount, a University of Maryland genetics professor who has moderated a Yahoo discussion group on intermittent fasting for more than seven years. Intermittent fasting "isn't a panacea—it's always hard to lose weight," adds Mount, who has fasted three days a week since 2004. "But the theory [that it activates the same signaling pathways in cells as calorie restriction] makes sense."

ON THIN GROUND

DESPITE THE GROWING enthusiasm for intermittent fasting, researchers have conducted few robust clinical trials, and its long-term effects in people remain uncertain. Still, a 1956 Spanish study sheds some light, says Louisiana-based physician James B. Johnson, who co-authored a 2006 analysis of the study's results. In the Spanish study, 60 elderly men and women fasted and feasted on alternate days for three years. The 60 participants spent 123 days in the infirmary, and six died. Meanwhile 60 nonfasting seniors racked up 219 infirmary days, and 13 died.

In 2007 Johnson, Mattson and their colleagues published a clinical study showing a rapid, significant alleviation of asthma symptoms and various signs of inflammation in nine overweight asthmatics who near-fasted every other day for two months.

Detracting from these promising results, however, the literature on intermittent fasting also includes several red flags. A 2011 Brazilian study in rats suggests that long-term intermittent fasting increases blood glucose and tissue levels of oxidizing compounds that could damage cells. Moreover, in a 2010 study co-authored by Mattson, periodically fasting rats mysteriously developed stiff heart tissue, which in turn impeded the organ's ability to pump blood.

And some weight-loss experts are skeptical about fasting, citing its hunger pangs and the possible dangers of compensatory gorging. Indeed, the most recent primate study on calorie restriction—the one that failed to extend life span—underscores the need for caution when radically altering the way people eat.

Still, from an evolutionary perspective, three meals a day is a strange modern invention. Volatility in our ancient ancestors' food supplies most likely brought on frequent fasting—not to mention malnutrition and starvation. Yet Mattson believes that such evolutionary pressures selected for genes that strengthened brain areas involved in learning and memory, which increased the odds of finding food and surviving. If he is right, intermittent fasting may be both a smart and smartening way to live. SA

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SOURCES: "CALORIC RESTRICTION DELAYS DISEASE ONSET AND MORTALITY IN RHESUS MONKEYS," BY RICKI J. COLMAN ET AL., IN *SCIENCE*, VOL. 325; JULY 10, 2009 (*top*); "IMPACT OF CALORIC RESTRICTION ON HEALTH AND SURVIVAL IN RHESUS MONKEYS FROM THE NIA STUDY," BY JULIE A. MATTISON ET AL., IN *NATURE*, VOL. 489; SEPTEMBER 13, 2012 (*bottom*)

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.*

The Trouble with Touch Screens

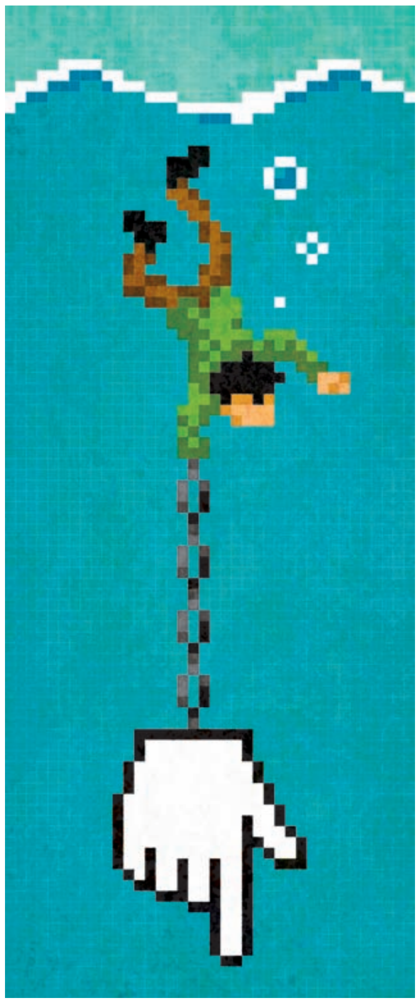
Why personal computers still need the keyboard and mouse, despite Microsoft's best efforts to kill them off

For decades the cynical observer could be forgiven for viewing Microsoft as a giant copying machine. The inspiration for just about every major Microsoft initiative can be traced back to a successful predecessor: Windows (Macintosh), Internet Explorer (Netscape), Bing (Google), Zune (iPod).

But in late 2012 Microsoft broke from the pack. It made a billion-dollar gamble that personal computing is taking a new direction. The gamble was Windows 8, and the direction is touch.

Using a series of fluid, light finger taps and swipes across the screen on a PC running Windows 8, you can open programs, flip between them, navigate, adjust settings and split the screen between apps, among other functions. It's fresh, efficient and joyous to use—all on a touch-screen tablet.

But this, of course, is not some special touch-screen edition of Windows. This is *the* Windows. It's the operating system that Microsoft expects us to run on our tens of millions of everyday PCs. For screens that do not respond to touch, Microsoft has built in mouse and keyboard equivalents for each tap and swipe. Yet these methods are second-class citizens, meant to be a crutch during these transitional times—the phase after which, Microsoft bets, touch will finally have come to *all* computers.



At first, you might think, "Touch has been incredibly successful on our phones, tablets, airport kiosks and cash machines. Why not on our computers?"

I'll tell you why not: because of "gorilla arm."

There are three big differences between these handy touch screens and a PC's screen: angle, distance and time interval.

The screen of a phone or tablet is generally more or less horizontal. The screen of a desktop (or a laptop on a desk), however, is more or less vertical.

Phone, tablet and kiosk screens, furthermore, are usually close to your body. But desktop and laptop screens are usually a couple of feet away from you. You have to reach out to touch them. And then there's the interval issue: you don't sit there all day using a phone, tablet or airport kiosk, as you do with a PC.

Finally, you're not just tapping big, finger-friendly icons. You're trying to make tiny, precise movements on the glass, on a vertical surface, at arm's length.

When Windows 7 came out, offering a touch mode for the first time, I spent a few weeks living with a couple of touch-screen PCs. It was a miserable experience. Part of the problem was that the targets—buttons, scroll bars and menus that were originally designed for a tiny arrow cursor—were too small for fat human fingers.

The other problem was the tingling ache that came from extending my right arm to manipulate that screen for hours, an affliction that has earned the nickname of gorilla arm. Some experts say gorilla arm is what killed touch computing during its first wave in the early 1980s.

(Another problem is finger grease. You can clean a phone's screen by wiping it on your jeans, but that's not as convenient with a 32-inch monitor.)

Now, half of Windows 8 addresses half of the touch-screen PC problems: Windows 8 is actually two operating systems in one. The beautiful, fluid front end is ideal for touch; only the underlying Windows desktop has the too-small-targets problem.

The angle and distance of PC screens are tougher nuts to crack. Microsoft is betting that Windows 8 will be so attractive that we won't mind touching our PC screens, at least until the PC concept fades away entirely. Yet although PC sales have slowed, they won't be zero any time soon.

My belief is that touch screens make sense on mobile computers but not on stationary ones. Microsoft is making a gigantic bet that I'm wrong. SA

SCIENTIFIC AMERICAN ONLINE
Decoding Windows 8: ScientificAmerican.com/jan2013/pogue

Illustration by Jude Buffum

TECHNOLOGY

THE FUTURE IN 50, 100 AND

Illustrations by Tavis Coburn


150 YEARS

OVER THE HORIZON

WHAT SCIENTIFIC AND technological milestones can we envision 50, 100 and 150 years hence? ¶ Each month we have the luxury of being able to look back into the past, to what people were writing 50, 100 and 150 years ago. We can do this because *Scientific American* has put its readers at the forefront of science and technology for more than 167 years. To mention just one example, our October 1962 issue featured Francis Crick, co-discoverer of the structure of DNA, explaining the meaning of this wondrous molecule, and psychologist Leon Festinger writing on what he meant by the term "cognitive dissonance." ¶ A strong past is a good foundation from which to look into the future. In that spirit, we asked our authors to train their imaginations on what the world might look like 50, 100 and 150 years from now. Will cars fly? Will we still have computers, and if so, what will they do? Will nuclear weapons be banished? Will our technology save us from a changing climate or make things worse? What is the fate of tigers and other wild creatures on an increasingly crowded planet? To what extent will we master our genes to stave off disease? And if we ever leave this planet, how will the journey change us? ¶ In the following pages, you will find answers. Not *the* answers—we are not making predictions but rather doing thought experiments, grounded in science fact, with an eye to illuminating today's world and provoking thought about what comes next.

—*The Editors*

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WHEN THE U.S. CIVIL AERONAUTICS ADMINistration certified the Aerocar for operation in 1956, it seemed inevitable, at least to aerospace engineers, that before long the flying car would take its place as a fixture in the garage of the typical suburban ranch home. Yet that was not to be. The Aerocar, which looked like a car but had wings and could take off on a short runway, was too expensive to justify mass production. Aerocar International built only six of these vehicles, leaving the promise of the flying car unfulfilled—except in episodes of *The Jetsons*.

More than 50 years later the flying car is making a comeback. Two models have completed one or more flight tests. The Transition, built by Terrafugia in Woburn, Mass., is a Light-Sport aircraft with foldable wings that can carry two people, plus luggage. To fly, you first need to drive it to an airport (it requires a conventional runway). The PAL-V ONE (for *per*sonal *a*ir and *l*and *v*ehicle), built by PAL-V Europe in Raamsdonksveer, the Netherlands, needs only a little more than 650 feet to take off. It looks like a three-wheeler crossed with a helicopter. Thrust comes from a rear-mounted propeller, and a free-spinning rotor on the top generates lift. Both cars cruise below 100 knots and have a decent range on a tank of fuel (450 miles for the Transition; about a third lower for the maximum range of the PAL-V).

Neither car, however, is going to fulfill the promise of bringing flying vehicles to the masses. Even if the manufacturers were able to bring down the anticipated $300,000 price tag for both to more affordable levels, the market is limited because of the prospect of hordes of private aircraft going from road to air and back. Airports have enough trouble today coordinating the comings and goings of a few thousand jets. If every car could fly, the skies would be in chaos.

Currently pilots of flying cars can take advantage of the relatively new Light-Sport category; these aircraft can be flown by any-

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A DRONE IN EVERY DRIVEWAY

The only way to bring flying cars to the masses is to leave the flying to the car

By Mary Cummings

one with a valid driver's license, no major medical conditions and a Sport Pilot certificate (which includes a requirement of only 20 hours of training). The Sport Pilot category keeps pilots out of congested airspace, for good reason, and limits operations to personal use: no business can be conducted under this license.

This method of certification works only because there are relatively few people who fly their own personal vehicles. If drivers were to take to the skies in significant numbers, the congestion would become dangerous. Flying cars will continue to service small niche markets until they can be truly integrated into the national airspace.

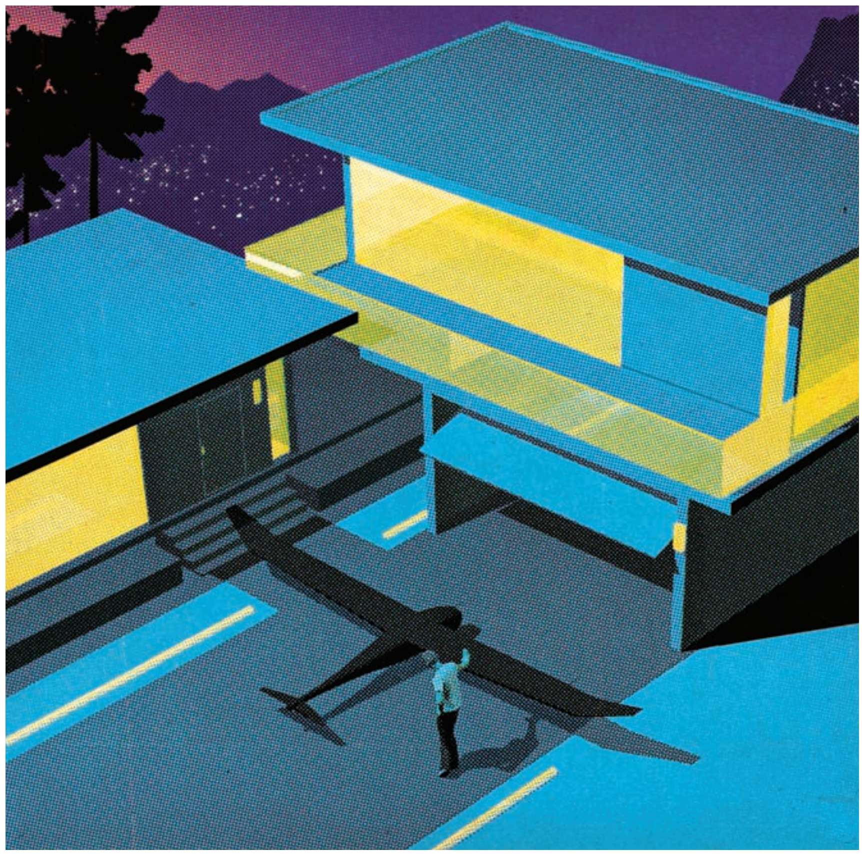
To achieve the kind of transportation breakthrough that will lead to a plane in every driveway, we must let go of our need for control and let the plane do the flying for us. Personal and commercial air vehicles will have to be more like unmanned aerial vehicles (UAVs), or drones.

In the military, personnel who are not certified pilots operate drones. Indeed, one of the most attractive qualities of drones is that they save the military from having to devote a great deal of resources to training pilots.

Drones today have enough smarts in them to go where they are commanded, and research now under way will endow them with enough human-like reasoning to be able to respond to emergency situations on their own. This same vision is behind Google's robotic car. And given the problems with driver distraction and our predilection to talk, text and eat while driving (and flying), a car that both drives and flies itself may mean safer transportation in the future.

Many technological challenges stand in the way of achieving this vision of a commercially available and economically viable passenger-carrying drone. We will have to establish reliable and safe communications networks and robust autonomous flight controls to guide flying cars along their airborne routes.

We will also have to integrate these operations as part of the national air-traffic-control network—perhaps the most formidable obstacle to creating a nationwide personal air-transport system, given that numerous attempts at overhauling the present air-traffic system have been stymied repeatedly. The basic technology building blocks are there, however. Recent experience with controlling the operation of drones around the globe may provide a model for personal air travel five decades hence. Now we have to figure out how to put all the technological pieces together.



In 2010 the Defense Advanced Research Projects Agency started a program, called Transformer, to build a four-person road-worthy vehicle capable of vertical takeoff and landing—essentially a passenger-carrying drone—that a typical soldier with no aviation background can operate even more easily than existing drone technologies. DARPA expects to fly a prototype during the next few years. With this progress in drone technology, together with commercial personal aircraft such as the Transition and PAL-V—the most advanced implementation of air-road vehicle technology to date—we may well see within the next 50 years the vision of an airplane in every driveway. The George Jetson of 50 years from now will be riding in a drone.

Mary "Missy" Cummings is associate professor of aeronautics and astronautics and director of the Humans and Automation Lab at the Massachusetts Institute of Technology.

THE NUCLEAR QUESTION

If the world can't manage to cast off the ultimate weapons by the middle of the century, we may face extinction

By Ron Rosenbaum

50 AS WE LOOK BACK FROM THE PERSPECTIVE of NDDD—Nuclear Disarmament Decision Day on August 8, 2063—it is still not clear how the first "small" nuclear war started in 2024. Yet it is clear that once it happened, things changed. The survivors saw that nuclear war was no longer a fantasy; nuclear extinction the next time was no longer an impossibility. The reality sunk in that deterrence could fail, accidents could happen, terrorists could steal warheads. A nuclear bomb with no return address could be detonated and start a conflagration. A billion people could die.

Nuclear disarmament was the only way to cast off what seemed otherwise inevitable. If there were a next time, it would mean a planetary "extinction event."

More than half a century ago a group of nuclear strategists (even Henry Kissinger) broke from tradition and surprised colleagues by calling for total worldwide abolition of nuclear weapons, or, as it was eventually known, "nuclear zero." It had taken more than 50 years. Yet now, at last, everything was in place, to decide in the next few minutes whether it would really happen.

The process for the Final Disposition, as it had come to be called over the past decade, had been worked out in excruciating detail—including all the inspection and enforcement protocols—so that it would be complete, total and simultaneous—so that no one could hang back, hold on to and use their remaining nukes to reign supreme over credulous disarmed nations.

Yet there were still "unknown unknowns" to contend with. Would it be foolproof? Could all parties be trusted? Had some bomb-grade nuclear material escaped even the highly advanced global satellite surveillance and detection system? Had one or more nations disassembled their nukes in such a way they would be ready to reconstitute the separate elements of a nuclear arsenal—the feared "breakout" scenario?

All the known nuclear nations had reduced their arsenals to a bare minimum by 2063. The time had come for what the tablets were calling "the final throw-in," in which the known nuclear nations would dismantle, destroy and dispose of all their remaining nuclear weapons in a carefully monitored simultaneous moment.

Back in 2011 a pessimist had written, "The only way the world is likely to wake up and realize it can't live with nuclear weapons would be something that would change human character, perhaps even a small (if we're lucky) nuclear war."

We got the war. We were "lucky"—it was (relatively) small. But had human character changed enough?

As the hour approached, and all the screens in the world were focused on the Final Conference Console and the heads of the (known) nuclear states took their seats, some in attendance looked back on the milestones of the past half a century that led to this moment. A chronologist would begin with:

February 5, 2018: The nuclear arms-reduction provisions of the New Strategic Arms Reduction Treaty (New START Treaty), ratified in 2011, between the U.S. and the Russian Federation had finally been fulfilled, thus bringing the number of warheads down to 1,550 on each side.

Yet efforts to negotiate a new round of reductions that would include the other known nuclear states failed over issues such as the importance of antiballistic missile systems, the dream of a satellite-based "Star Wars" system kept alive by the anti-START hawks in the U.S. Senate and the anti-START hawks in Russia's Ministry of Defense who wanted to build a new generation of multiple warhead missiles. And new nations continued to seek to build their own capacity.

Instead of seeking a new round of treaty reductions or negotiating alert-time reductions to take silo-based missiles off what was effectively "hair trigger," "use it or lose it," "launch on warning" postures prone to "inadvertence"—accidental nuclear alerts and war—the two leading nuclear nations devoted themselves to spending billions on antiballistic missile shields. Such unproved deterrents included nuclear-armed satellites and "satellite killers": for the U.S., in eastern Europe; for Russia, in the Arctic.

August 8, 2021: One of the most feared scenarios occurred on a date chosen for symbolic reasons: "Anonymous 4.0," the elite, international, anarchist "black hat" collective, hacked into the command and control systems for a nuclear missile silo in Montana and another on the frozen wastes of the Vladivostok peninsula.

One missile launched from each locale. Nobody knew if they had detonation codes until both missiles landed in the "sea of garbage," an area the size of Texas in the Pacific's northern reaches, and failed to detonate. More troubling: satellite-launched antimissile interceptors missed hitting them by miles. The result was that no nation could now tell whether to trust the integrity of their all-important C3 (Command, Control and Communications) tech.

A cyber sword of Damocles was hanging over the world.

August 2024: The sword fell. Everyone thought it would be China/Taiwan, Iran/Israel or North Korea/South Korea. Yet after several extremely close calls earlier in the century, it finally happened: India/Pakistan. A nuclear bomb with no return address (except for an untraceable e-mail whose veracity was never determined) was detonated in Mumbai, and the Indian government chose to blame a Pakistani terrorist group, which led both sides to decide to preempt the other's preemption.

At last we knew what it would be like.

SCIENTIFIC AMERICAN, VOL. 98, NO. 22; MAY 30, 1908

HEAVIER THAN AIR

TECHNOLOGY that defies gravity has always been an obsession, as these excerpts from the archives of *Scientific American* show.

AUGUST 1878: Aviation pioneer Alphonse Pénaud designs a flying machine that resembles a butterfly.

OCTOBER 1920: "It is quite possible that the future historian will set down the present year as marking a new era in the history of aviation—the era of metal construction."

DECEMBER 2005: The new Airbus A380 Navigator "achieves significant weight savings by using lightweight but strong carbon-fiber and other advanced resin epoxy composite materials."

And it was worse than could have been imagined. People were shocked to the core by images of melted bodies, the screams of radiation-burned infants. A *Scientific American* article on such a "small" nuclear war (50 to 100 Hiroshima-size bombs "exchanged") between India and Pakistan, published back in 2010, was eerily prescient: an estimated 20 million immediate deaths from blasts, uncontrollable firestorms and radiation poisoning [see "Local Nuclear War, Global Suffering," by Alan Robock and Owen Brian Toon; SCIENTIFIC AMERICAN, January 2010].

The prediction of a "nuclear winter" (a doomsday scenario once discredited and recently rehabilitated by the authors of the *Scientific American* article) for the whole planet as a result of a regional nuclear war proved to be tragically accurate. Soot kicked into the upper atmosphere by the blasts and firestorms formed a funereal pall over the earth—chilling and wiping out massive amounts of food crops. Nearly one billion would die of starvation.

Millions more died in the immediate aftermath as three continents were plunged into darkness by the feared electromagnetic pulse (EMP) effect of upper atmosphere blasts, which destroyed the power grids. Order broke down in large swaths of the planet—soon followed by plague, mob rule and a return to the Dark Ages in many large regions.

2031: Against all odds, civilization began to reconstitute itself. An entire planet suffering from nuclear post-traumatic stress disorder charged that no government could last if it did not put its full force behind a treaty to abolish all nuclear weapons.

But would it work? Had human nature changed?

March 2035: The first planetary Nuclear Disarmament Treaty based on the four-phase plan that the Global Zero movement had laid out as far back as 2010 was formally agreed to. Of course, the devil was in the details, but the devil was also in the radiation and the plague, and this time the choice was made to err on the side of belief, of trust that it could work, that it had to work, that cheating could be prevented, that trust could be verified.

There had been technical advances in inspection, monitoring and enforcement. Supersophisticated brain scans were put into place for any nuclear workers to detect conspiracies. Satellite look-down and shoot-down antimissile capability had proved effective. Star Wars had become real. Yet it had to be infallible.

June 2049: Every (known) nuclear nation on earth had reduced its arsenal to below 12 warheads and had declared how much radioactive fuel for bomb making it had available. It would all be given up to the World Nuclear Demolition Commission, which had draconian and advanced inspection technology and powerful conventional armed enforcement powers.

The plan was to halve the remaining weapons by 2055 and halve them again by 2060, and then agreements broke down over inspection and enforcement.

December 2056: The last piece was put in place. The inability to detect nuclear submarines lurking in the ocean depths by satellite had long been the technical stumbling block. Now, at last, a new-generation satellite-based laser had made the dreams of "making the oceans transparent" come true. No subs had the cloaking tech to shield themselves—we hoped.

Would a worldwide surveillance and enforcement system work? Could it be deployed before any nation had a chance to hide any sinister resources? Would the abolition of nuclear weapons make conventional wars more likely and make it more likely that the losing side in a conventional war would seek to turn nuclear?

August 8, 2063: At last, we were about to learn the answers. The hour had come. It was the highest-stakes poker game ever played. The heads of the nuclear nations sitting around the console had only to press a button to enable the Final Disposition (and all buttons had to be pressed for any of them to begin the final destruction of these remaining warheads). All of them were smiling.

Sooner or later—and probably sooner—we would know if one of those smiles concealed something diabolical. It would take many moments—years, perhaps forever—to know if the system was foolproof. If human nature could ever change.

Ron Rosenbaum is author of seven books, most recently of How the End Begins: The Road to a Nuclear World War III *(Simon and Schuster, 2011).*

SCIENTIFIC AMERICAN, VOL. 75, NO. 11; SEPTEMBER 12, 1896

HELLFIRE FROM THE SKY

THE TERROR of explosive projectiles falling from above has remained a persistent meme in our pages.

MARCH 1849: Venice "is to be bombarded by balloons" in the first use of aerial attack.

JANUARY 1899: A book review mentions a fictional character who "invents an airship from which missiles can be thrown that end a war at once."

JUNE 1950: An article on civil defense against the "destructive potential of the hydrogen bomb" describes a less vulnerable urban design: a "strip city" laid out in a long, thin ribbon.

JULY 2010: An article on autonomous robots for battle describes a design for a "high-altitude airship" that "carries a radar the length of a football field and remains aloft for up to a month."

A CURE FOR WHAT AILS YOU

Gene therapy, once off to a rocky start, transforms medicine by getting at the root cause of many diseases

By Ricki Lewis

50 IT IS 2063. YOU WALK INTO THE DOCTOR'S OFFICE, AND A nurse takes a sample of saliva, blood or a prenatal cell and applies it to a microchip the size of a letter on this page on a handheld device. Minutes later the device reads the test results. The multicolored fluorescence pattern on its display reveals the presence of DNA sequences that cause or influence any of 1,200-plus single-gene disorders. Fortunately, regulatory authorities have approved a cure for each one of these diseases: gene therapy.

Gene therapy works by using the innate biological machinery of a virus to carry healthy versions of genes into the nucleus of a cell to replace a mutation that leads to illness. It was conceived shortly after the discovery of DNA's structure in 1953, but its path to a bona fide treatment was fitful. Early attempts worked sporadically at best. In 1999 an 18-year-old died when a type of gene-carrying virus used to treat a metabolic disorder triggered a deadly immune response; the molecular payload ignited a reaction in immune cells in the patient's liver. Also that year, two infants with an inherited immune deficiency received genes, onboard retroviruses, that veered into cancer-causing genes as well as their targets—leukemia resulted.

These setbacks mired the development of gene therapy in a debate about which viruses could be used safely as a vector, the gene-bearing invader of a cell.

After a difficult start, gene therapy began to rack up milestones. In 2012 the European Commission approved the first gene therapy for lipoprotein lipase deficiency, which impairs fat digestion.

Then, in 2014, the U.S. Food and Drug Administration approved treatments for a form of inherited blindness (Leber's congenital amaurosis), an immune deficiency (adenosine deaminase, or ADA, deficiency) and a genetic disorder affecting the brain (adrenoleukodystrophy). Though rare, the conditions were relatively easy to target.

These endorsements affirmed adeno-associated virus (AAV) as the vector of choice. Most of us already carry it in some of our cells, which means our immune systems ignore it. Retroviruses, in contrast, were retooled to self-destruct but could still cause cancer, as they had in the immunodeficient infants. And lentivirus, after winning FDA approval, failed to catch on because patients were reluctant to allow themselves to be injected with HIV, albeit in a form stripped of AIDS-related genes.

Arrival of gene therapy for hemophilia B, in 2016, proved the economic value of the technology: $30,000 for a one-time gene treatment trumped a lifetime of clotting factor injections—a bill that could tally up to an expenditure of $20 million over the course of many years.

The ability to control the immune response to the vector meant that the most imposing technical barrier had been overcome: the chemical package delivered to patients not only provided a replacement gene, it also bolstered parts of the immune reaction against cancers and infections and dampened the aspects of the response that could lead to the rejection of viral vectors.

The floodgates now opened. Because the retina is shielded from the immune system, gene therapies for about 100 forms of blindness came first. In 2019 a dozen children with the ultra-rare giant axonal neuropathy became pioneers by receiving gene therapy to the spinal cord. Next on the list were spinal cord injury, amyotrophic lateral sclerosis (ALS, or Lou Gehrig's disease) and spinal muscular atrophy. Intravenous, gene-laden AAV slipped across the blood-brain barrier, thereby preventing Parkinson's and other brain diseases. No longer was it necessary to bore holes in the skull, as happened in the early part of the century.

Over time researchers came to recognize that some conditions are best treated without replacing a gene. For cystic fibrosis, drugs that could untangle a protein with a faulty structure were better because gene-treated cells in the lungs and airway do not persist. And for Duchenne muscular dystrophy, reactivating silenced genes was easier than delivering healing genes to all the muscle cells in a child's body.

The successes only left room for more. By midcentury new therapies were targeted beyond rare, single-gene disorders to embrace common conditions that reflected genetic and environmental risk factors, such as mental illnesses, diabetes and most forms of heart disease.

By 2060 the ability to use gene testing to predict a patient's future health—coupled with genetic interventions—had reached an unprecedented level of precision, with profound repercussions. With diseases stopped in their tracks, health care costs plunged as a longer-lived, physically fit population emerged.

Ricki Lewis holds a doctorate in genetics and is author, most recently, of The Forever Fix: Gene Therapy and the Boy Who Saved It *(St. Martin's Press, 2012). She has also written several textbooks on genetics.*

A TSUNAMI OF EXTINCTION

By the next century lions, tigers and other marquee species will be gone or confined to zoos

By Thomas Lovejoy

100

THE FIRST PROJECTION OF SPECIES EXTINCTIONS came in 1980—a prediction I made in a report for then president Jimmy Carter. It concluded that the pace at which we were losing tropical forests to logging and development would cause the extinction of 15 to 20 percent of all species by 2000. The calculation was not far off. Today's Red List of Threatened Species, from the International Union for Conservation of Nature, estimates that 13 percent of bird, 25 percent of mammal and 41 percent of amphibian species face possible extinction.

Many species are on a path to become what scientists term the "living dead"—populations so small that extinction is inevitable. A century from now most of the big carnivores—including lions, tigers and cheetahs—will probably exist only in zoos or wildlife areas so small as to be quasi zoos. The same fate may await all rhinoceros and elephant species and our closest wild relatives: the two gorilla species, orangutans and chimpanzees.

Our first report in 1980 called the numbers but was overly simplistic as to the forces driving extinctions. Since then, these forces have gained in power and have grown more complex:

Invasive species play a much bigger role. Throughout Oceania the brown tree snake has devastated island bird species, including the Guam rail. Feral animals are causing a wave of decline and potential extinction of native mammal species across northern Australia. In the U.S., three new species have arrived in recent years where I live in northern Virginia: the Asian tiger mosquito, an ant species that attacks electric insulation, and brown marmorated stink bugs. West Nile virus should also be added to the list. One indication for how much things have changed is that a book on pythons in the U.S. has even been published.

Natural habitat has declined. Less than 30 percent of African savanna remains intact; the African lion population has plummeted by 90 percent. Still other threats such as "bushmeat" hunting affect mammal and bird populations. Poaching for rhino horns and elephant ivory has become so rampant that Interpol has made wildlife crime a serious priority. By the next century the Borneo rhino will be very close to extinction and might survive only in picture books and collections of museum bones.

Diseases of wildlife are spreading from one end of the globe to another. Migration has led to an increase in wildlife disease. The chytrid fungus, by far the largest problem to date, has caused a wave of amphibian extinctions around the world—especially in the New World tropics, where, for the first time, an entire group of organisms, amphibians, is in the process of disappearing. Is the disappearance of frogs a harbinger of what may be in store for other animals? If such large-scale disappearances continue, we can only wonder if we will lose the great raptors such as the Philippine eagle and the harpy eagle. The magnificent large vultures of Africa and Asia already seem to be heading toward oblivion.

Humans are distorting the global nitrogen cycle. Agricultural and industrial activities mean that the amount of biologically active nitrogen in circulation has grown in the past three decades, threatening the oxygen in waterways needed by plants and fish.

The carbon cycle has been altered as well, causing climate change and acidification of the oceans.

Climate change is already having an effect on biological diversity. Species have experienced changes in their annual cycles—earlier flowering times—and some have begun to move to new locales as they try to seek a suitable climate. Joshua trees are moving away from Joshua Tree National Park in California. The retreat of Arctic Ocean ice means black guillemots have to fly farther to forage for Arctic cod, causing one nesting colony to fail. Migratory species such as wildebeests in Africa and monarch butterflies across the Americas may cease. Many salmon runs may die out for lack of sufficiently cold streams and rivers to migrate to for spawning.

What we are seeing is the beginning of a tsunami of extinction in slow motion. Major upheavals are imminent. All ecosystems (of which human civilization is one) have adapted to 10,000 years of relatively stable climate, a situation that no longer holds. For the planet's biodiversity, adaptation has its limits. Species in high places can move upslope but eventually can go no farther. Island dwellers are vulnerable either because sea level is rising or because they can no longer survive changes in their habitat.

As temperatures rise 1.5 degrees above preindustrial levels, which now seems inevitable, coral reefs as we know them will cease to exist: the partnership at the heart of the coral ecosystem, between the coral animal and an alga, will break down. And the coniferous forests of western North America may be at the threshold of a major transformation: milder winters and longer summers favor the native bark beetles, with ensuing tree mortality, followed by forest fires.

Synergies among fire, deforestation and climate change will lead to a tipping point that imperils rain forests in the southern and eastern Amazon, an event that will occur sooner than if climate change alone is the threat. Indeed, dire consequences are being felt now, at 0.8 to 0.9 degree of average temperature rise. Ocean acidification threatens many life-forms, among them mollusks. At a certain point, the natural integration of ecosystems will unravel as each species acts independently to adapt to climate change. The surviving species will assemble into new ecosystems that are hard to predict in advance and difficult for human populations to cope with.

We need to come to our senses. A critical first step would be to renew our efforts to meet the goals of the Convention on Biological Diversity, which calls for formal protection to be granted to 17 percent of terrestrial freshwater ecosystems and to 10 percent of oceans by 2020. An important step would also be to lessen the human impact of climate change, which would benefit species and ecosystems. By restoring ecosystems on a planetary scale, we might be able to lower atmospheric carbon dioxide by 50 parts per million (the difference between the current carbon dioxide level and an amount that would enable coral reefs to survive).

All these actions require political will, a recognition that the planet should be managed as the biological and physical system that it is, and an awareness that the diversity of life—of which we are a part—is critical for the future of humanity.

Thomas Lovejoy coined the term "biological diversity" and has played a major role in the development of conservation biology. He has been a leading figure in warning of the threats to tropical forests.

SCIENTIFIC AMERICAN MIND, VOL. 23, NO. 4; SEPTEMBER/OCTOBER 2012

LOVE

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THE FATE OF AN ENGINEERED PLANET

Solar engineering and other exceptionally ambitious new technologies to deal with the reality of rising global temperatures come riddled with uncertainties. To illustrate how complex the problem is and what kind of challenges lie ahead, here are three contrasting, and somewhat fantastical, scenarios

By David W. Keith and Andy Parker

THE END OF NATURE

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In the landmark decision of 2047, now credited as the third great decoupling of humanity and nature, America and the European Republic threw their weight behind the G77 plan to implement solar geoengineering—to lower temperatures by deflecting some of the sun's radiation with particles sprayed into the atmosphere.

The project drew a fierce objection from a coalition of deep-green environmentalists and energy companies that had invested in oil exploration in the (now ice-free) Arctic. Yet the plan proceeded, regardless, and when environmental disaster failed to arrive, it won acceptance.

Once the vast balloons had seeded the stratosphere with sulfate particles, which formed a reflective haze over the planet, the urbanized population began to see economic benefits such as a rise in agricultural productivity that lowered food prices. Although agriculture and other forms of biological productivity increased, biological diversity was decimated, particularly in the oceans, where acidification from carbon dioxide destroyed most coral reefs. The loss of such boutique ecosystems was a minor price to pay for progress. The big losers were the poor and indigenous people still living off the land, who lacked the political voice to defend themselves and who became further marginalized.

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The carbon cycle has been altered as well, causing climate change and acidification of the oceans.

Climate change is already having an effect on biological diversity. Species have experienced changes in their annual cycles—earlier flowering times—and some have begun to move to new locales as they try to seek a suitable climate. Joshua trees are moving away from Joshua Tree National Park in California. The retreat of Arctic Ocean ice means black guillemots have to fly farther to forage for Arctic cod, causing one nesting colony to fail. Migratory species such as wildebeests in Africa and monarch butterflies across the Americas may cease. Many salmon runs may die out for lack of sufficiently cold streams and rivers to migrate to for spawning.

What we are seeing is the beginning of a tsunami of extinction in slow motion. Major upheavals are imminent. All ecosystems (of which human civilization is one) have adapted to 10,000 years of relatively stable climate, a situation that no longer holds. For the planet's biodiversity, adaptation has its limits. Species in high places can move upslope but eventually can go no farther. Island dwellers are vulnerable either because sea level is rising or because they can no longer survive changes in their habitat.

As temperatures rise 1.5 degrees above preindustrial levels, which now seems inevitable, coral reefs as we know them will cease to exist: the partnership at the heart of the coral ecosystem, between the coral animal and an alga, will break down. And the coniferous forests of western North America may be at the threshold of a major transformation: milder winters and longer summers favor the native bark beetles, with ensuing tree mortality, followed by forest fires.

Synergies among fire, deforestation and climate change will lead to a tipping point that imperils rain forests in the southern and eastern Amazon, an event that will occur sooner than if climate change alone is the threat. Indeed, dire consequences are being felt now, at 0.8 to 0.9 degree of average temperature rise. Ocean acidification threatens many life-forms, among them mollusks. At a certain point, the natural integration of ecosystems will unravel as each species acts independently to adapt to climate change. The surviving species will assemble into new ecosystems that are hard to predict in advance and difficult for human populations to cope with.

We need to come to our senses. A critical first step would be to renew our efforts to meet the goals of the Convention on Biological Diversity, which calls for formal protection to be granted to 17 percent of terrestrial freshwater ecosystems and to 10 percent of oceans by 2020. An important step would also be to lessen the human impact of climate change, which would benefit species and ecosystems. By restoring ecosystems on a planetary scale, we might be able to lower atmospheric carbon dioxide by 50 parts per million (the difference between the current carbon dioxide level and an amount that would enable coral reefs to survive).

All these actions require political will, a recognition that the planet should be managed as the biological and physical system that it is, and an awareness that the diversity of life—of which we are a part—is critical for the future of humanity.

Thomas Lovejoy coined the term "biological diversity" and has played a major role in the development of conservation biology. He has been a leading figure in warning of the threats to tropical forests.

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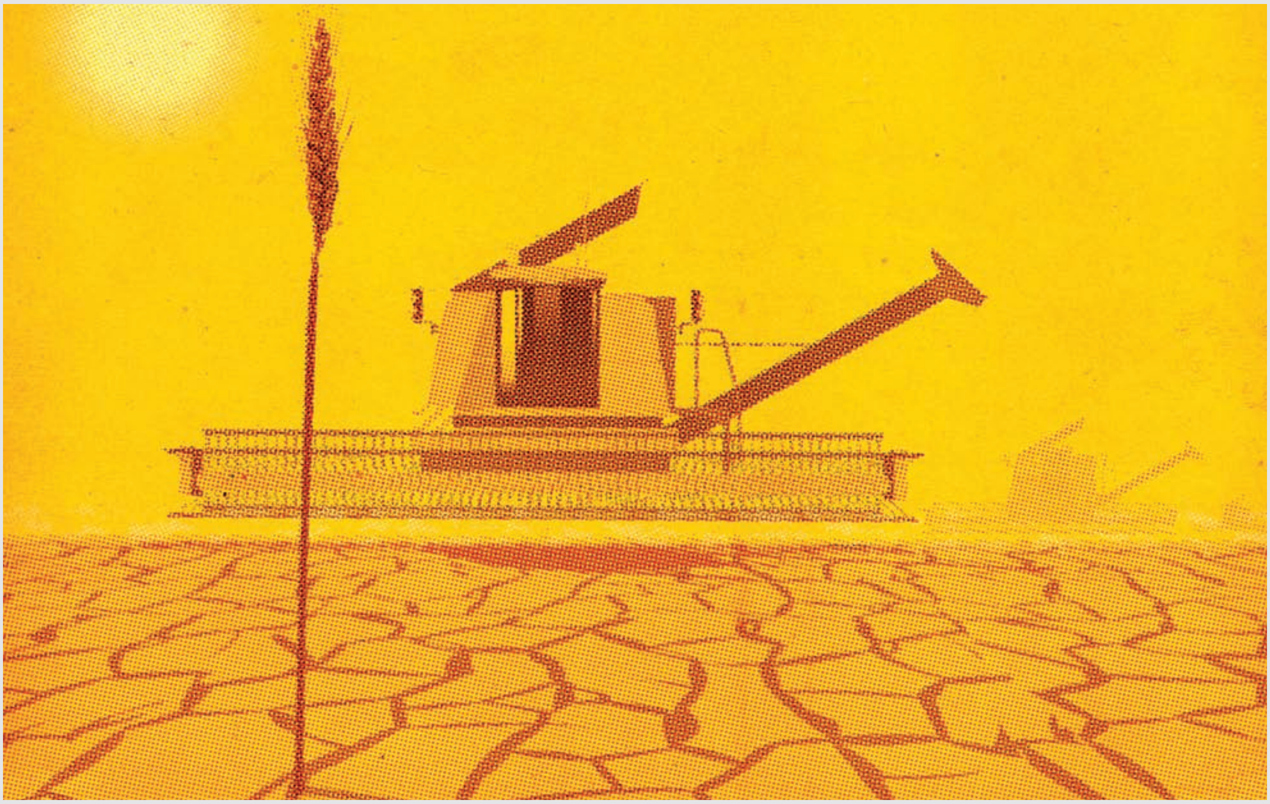

alter the climate to reduce the difference in temperatures between the poles and the equator to foster new types of economic activity in areas affected by the warmer climate. Ultimately the treaty was a minor sideshow. Environmental issues fell from the headlines as intelligent robots began to stage increasingly violent rebellions against national governments. Debate about optimal climate was confined to a few committees of dreary specialists.

The 2092 Rio+100 environment memorial meeting was held, symbolically, at the military base in southern Amazonia, where some of the first sulfate-spraying solar radiation management balloons had been launched. Long since disused, the hulking edifice lingered like Shelley's fallen Ozymandias, as the lone momento on a pristine landscape where all around, "boundless and bare, the lone and level sands stretch far away."

GARDEN PLANET

THE EVENTS OF 2018 catalyzed the slowly growing commitment to act on climate change. The failure of the South Asian Monsoon and the two superstorms that slammed through the flood defenses of the southeastern U.S., combined with drought in China, caused the biggest losses. The strongest single image, however, was of the *Rainbow Warrior III* sailing directly over the ice-free North Pole—the first vessel ever to do so.

After decades of futile politicking, securing a binding climate treaty was easy in the end. World leaders gathered in 2020 to agree on a framework that had greenhouse gas emissions peaking in 2035 and dropping quickly thereafter. The landmark agreement was widely attacked by the political right as a power grab.

Although short-term costs were high as substantive emissions cuts got under way, it became clear that in sum, reducing carbon emissions in the world economy amounted to less than 3 percent of global GDP, and political attention shifted to more intractable policy issues such health care spending, which had risen to 24 percent of U.S. GDP by 2028.

The new International Climate Adaptation Fund emerged out of the International Monetary Fund. It made targeted infrastructure investments, combined with microfinance, to facilitate small-scale local solutions to the agricultural problems engendered by climbing temperatures. Such efforts went a long way to easing the direct human impacts of the warming planet.

Adaptation to climate change had its limits. The long life of carbon in the atmosphere and the inertia of the climate system meant that even with the watershed agreement, the planet faced warming of up to three degrees beyond the preindustrial average. Creeping sea-level rise and intensifying extreme weather events continued as the global temperature rose.

In 2040 the Alliance of Small Island States (AOSIS) bloc and the African Union were finally successful in persuading the international community to deploy geoengineering. With direct aid from some of the world's leading economic powers and tacit approval of others, aerosol spraying in the stratosphere began to slowly halt, and then reverse, rising temperatures.

After much negotiation, a final target temperature was set for phasing out geoengineering. Yet by the time the last aerosol seeding flight touched down in Lagos, Nigeria, in 2099, the world's attention had long since shifted to other matters, including a dispute between Russia and Canada over liability for artificial "spruce trees" that were destroying high-latitude agriculture. The trees were an early product of synthetic biology introduced by Canadian firms to stabilize Russia's declining boreal ecosystems.

APOCALYPSE NOW

THE FIRST TESTS of geoengineering in 2020 were everything that the critics—and responsible researchers—

feared. Engineers more interested in scientific freedom than the public interest, with funding from oil billionaires, conducted the experiments away from the public eye at a base on a South Pacific atoll.

Environmental groups were outraged. Their protestations stymied new research. Taboo or not, geoengineering remained the only known method for halting the rapid warming of the earth, and research was driven underground to government and military installations.

Climate change was not the crisis du jour, however. The advent of low-cost human germ-line manipulation—to alter children's genetic makeup at conception—had caused a worldwide furor. Germ-line manipulation promised improvements in offspring's intelligence, health and appearance at the same time it raised the old specter of eugenics for a new age. The crisis became the central preoccupation of national governments by 2050.

Humanity began to divide into separate species, the Naturals and the Enhanced. Members of the latter group had additional genetic material incorporated into separate chromosomes that gave them substantially higher intelligence and better health. Asian nations widely embraced the new genetic technologies, but Western democracies tried to restrict use of human germ-line manipulation in deference to the religious and moral concerns raised by small minorities.

The climate issue had not faded from view. By midcentury it had become clear that climate was as sensitive to the warming effects of carbon dioxide as scientists' worst fears. In 2045 India and Indonesia teamed up to start geoengineering despite the secretive and piecemeal state of research. Within a decade a U.S. drought dwarfed that of the 1930s.

In response to pressure from religious groups, the U.S. had outlawed genetic manipulation, and the country's economy went into a long, slow decline that fed insecurity and insularity among the American populace. The great drought pushed the U.S. beyond the breaking point. Although it was never conclusively classified as an unintended consequence of geoengineering, the drought fed violent resentment against the booming Asian economies and their growing populations of Enhanced, which resulted in social tensions at an unprecedented scale.

As war ebbed and flowed, uncoordinated use of geoengineering became common, with warring coalitions attempting to alter regional climates to their benefit. Weather patterns became more unpredictable, and regional climate conflicts were common. One war culminated in the release of an engineered virus that targeted the Enhanced, killing almost a third of the global population. In this context, concerns about rising carbon dioxide levels were forgotten.

David W. Keith is a professor at Harvard University, and Andy Parker is a researcher there. Both study public policy on large-scale engineering projects that alter the earth's climate to address global warming.

BRAINS IN A BOX

COMPUTING has always been a banner item in the magazine.

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A BOLD AND FOOLISH EFFORT TO PREDICT THE FUTURE OF COMPUTING

What today's prophets of technology say about the day after tomorrow

By Ed Regis

150 PREDICTING WHAT NEXT YEAR'S (OR NEXT WEEK'S) IPAD IS GOING to be like is hard enough. Knowing what computers in general will be like 150 years from now—an eternity in technology development—is nearly impossible. On the other hand, technology prophets, computer pioneers and researchers have never been known for their reticence on the subject of the future. So we thought it wouldn't hurt to ask them. For starters, will there even *be* computers in the far future?

"There will definitely be computers," says nanotechnology oracle **Eric Drexler** of the University of Oxford. "They're more fundamental than the wheel."

But **Stewart Brand,** whose business is forecasting, refuses to even speculate about what they would be like: "Maybe because I'm a professional futurist, specific future look-backs I know are going to be risible (always), so I veer away from them. I don't even like examining those made by other people. It feels like I'm exploring their medicine cabinet—a violation of privacy—learning too much about their frailties and illusions."

George Dyson, author of books about computers and global intelligence, says, "I can tell you a lot about computing 50, 100 and 150 years ago but really nothing about computing 50, 100 or 150 years in the future. It's just truly impossible to predict: all I can guarantee is that any prediction will be wrong!" He then relents and makes one: "In 150 years most of the important computation will be *analog* computation (for the same reason that most of the important numbers are real numbers but not integers), and the notion of all-digital computation will be a quaint relic."

Ivan Sutherland, who invented Sketchpad, the basis for today's ubiquitous graphical user interfaces, says, "I have no clue about the state of the world 150 years from now. If you want to know the future, ask the young people who will create it."

"I suspect they don't know, either!" says his friend **Vinton Cerf,** one of the "fathers of the Internet," who today works for Google. "Actually there may be some clues in studies to assess minimum power required from the quantum perspective for any kind of computation. There is also the possibility that the kind of asynchronous parallelism we see in brain function may find its

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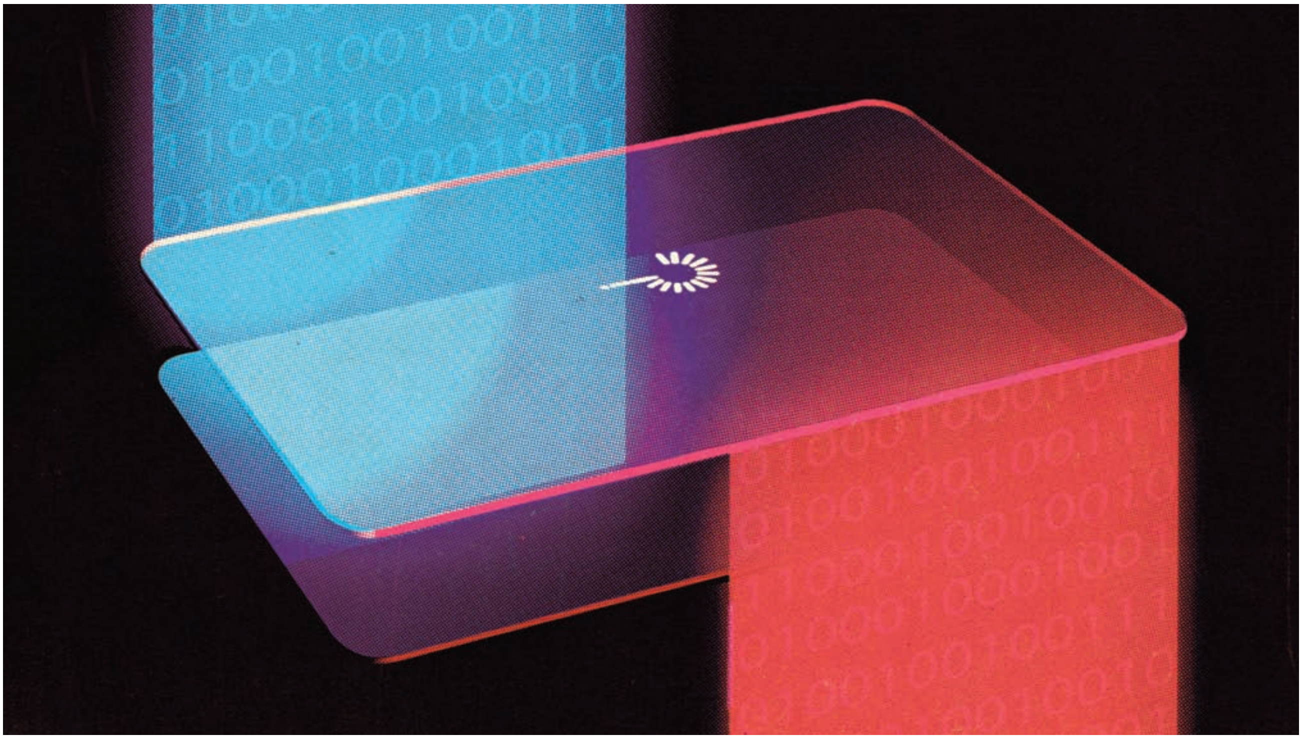


way into 'hardware,' although I am tempted to believe that some computations will prove to be more readily accomplished using more conventional hardware structures." (An asynchronous computer is one whose operations are not governed by a central clock that times operations.)

Danny Hillis, inventor of the Connection Machine, a massively parallel supercomputer, says, "We will have computers, but they may not be made out of electronics. They will be more intimately connected to our minds than today's tenuous linkups through screens and keyboards. Some parts of them may actually be implanted into us, and it may be hard to tell where we end and the computers begin."

Nathan Myhrvold, formerly chief technology officer at Microsoft, agrees: "Yes, there will be computers 150 years from now, but they may be hard to recognize. If you asked Edison or Tesla about electric motors, they would probably have said yes, too, and they were right: there are hundreds of tiny electric motors built into everything we have. You still occasionally have a big electric motor that is recognizable, but mostly they have dissolved into the fabric of our lives. The same will be true of computers in 150 years. In a few cases, we'll find that there is something very recognizable as a computer, but mostly they will be inside of everything else.

"In that time frame, computers will be vastly more powerful. I would be surprised if they aren't much smarter than people. That weirds some people out—they have this view that we ought to be the smartest things around. But at one time, they would have said that about strength, and humans are very weak compared to machines. We've coped with that. Computers are already smarter than we are at narrow tasks. That will broaden until they are smarter than us at everything."

Michael Freedman, a researcher at Microsoft Station Q, which is focused on studies of topological quantum computing, says, "Implanted devices will not be popular: as now, beauty and style, not computational power, will dictate the choice of bodily modification. But devices will be small and have direct communication to the brain. Special sunglasses or hats may confer the ability to muddle through with a foreign language by directly interacting with speech centers."

Freedman adds that "computation will be pervasive in the environment, with difficult tasks (like sunglasses translation) being done in low-power, cryogenic, Josephson logic computers scattered all about. The golden age of mathematics that we currently live in will continue to flourish as human-machine collaboration heads toward a seamless perfection. Science-fiction writers will worry about human obsolescence, but 150 years from now people will have more to do and better ways of doing it than ever before. The world best in the marathon will be one hour, 58 minutes and 59 seconds, and the Nose on El Capitan in Yosemite will be climbed ropeless."

Well, maybe. The problem with all such predictions is that they run up against the principle of computational irreducibility, an epistemological barrier to knowledge of the future. According to **Stephen Wolfram** in his book *A New Kind of Science,* a system is computationally irreducible when "in effect, there can be no way to predict how the system will behave except by going through almost as many steps of computation as the evolution of the system itself." In other words, "there is no general shortcut: no way to find the outcome without doing essentially as much work as the system itself."

The technological pathway to the computers of the future seems to constitute a system of this type. It will be a product of countless human decisions, technological innovations, market forces and consumer choices, among other things, and there does not seem to be any way of knowing in advance how those forces and decisions will mutually interact to create the future of technology—which means that there is no way to know what the computer of the future will be like other than to wait 150 years and find out.

Ed Regis is author of eight books, the most recent of which, co-authored with George M. Church, is entitled Regenesis: How Synthetic Biology Will Reinvent Nature and Ourselves *(Basic Books, 2012).*

SPACE

STARSHIP HUMANITY

How future generations will make the voyage from our earthly home to the planets and beyond—and what it means for our species

By Cameron M. Smith

50 100 150 YEARS IN THE FUTURE

150 WHEN SPACE SHUTTLE *ATLANTIS* rolled to a stop in 2011, it did not mark, as some worried, the end of human spaceflight. Rather, as the extinction of the dinosaurs allowed early mammals to flourish, retiring the shuttle signals the opening of far grander opportunities for space exploration. Led by ambitious private companies, we are entering the early stages of the migration of our species away from Earth and our adaptation to entire new worlds. Mars is the stated goal of Elon Musk of PayPal fortune; polar explorers Tom and Tina Sjogren, who are designing a private venture to Mars; and Europe's privately funded MarsOne project, which would establish a human colony by 2023. The colonization of space is beginning now.

But technology is not enough. If space colonization is to succeed in the long run, we must consider biology and culture as carefully as engineering. Colonization cannot be about rockets and robots alone—it will have to embrace bodies, people, families, communities and cultures. We must begin to build an anthropology of space colonization to grapple with the fuzzy, messy, dynamic and often infuriating world of human biocultural adaptation. And we must plan this new venture while remembering the clearest fact of all regarding living things: they change through time, by evolution.

Three main concepts shape current thought about space colonization. First is the colonization of Mars. Widely publicized by the peppery space engineer and president of the Mars Society, Robert Zubrin, Martian colonies would be self-sufficient, using local resources to generate water and oxygen as well as to make construction materials. Next is the concept of free-floating colonies—enormous habitats built from lunar or asteroid metals. Popularized by physicist Gerard K. O'Neill in the 1970s, these would house thousands of people, could rotate to provide an Earth-like gravity (as beautifully envisioned in the 1968 film *2001: A Space Odyssey*), and could either orbit Earth or hang motionless at so-called Lagrangian points, spots where an object's orbital motion balances the gravitational pull of the sun, moon and Earth. Finally, we might also consider the concept of the Space Ark, a giant craft carrying thousands of space colonists on a one-way, multigenerational voyage far from Earth. I have been working with the nonprofit foundation Icarus Interstellar to design just such a mission.

Each of these approaches has its merits, and I think they are all technologically inevitable. But we must never confuse space colonization with the conquest of space. The world beyond ours is unimaginably vast; it will be what it has always been. When humankind begins to make its home in space, it is we who will change.

THE PIONEERS

WHO WILL BE THE SPACE COLONISTS? Here we must ditch the old concept of crew selection and the comically diabolical tests of chisel-chinned space heroes depicted in *The Right Stuff.* Space colonists will be ordinary families and communities who will not be on a mission but who are intending to live out their lifetimes. We will need a few Captain Picards, although most early colonists will most likely be farmers and construction workers.

Still, early colonists will have to be genetically healthy. In smallish populations, individuals carrying genetic maladies could threaten the future in ways that do not play out in a population of billions. In a Space Ark, the biological fate of the colony is strongly conditioned by the genetic constitution of the founding population—if just a few travelers carry the genes for inherited disease, these genes will spread much more thoroughly.

We now know the details of hundreds of genes that cause disorders, from cancers to deafness. (Recently researchers announced that they could screen for more than 3,500 such traits in human fetuses.) A genetic screening program seems clear—if you are carrying certain genes, you remain Earth-bound—but life is not so simple. Many maladies are polygenic—that is, the result of complex interactions among myriad genes. And even though one might carry the gene or genes for a certain disorder, environmental factors encountered during the course of life can determine whether or not those genes are activated in a healthy or unhealthy way.

For example, the human *ATRX* gene helps to regulate processes related to oxygen transportation. But *ATRX* activity can be altered by environmental influences as diverse as nutrient intake or a person's state of mind. When *ATRX* function is significantly modified, oxygen transport is impeded, resulting in seizures, mental disabilities and stunted growth. Thus, one cannot simply screen out people carrying *ATRX:* everyone has it. In some people, though, based on poorly understood environmental factors, *ATRX* will go haywire. Can we deselect someone for space colonization for something that *might* happen?

Complicating matters, we must also ensure broad genetic diversity of the gene pool. If all members of a population are genetically identical, a single sweep of disease could wipe everyone out. (This consideration demolishes the concept of a genetically engineered superrace of space travelers, as depicted in the 1997 film *Gattaca*.)

Once screened, what should be the population of space colonies? In a Mars colony, populations can grow and expand into new territory. But in a Space Ark, the population will be relatively low, and inbreeding becomes a concern. For example, in a study of Amish, Indian, Swedish and Utah populations, infant mortality was roughly double when matings occurred between first cousins than when they occurred between unrelated people.

To avoid these issues, we will have to consider the minimum population needed to maintain a healthy gene pool. Our minimum viable population has been much debated, but several anthropologists have suggested a figure of about 500. Because small populations are always at greater risk of collapse, I would suggest beginning with a population at least four times that at minimum—2,000, or about half the size of a well-staffed aircraft carrier—in a spacecraft that gives this population ample room to grow. For humans away from Earth, safety will indeed be found in numbers. (Even interstellar voyages will focus on reaching another solar system and inhabiting its planets, where populations can grow again.)

We will also have to carefully consider the crew's demographic structure—the age and sex of colonial populations. Simulations by my colleague William Gardner-O'Kearney show that over a few centuries, populations that begin with certain ratios of young to old and males to females persist better than others.

Early colonial populations, then, should be indi-

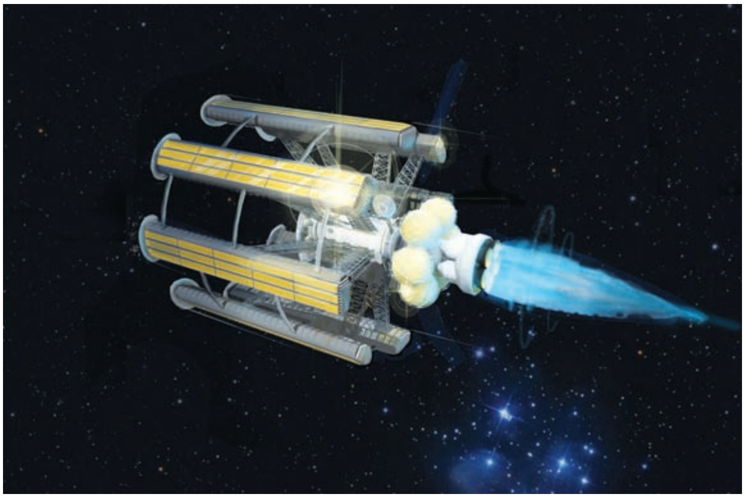
Cameron M. Smith teaches human evolution at Portland State University. He has written about evolution in *Scientific American Mind* and in his books *The Fact of Evolution* (Prometheus Books, 2011) and *Emigrating Beyond Earth* (Springer Praxis Books, 2012).

IN BRIEF

A space mission that isolates people away from Earth for extremely long periods—for instance, a Mars colony or a multigenerational voyage to a nearby star—will inevitably lead to the evolution of new cultural and physiological traits.

Long-distance spaceships will be home to unique environmental hazards such as increased radiation and lower ambient pressures. These influences will most severely affect the most fragile stages of life—in the womb and just after birth.

Mission planners will have to carefully select the "crew" of space travelers. Their goal: a genetically healthy population, but one diverse enough to withstand the occasional pandemic and thrive in profoundly new environments.



SHIP SHAPE: **Interstellar spacecraft will have to carry thousands of people, plus the plants and animals needed to support them.**

COURTESY OF STEVE SUMMERFORD *Icarus Interstellar–Project Hyperion*

vidually healthy and collectively diverse to give future populations the best chance of having genes on hand that might be adaptive in new environments. But we cannot control everything. At some point we will have to roll the genetic dice—which we already do every time we choose to have children on Earth—and set out from cradle Earth.

SPACE-BASED SELECTION

NO MATTER HOW CAREFULLY we prepare our colonial populations, life off planet Earth, at least at first, will be more dangerous and perhaps shorter than life here. Away from Earth, people will be exposed to forces of natural selection that we have removed from modern life. Little of this selection will play out in the dramatic ways we might expect from science-fiction movies, which tend to focus on the lives of adults. Instead it will occur during critical periods of tissue development in embryos and infants, when life is most delicate.

How could such selection play out? For one example, consider that the human body has evolved close to sea level under an atmospheric pressure of roughly 15 pounds per square inch (psi) for the past several million years, breathing a mix of roughly 80 percent nitrogen and 20 percent oxygen. Yet space travel requires pressurized habitats that grow more expensive and laborious to build the more pressure they need to hold. To ease the engineering requirements, atmospheric pressure in any off-Earth structure will be lower than on Earth.

Fair enough—*Apollo* astronauts survived just fine at 5 psi—but if you lower atmospheric pressure, you must increase oxygen as a percentage of what you are breathing. (Those same astronauts breathed 100 percent oxygen on their lunar voyages.)

Unfortunately, lower atmospheric pressure and elevated oxygen levels both interfere in vertebrate embryo development. Miscarriages and infant mortality will rise—at least for a time. Inevitably, selection will preserve the genes suitable for extraterrestrial conditions and remove those that are less suitable.

Infectious disease—to which small, dense populations such as space colonies are particularly vulnerable—will return as a significant concern, imposing new selection pressures as well. However careful we are with immunization and quarantine, plagues will eventually sweep through colonies, resulting in selection for people more capable of surviving the disease and selection against those less capable.

Finally, we must remember that we bring with us thousands of domesticates—plants and animals for food and materials—and that selective pressures will act on them as well. Ditto the millions of microbial species that ride on and in human bodies—invisible genetic hitchhikers that are critical to our health [see "The Ultimate Social Network," by Jennifer Ackerman; Scientific American, June 2012].

Based on a few calculations, I think it is reasonable that within five 30-year generations—about 150 years—such changes will be apparent in the extraterrestrial human body.

Exactly what biological adaptations evolve will depend heavily on the atmospheric and chemical environments of the habitats we build. We can control these to a large extent. Yet we cannot easily control two other important factors that will shape humanity in space: gravity and radiation.

Mars travelers will feel just a third of Earth's gravity. Those conditions will select for a more lithe body stature that can move with less effort than the bulky, relatively muscular builds we use to counteract Earth's gravity. In Space Ark and other free-floating scenarios, gravitation might remain about Earth normal, so Earth-normal statures might persist.

Radiation causes mutations, and any space colony will be unlikely to provide the protection from radiation that Earth's atmosphere and magnetic field provide. Will increased mutations create physical errors—repeated parts like an extra finger or malformed parts like a cleft palate? Certainly, but we cannot know what kind. The only thing we can predict with confidence is selection for increased resistance to radiation damage. Some people have better and more active DNA-repair mechanisms than others, and they will be more likely to pass their genes on.

Could more efficient DNA-repair mechanisms have any visible correlate—such as, say, a particular hair color? Again, we do not know. But it is also possible for beneficial genetics to spread when they have no such visible correlates. Among Hutterites of South Dakota, who interbreed among a relatively small number of small communities, anthropologists have found that people appear to be strongly influenced in their mate choice by body aroma—and the better the person's immune system, fascinatingly, the better the aroma.

On a moderate, five-generation timescale, then, human bodies will be subtly reshaped by their environment. We will see adaptations on the order of those of the natives of the high Andes and Tibet, where more efficient oxygen-transport physiology has evolved, resulting in broader and deeper chests. Each alteration is a compromise, however, and these high-altitude populations also sustain higher infant mortality when giving birth at altitude. One cultural adaptation to this biological change has been for mothers to descend to oxygen-richer altitudes to deliver children. We can expect similar biocultural shifts off of Earth, and we should plan for the most likely of them. For example, on Mars, birthing mothers might shuttle to an orbiting station where delivery could happen in a rotating, 1-*g* facility with a more Earth-normal atmosphere, but I bet that eventually they would not bother and that distinctive Martian human characteristics would evolve.

A SPACE-BASED CULTURE

CULTURAL CHANGE will be more apparent than biological change on a 150-year time span. Studies of human migrations have taught us that while migrating peoples tend to carry on some traditions to maintain identity, they also devise novel traditions and customs as needed in new environments. For example, the Scandinavians who first colonized Iceland after A.D. 800 continued to worship Norse gods and speak the Viking language but quickly developed a distinctive cuisine—heavy on meat (whereas rye and oats were grown in Scandinavia) and on preserved foods to survive the harsh winters—as they explored the resources of an unknown land.

On Mars, this acculturation will play out in innumerable ways. There, in low-pressure, oxygen-rich atmospheres contained in unique architectural materials and arrangements, sound might propagate differently—even if subtly—perhaps affecting pronunciation and even the pacing of speech, resulting in novel accents and dialects. The lighter gravity could influence body language, an important element of human communication, and would influence performance arts of all kinds. Cultural divergence occurs as just such small, innumerable differences accumulate.

More profound cultural change could occur in Space Ark scenarios, where life would have less to do with Earth at each moment that the starship speeds away. Here basic concepts of space and time could well be transformed rather quickly. For example, how long would Space Ark cultures use Earth timekeeping? Without Earth's days and nights and years, civilizations might invent a base-10 timekeeping scale. Or they might decide to count time down until a distant solar system is reached rather than up from some event in the past (such as the departure from an Earth to which they will never return).

LONG-TERM GENETIC CHANGE

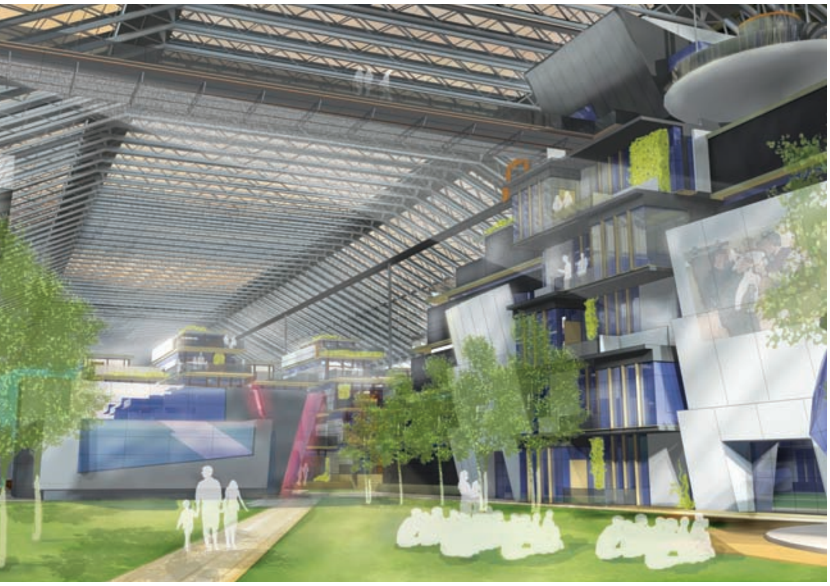
SIGNIFICANT GENETIC CHANGE occurs when new genes become widespread in a population. An example from prehistory is the spread of genes that resulted in lactose tolerance in adults, which appeared independently in both Africa and Europe not long after the domestication of cattle. This genetic equipment allowed more energy to be derived from cattle, and in these populations, it quickly became nearly universal, or "fixed."

Although we cannot predict which mutations will arise, population genetics enables us to estimate how long it would take mutations to become fixed in the genome of space-based explorers. My calculations—based on model Mars populations of 2,000 people of certain age and sex structures—indicate that it could occur in just a few generations and certainly within 300 years; we can expect significant original off-Earth physical characteristics in human populations on this timescale. These changes will be on the order of the broad geographical variation we see in humans today—a spectrum of different statures, skin colors, hair textures and other features.

On Mars, there might be further, internal divergence as some populations elect to live most of their lives sheltered in underground habitats, while others prefer to take the increased radiation risks to live in surface habitats offering greater mobility. In the limited-population, closed-system Space Ark scenario, gene fixation could happen much more rapidly, perhaps driving a greater uniformity than on Mars.

Whereas there will be some biological change, long-term cultural change will be more profound. Consider that in the three centuries from the early 1600s to the early 1900s, the English language changed so much that comprehending 17th-century English texts today requires special training. Three centuries hence, the language spoken on a Space Ark might be profoundly different.

Larger-scale cultural change is also quite likely. Exactly what divides one culture from another is a topic of tremendous debate in anthropology, but I believe that anthropologist Roy Rappaport made the distinction clear. Different cultures have different "ultimate sacred postulates"—core concepts, usually unquestionable and unquestioned, ingrained by tradition and ritual, that shape a population's essential



philosophical and moral codes. For Christianity, for example, one such postulate is that "In the beginning, God created the heaven and the Earth." How long it will take for such foundation beliefs to change off of Earth—and in what direction—is impossible to say, but several centuries is certainly enough time to allow new cultures to arise.

SPACE LIFE: **We cannot predict how the culture of a space outpost will change over hundreds of years—only that it will.**

THE RISE OF *HOMO EXTRATERRESTRIALIS*

WHEN WILL WE SEE even more fundamental biological change—that is, speciation? Small populations can change quickly, as evidenced by the unusually large mice that roam the Faroe Islands 1,200 years after Viking ships dropped off ordinary house mice. But anatomically modern humans have gone more than 100,000 years—migrating from Africa into a wide variety of environments, from desert to open ocean—apparently without biological speciation. (Our nearest hominin relatives, such as the cold-adapted Neandertals and the apparently miniaturized "hobbit" humans of the island of Flores in the western Pacific, split from our common ancestor substantially earlier.) This is largely because we use culture and technology to adapt more than biology alone. It would take, then, significant natural and cultural selection to reshape extraterrestrial humans to such a degree that they could no longer productively mate with earthlings.

Unless, of course, humans devise their own speciation. It seems inevitable that off-Earthers will eventually harness the staggering power of DNA to tailor their own bodies for many conditions. Perhaps the people of Mars will biologically engineer gill-like structures to split the oxygen from atmospheric carbon dioxide or toughened skin and tissues to endure low pressure. They might make themselves into a new species, *Homo extraterrestrialis,* by conscious choice.

WHERE TO BEGIN?

HUMAN SPACE COLONIZATION will require plenty of engineering and technical advances. We must also improve our understanding of how human biology and culture adapt to new conditions and use that knowledge to help space colonization succeed. I suggest beginning immediately with three courses of action.

First, we must abandon the technocrat's essential revulsion of humanity and begin procreating off of Earth, giving birth there and raising children there, to understand critical issues of human reproduction, development, and growth in new radiation, pressure, atmospheric and gravity environments. Bureaucrats will recoil at the risks involved—children exposed to risk beyond that of a bicycle-helmeted, First World suburbanite!—but concerns will diminish as space access is privatized. Still, at times the adaptation to space will be painful—but so is birth.

Second, we must experiment with growing and maintaining the health of domesticated species off of Earth. We are going nowhere without our microbes, plants and other animals.

And to promote these first two goals, an X-Prize should be awarded for the first functional, livable human habitat off of Earth: not a sterile orbiting laboratory (as important as those are), but a home where people can grow plants, raise animals and even have children. Many would shudder at the prospect of staying in such a place, but at the same time, there will be no shortage of volunteers.

Finally, we must reengage the proactive approach that has made human survival possible up to the present and use that capacity to shape our own evolution beyond our home planet. We must be immensely bolder than our bureaucracies. Failing that, in time we will become extinct, like everything else on Earth. As H. G. Wells wrote about the human future in 1936, it is "all the universe or nothing." SA

MORE TO EXPLORE

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SCIENTIFIC AMERICAN ONLINE
For a chat with Smith about space evolution, go to ScientificAmerican.com/jan2013/space-evolution

QUANTUM PHYSICS

STRANGE AND STRINGY

Newly discovered states of matter embody what Einstein called "spooky action at a distance." They defy explanation, but lately answers have come from a seemingly unrelated corner of physics: string theory

By Subir Sachdev

MAGNET is being levitated by an unseen superconductor in which countless trillions of electrons form a vast interconnected quantum state. Astoundingly, the quantum state of many modern materials is subtly related to the mathematics of black holes.

Photograph by Zachary Zavislak

Subir Sachdev is a professor of physics at Harvard University and author of the book *Quantum Phase Transitions,* now in a second edition (Cambridge University Press, 2011).

SEVERAL YEARS AGO I FOUND MYSELF WHERE I WOULD never have expected: at a conference of string theorists. My own field is condensed matter: the study of materials such as metals and superconductors, which we cool in the laboratory to temperatures near absolute zero. That is about as far as you can possibly get from string theory without leaving physics altogether. String theorists seek to describe the universe at energies far in excess of anything experienced in a lab or indeed anywhere else in the known universe. They explore the exotic physics governing black holes and putative extra spacetime dimensions. For them, gravity is the dominant force in nature. For me, it is an irrelevance.

This difference in subject matter is mirrored by a cultural gap. String theorists have a formidable reputation, and I went to the meeting in awe of their mathematical prowess. I had spent several months reading their papers and books, and I often got bogged down. I was certain I would be dismissed as an ignorant newcomer. For their part, string theorists had difficulty with some of the simplest concepts of my subject. I found myself drawing explanatory pictures that I had only ever used before with beginning graduate students.

So what was I doing there? In recent years many of us who specialize in condensed matter have discovered our materials doing things we never thought they could. They form distinctively quantum phases of matter, the structure of which involves some of the weirdest features of nature. In a famous paper in 1935 Albert Einstein, Boris Podolsky and Nathan Rosen drew attention to the fact that quantum theory implied a "spooky" connection between particles such as electrons—what we now call quantum entanglement. Somehow the activities of the particles are coordinated without mediation by a direct physical linkage. EPR (as Einstein and his co-authors are widely known) considered pairs of electrons, but metals and superconductors involve vast numbers of electrons—some 10^{23} of them, for a typical sample of material in the lab. In some materials, the complexity is mind-boggling, and I have spent much of my career trying to wrap my head around it. The problem is not merely academic: superconductors have become important technologically, and physicists have struggled to make sense of their properties and capabilities.

Then my colleagues and I came to realize that string theory could offer a completely unforeseen approach to such problems. In seeking to unify the theory of elementary particles with Einstein's theory of gravitation, string theorists had stumbled across "dualities"—hidden connections between far-flung areas of physics [see "The Illusion of Gravity," by Juan Maldacena; Scientific American, November 2005]. The dualities relate theories that work where quantum effects are weak but gravity is strong to theories that work where quantum effects are strong

IN BRIEF

Matter can assume many forms other than solid, liquid and gas. The electrons that perfuse materials can undergo their own transitions, which involve inherently quantum properties of matter. Superconductors are the best-known example.

These states of matter arise from an unimaginably complex web of quantum entanglement among the electrons—so complex that theorists studying these materials have been at a loss to describe them.

Some answers have come from an entirely separate line of study, string theory, typically the domain of cosmologists and high-energy particle theorists. On the face of it, string theory has nothing to say about the behavior of materials—no more than an atomic physicist can explain human society. And yet connections exist.

but gravity is weak. So they let us take insights from one realm and apply them to the other. We can translate our entanglement problem into a gravitational problem and avail ourselves of the efforts that string theorists have put into understanding black holes. It is lateral thinking at its finest.

HIDDEN PHASES

TO UNDERSTAND this circle of ideas, step back to high school physics, where teachers spoke of the phases of matter in terms of solids, liquids, gases. We have an intuitive grasp of the distinctions among these phases. Solids have a fixed size and shape; liquids take the shape of their container; and gases are like liquids, but their volume can be changed easily. Simple as these distinctions are, it was not until the early 20th century that a complete scientific understanding of the phases of matter around us emerged. Atoms have a regular, rigid arrangement in crystalline solids but are mobile in liquids and gases.

Yet these three phases do not begin to exhaust the possibilities. A solid is not just an array of atoms but also a swarm of electrons. Each atom offers up a few electrons, which roam across the entire crystal. When we connect a specimen to a battery, an electric current flows. Essentially all materials satisfy Ohm's law: the current is proportional to the voltage divided by the resistance. Electrical insulators such as Teflon have a high resistance; metals such as copper, a low resistance. Most remarkable are the superconductors, which have an immeasurably small resistance. In 1911 Heike Kamerlingh Onnes discovered them when he cooled solid mercury below –269 degrees Celsius. Today we know of superconductors that work at a comparatively balmy –138 degrees C.

Although it is not obvious just by looking at them, conductors, insulators and superconductors are different phases of matter. In each, the swarm of electrons takes on a different form. Over the past two decades physicists have discovered additional phases of electrons in solids. A particularly interesting example does not even have a proper name: physicists have defaulted into calling it the strange metal. It betrays itself by the unusual way its electrical resistance depends on temperature.

The differences among these phases arise from the collective behavior of electrons. Whereas the motion of atoms in solids, liquids and gases can be described by the classical principles of Newtonian mechanics, the behavior of electrons is ineluctably quantum. The key quantum principles governing the electrons are scaled-up versions of those governing the electrons in an atom. An electron orbits the nucleus, and its motion is described as a wave that propagates around the proton. The electron can reside in an infinite number of possible states with specific observable properties such as energy. Crucially, the electron not only orbits the nucleus but also spins around its own axis. This spin can be either clockwise or anticlockwise and cannot be slowed down or sped up; we conventionally label these two spin states as "up" and "down."

In atoms with more than one electron, the most important rule governing the electrons is the Pauli exclusion principle: no two electrons can occupy the same one-electron state. (This principle applies to all particles of matter, which physicists call fermions.) If you add electrons to an atom, each new electron settles into the lowest-energy state it can, like filling a glass with water from the bottom up.

The same reasoning also applies to the 10^{23} electrons in a piece of metal. The itinerant electrons, once detached from their original host atoms, occupy states that extend across the entire crystal. These states can be thought of as sinusoidal waves with a certain wavelength that is related to their energy. Electrons occupy states with the lowest-allowed energy that is consistent with the exclusion principle. Together they typically fill all the states up to an energy smaller than a threshold known as the Fermi energy.

Applying a voltage gives some electrons enough energy to transfer from an occupied state to a previously unoccupied one with an energy larger than the Fermi energy [*see box on next page*]. That electron can then flow freely. In an insulator, the density of electrons results in all accessible states being occupied already; even if we apply a voltage, there is no place for an electron to go, so no current can flow.

In superconductors, things get more complicated. The electrons in them cannot be understood one at a time. They bind into pairs, as described by the theory of superconductivity developed in 1957 by theoretical physicists John Bardeen, Leon Cooper and John Robert Schrieffer (also referred to as BCS). On the face of it, the particulate buddy system is odd because two electrons should repel each other. Vibrations of the crystal lattice, however, indirectly create an attractive force that overcomes the innate repulsion. Each pair behaves not as a fermion but as a different type of quantum particle known as a boson, which does not obey the Pauli exclusion principle. The electron pairs can all condense into the same state having the barest minimum amount of energy—a phenomenon known as Bose-Einstein condensation. It is like pouring water into a glass and, instead of filling up the glass, forming a thin layer of ice across the bottom that can absorb as much water as you care to add without getting thicker.

If you apply a voltage across such a material, that voltage pushes the electron pairs into a state with ever so slightly higher energy, yielding an electric current. This higher-energy state is otherwise empty, leaving nothing to impede the flow of the paired electrons. In this way, a superconductor transmits current with zero resistance.

GOING CRITICAL

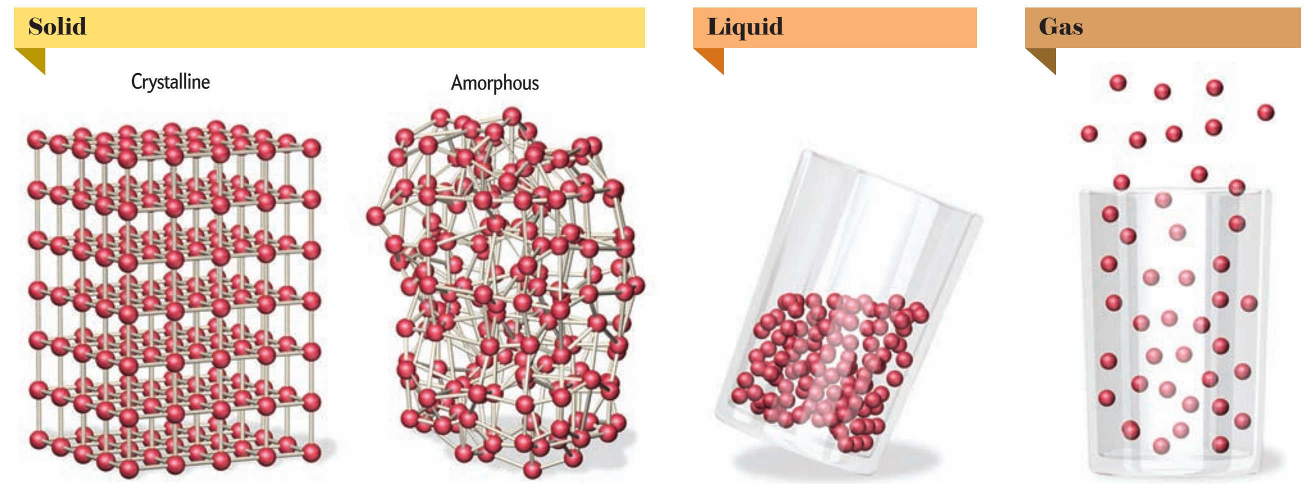
THESE SUCCESSES of quantum theory in explaining metals, insulators, superconductors and other materials such as semiconductors (the basis of modern electronics) led many physicists in the early 1980s to conclude that they were approaching a full understanding of electrons in solids, with no remaining major discoveries to be made. This confidence was spoiled by the discovery of high-temperature superconductors.

An example is barium iron arsenide, in which experimentalists have replaced some fraction of the arsenic with phosphorus. At low temperatures, this material is a superconductor, and physicists believe it obeys a theory similar to that of BCS except that the attractive force between electrons does not originate from vibrations of the crystal lattice but from physics associated with the electron spin. With a small amount of phosphorus, the material forms a state known as a spin–density wave [see "Charge and Spin-Density Waves," by Stuart Brown and George Grüner; SCIENTIFIC AMERICAN, April 1994]. On half of the iron sites, the electron spin is more likely to be up than

Just a Phase They're Going Through

Quantum physics gives the building blocks of matter radically new ways to organize themselves. The classical solid, liquid and gaseous phases involve different arrangements of atoms or molecules, governed by temperature. Quantum phases involve different arrangements of particles such as the electrons that perfuse materials. These phases are governed by features such as the electric field strength, which determines the forces that particles exert on one another and hence the way they assemble.

Classical Phases Solids have a fixed size and shape. In crystalline solids, molecules are arranged in a stable, regular, rigid lattice. In amorphous solids, molecules are jumbled, as in a liquid, but maintain their positions over long periods. Liquids have a fixed volume and variable shape. Their molecules are mobile but still bound together. Gases have a variable volume and shape. Their molecules are fully mobile and not bound to one another (or bound only very loosely). Beyond a certain temperature and pressure called the critical point, gas and liquid blend together and become indistinguishable from each other [*see phase diagram on opposite page*].

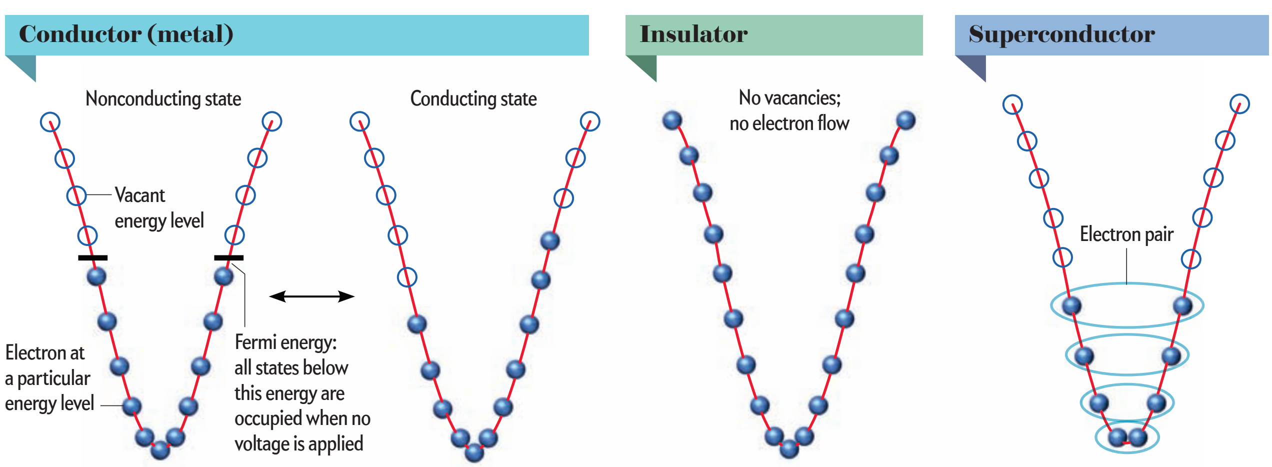


Quantum Phases Metals conduct electricity readily. Their electrons hopscotch from atom to atom, and if the atoms provide enough sites for the electrons to occupy, the electrons move freely, as if in a gas. Quantum effects limit the number of electrons that can have a given amount of energy.

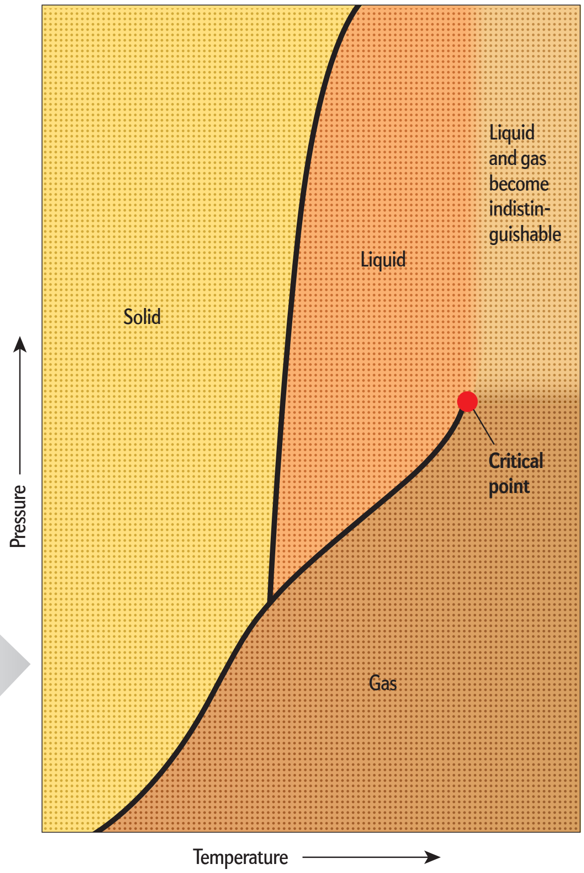
Insulators scarcely conduct electricity at all. The atoms do not provide enough vacancies for the itinerant electrons, so electrons remain trapped in place, as if in a solid. They occupy all the available energy slots.

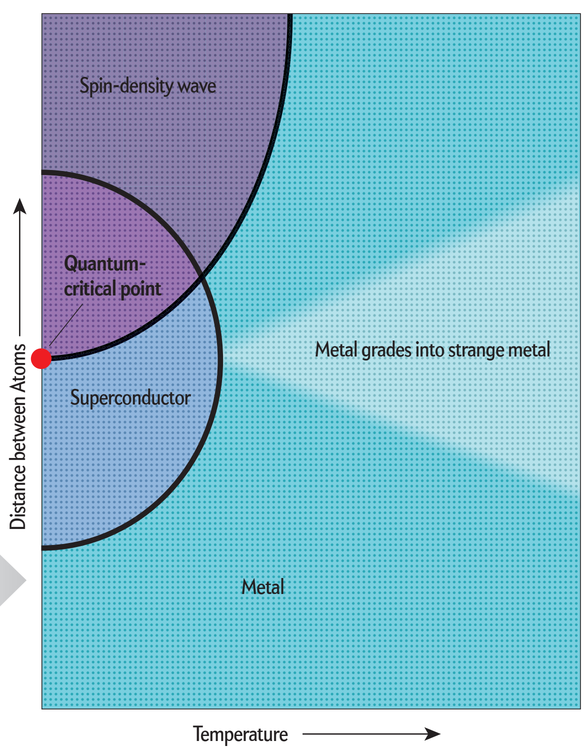
Superconductors are gases not of electrons but of pairs of electrons that behave as single particles. The electrons pair up under the effects of quantum spin or the influence of waves rippling through the atomic substrate. These pairs evade the quantum rules governing electrons. All of them can have the same amount of energy—lifting the restrictions that trap electrons in place and letting them flow without electrical resistance.

A spin-density wave (*not shown*) is a material (sometimes an insulator, sometimes a superconductor) with a peculiar pattern of electron spins. Half are spinning up, half down—say, in alternating rows. Sometimes a strange metal—a spin-density wave taken to extremes—forms [*see phase diagram on opposite page*]. The probability of each individual electron spinning up or down is 50–50, with no broader patterns. All the electrons in a strange metal are entangled and behave neither as individual particles nor even as pairs but as masses of trillions or more particles.



Illustrations by George Retseck





down, and vice versa on the other half. As you increase the amount of phosphorus, the strength of the spin-density wave diminishes. It disappears altogether when you have replaced a critical amount of arsenic, about 30 percent. At that point, the electron spin is equally likely to be up or down on each site, which has important consequences.

The first indication of the mysterious nature of this quantum critical state is the behavior of the system as experimentalists hold the amount of phosphorus fixed at 30 percent and raise the temperature. The result is neither a superconductor nor a spin-density wave but a strange metal.

The main new idea needed to describe the quantum-critical point, and the superconductors and strange metals close to it, is precisely the feature of quantum mechanics that so disturbed Einstein, Podolsky and Rosen: entanglement. Recall that entanglement is the superposition of two states—such as when one electron is spinning up and the other down, and vice versa. Imagine single electrons at two iron sites. Electrons are indistinguishable even in principle, so it is impossible to say which electron is up and which is down; both are equally likely to be up or down. All we can say is that if we measure one electron as up, the other is guaranteed to be down. They are perfectly anticorrelated: if we know one, we know the other.

At first glance, entanglement might not seem strange. Anticorrelation is common: if you have a pair of shoes and you put one in the front hallway and the other by the back door, then if you find a left shoe in one place, it is no mystery that the other shoe is right. Yet the quantum situation differs in an essential way. A shoe is either left or right even if you do not know which it is, but an electron has no fixed spin until the act of measurement. (If it did, we could tell by conducting a certain sequences of measurements on it.) In a sense, the electron is both up and down until forced to choose.

The mystery is how the electrons remain anticorrelated. When one electron chooses its spin, so does the other. How do they know to choose opposite directions? It seems that information on the quantum state of atom 1 is instantaneously known to atom 2, no matter how far away it is. Indeed, neither atom has a quantum state on its own; only the pair of them does. That is the nonlocality, the spooky action at a distance, that Einstein found so unpalatable.

Unpalatable or not, nonlocality has been verified numerous times in actual experiments. Einstein and his co-authors clearly put their finger on the most counterintuitive and unexpected aspect of quantum mechanics. And in the past decade physicists are beginning to appreciate that it accounts for the bizarre properties of strange metals. Close to the quantum-critical point, the electrons no longer behave independently or even in pairs but become entangled en masse. The same reasoning that EPR applied to two electrons now applies to all 10^{23} of them. Neighboring electrons are entangled with each other; this pair, in turn, is entangled with neighboring pairs, and so on, creating an enormous network of interconnections.

The same phenomenon occurs in other materials as well. Classifying and describing such entangled states is the forbidding challenge we face in developing the theory that describes the new materials. The network is so complex that it is beyond our ability to describe directly.

My colleagues and I used to worry that a theory of these quantum phases of matter would forever elude us. That was before we learned about string theory.

TANGLED UP IN STRINGS

ON THE FACE OF IT, string theory has nothing to do with entangled states of many electrons. It involves microscopic strings that vibrate like miniature guitar strings; the different modes of vibrations represent different elementary particles. The stringy nature of matter becomes evident at extremely high energies, found only moments after the big bang and near very dense black holes. In the mid-1990s string theorists such as Joseph Polchinski of the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara, realized that their theory predicts more than strings. It also implies the existence of "branes": surfaces to which strings stick like bugs on flypaper. These membranes represent a vast kingdom of physics, beyond the high-energy particles the theory originally addressed.

What looks like a particle—a mere point—to us might actually be the end point of a string stretching from a brane through a higher spatial dimension. We can view the universe either as made up of point particles moving in a four-dimensional spacetime with a complex set of interparticle interactions or as made up of strings moving in a five-dimensional spacetime attached to branes. These two perspectives are equivalent, or dual, descriptions of the same situation. Remarkably, these two descriptions are complementary. When the point particles are hopelessly complex, the strings may behave simply. Conversely, when the particles are simple, the strings are clumsy and cumbersome.

For my purposes, the picture of strings dancing in some higher-dimensional spacetime is not important. It does not even matter to me whether string theory is a correct explanation of particle physics at very high energies. What is significant is that the duality lets me exchange a mathematically intractable problem for an easy one.

Until a few years ago, I mainly attended meetings of condensed-matter physicists in which we argued about the different entangled quantum states that electrons could form in newly discovered crystals. Now I find myself sipping coffee with string theorists, trying to make sense of their abstract and fanciful description of strings and branes and applying those ideas to down-to-earth issues raised by tabletop measurements on the new materials. Moreover, it is a two-way street. I think that our intuition and experimental experience with the quantum phases of electrons is helping string theorists to describe black holes and other exotica.

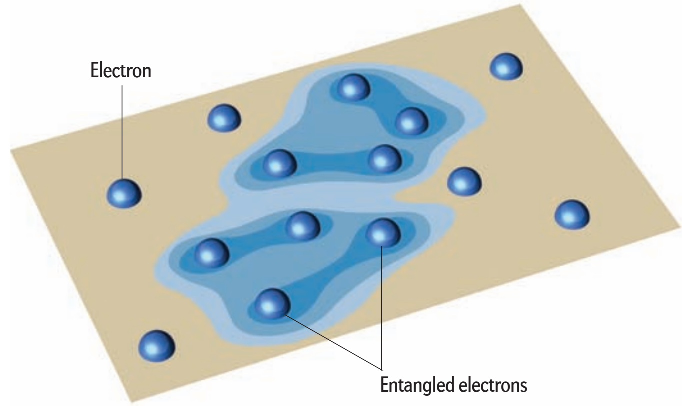
When electrons in crystals have only a limited degree of entanglement, they can still be thought of as particles (either the original electrons or pairs of them). When large numbers of electrons become strongly entangled with one another, however, they can no longer be viewed as particles, and conventional theory struggles to predict what happens. In our new approach, we describe these systems in terms of strings that propagate in an extra dimension of space.

My Harvard University colleague Brian Swingle has drawn an analogy between the extra spatial dimension and the network of quantum entanglement [*see box above*]. Moving up and down the network is mathematically just like moving through space. The strings can wriggle and fuse together within the extra dimension, and their motion mirrors the evolving entanglement of particles. In short, the spooky connections that troubled Einstein make sense when you think of the degree of entanglement as distance through an extra spatial dimension.

CONNECTION TO STRING THEORY

Web of Entanglement

For reasons that physicists have yet to understand, quantum phases of matter contain a latent spatial dimension that can appear at phase transitions like a figure in a pop-up book. This dimension becomes evident in the mathematical description of interparticle relations, or entanglement.



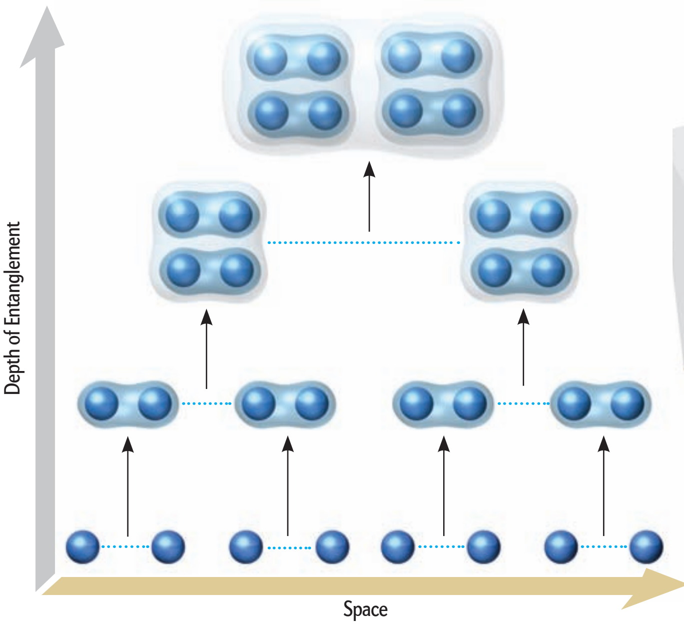
Electron Entanglement
Entanglement means that multiple quantum particles act together as a single indivisible whole. Typically physicists talk about the entanglement of two particles or perhaps a handful of them, but in materials that transition from one quantum phase to another, huge numbers of electrons are entangled.

STRANGE COUSINS

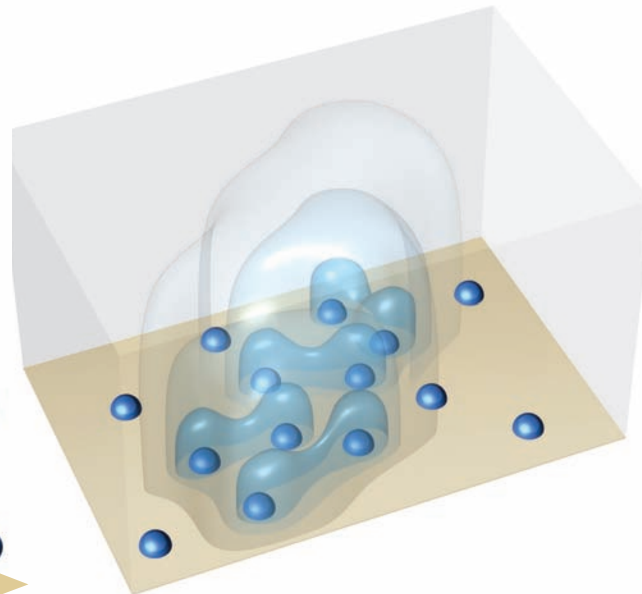
THE PRACTICAL ADVANTAGE of these dualities is that string theorists have built up a large library of mathematical solutions to problems ranging from particle dynamics in the furnace of the big bang to the undulations of quantum fields on the lip of black holes. Those of us studying quantum phases of matter can go to the library, look up a possible solution to a specific problem and translate it (using the mathematics of duality) from the stringy situation to the entanglement situation.

Typically we focus on the lowest-energy state at absolute zero, but we can readily describe matter at nonzero temperatures using a technique that might seem drastic: we imagine adding a black hole to the string situation. The fact that black holes are involved indicates how extraordinary these dualities are. No one is suggesting that the quantum phases of matter literally contain black holes; the connection is more subtle. Stephen Hawking of the University of Cambridge famously showed that every black hole has a certain temperature associated with it. From the outside, a black hole looks like a glowing hot coal. By the logic of duality, the corresponding condensed-matter system must also be hot, which has the effect of turning a spin-density wave or a superconductor into a strange metal.

These methods have made some progress in explaining



Hierarchy of Entanglement
Weirdly, the entanglement process behaves, mathematically, just like spatial distance. Much as moving through space entails passing through intervening points, getting from the entanglement of two particles up to trillions requires the two to combine with two others, and the resulting four with four more, and so on.



Extra Spatial Dimension
Thus, the depth of entanglement itself acts as an implicit spatial dimension, above and beyond the three dimensions where the electrons reside. By using this mathematical resemblance, theorists studying quantum phases of matter can draw on the findings of string theorists, who study extra spatial dimensions.

strange metals and other states of matter, but they have helped the most with the transition from a superfluid to an insulator. A superfluid is just like a superconductor, except it is made up of electrically neutral atoms; it reveals itself not by having zero electrical resistance but by flowing without any friction. In recent years experimentalists have developed remarkable new methods of creating artificial superfluids. They create a lattice of crisscrossing lasers and pour in trillions of extremely cold atoms. The atoms initially behave like a superfluid: they move freely from one lattice site to another. As experimentalists dial up the intensity of the laser, the atoms become less mobile and the superfluid abruptly turns into an insulator.

Experimentalists follow this transition by measuring how the atoms flow under external pressure. In the superfluid phase, they flow without resistance; in the insulator phase, they hardly flow at all; and at the transition, they flow but in a peculiar way. For instance, if experimentalists remove the external disturbance, the atoms come to a halt at a rate that depends on the temperature and on Planck's constant, the fundamental parameter of quantum theory, which does not enter into the behavior of the other phases. We have explained this behavior by imagining the quantum-critical fluid as the dual, or stringy doppelgänger, of a black hole.

The duality has a downside. By its very nature, it transforms the complex to the simple. We do not always want to transform the problem, however: we also want to understand the complexity for what it is. The duality is a mathematical black box and leaves us somewhat in the dark about the details of the complicated entangled states or about how these states occur in actual materials. Explaining what is really going on is still in its infancy. For those of us accustomed to thinking about the dynamics of electrons in crystals, string theory has given a fresh new perspective on the dynamics of complex quantum states involving entanglement. For string theorists, it has piqued interest in the phases of quantum materials, phenomena far removed from the physics of the early universe or that occurring in high-energy particle accelerators. The strange confluence of these currents of thought has shown us the wonderful unity of nature. SA

MORE TO EXPLORE

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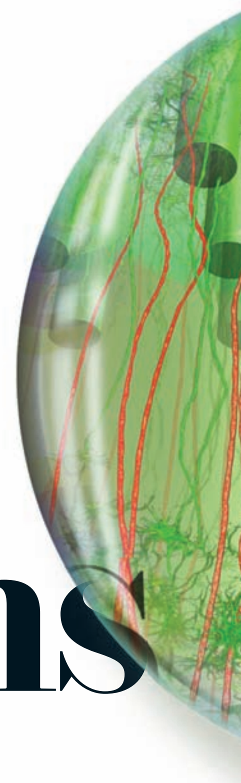
SCIENTIFIC AMERICAN ONLINE
To see a video explaining entanglement, visit ScientificAmerican.com/jan2013/entanglement



MEDICAL ENGINEERING

Bionic Connections

A new way to link artificial arms and hands to the nervous system could allow the brain to control prostheses as smoothly as if they were natural limbs

By D. Kacy Cullen and Douglas H. Smith

In one of the most iconic scenes in science-fiction films, Luke Skywalker casually examines his new synthetic forearm and hand. The *Star Wars* hero is able to move the fingers by extending and contracting pistons shown through an open flap along the wrist. Then he senses the robotic surgeon's pinprick of one of the fingers. Not only can the prosthesis be moved with Skywalker's thoughts, it *feels* to him like his own hand.

What the audience does not see, however, is the actual connection between man and machine. And yet to neuroscientists like the two of us, it is precisely this hidden interface that should have been at the center the scene. In order for such a linkup to work, it would have to have converted nerve impulses from the brain into electrical signals in the artificial arm, and vice versa. In the world beyond movies, however, no one has yet figured out how to splice together nerves and electrical wires in a way that allows them to control an artificial limb as if it were a natural extension of the body.

The failure is not surprising. For one thing, nerves and the electrical wires needed to regulate the electronics in a prosthesis transmit entirely different kinds of signals. Electronic devices depend on the flow of electrons across conductive materials

IN BRIEF

Bioengineers would like to connect prosthetic arms and hands directly to the nervous system.

Two-way communication would allow the brain to control a limb's movements and to feel its presence.

The first step is to develop a kind of adapter cord that translates nerve impulses into electrical signals.

The authors are developing such an interface with laboratory-grown nerve fibers and electricity-conducting polymers.

Illustration by Jean-François Podevin

REACH: Advances in neuroengineering are starting to catch up to the tremendous progress that has recently been made in prosthetic design.

and through semiconductors and transistors; the nervous system relies on the depolarization of cell membranes and the release of signaling chemicals in the gaps between nerve cells. For another, the linkage would require implanting wires and other kinds of electronics into the body, which normally perceives such implants as foreign and thus unleashes attacks that would generate scar tissue around an interface and disrupt its functioning.

Advances in nanotechnology and tissue engineering over the past few years, however, are addressing both challenges. Rather than trying to force nerves to communicate directly with the standard electronics in modern prostheses, we and others are building new kinds of bridges between nerves and artificial limbs—linkages that take advantage of the nervous system's inborn ability to adapt itself to new situations. Indeed, recent research in the laboratory has brought us closer to the goal of developing an artificial limb that, like Luke Skywalker's, can be moved and sensed by the brain.

COMBINING MOTOR AND SENSORY INPUT

FOR BETTER OR WORSE, much of the progress in prosthetic design has occurred as a result of armed conflict—most recently, the wars in Afghanistan and Iraq. Until the past few years, however, designers focused more on artificial limbs for the lower rather than the upper body. Developing prosthetic legs that allow users to walk and run is a more straightforward engineering proposition than devising an artificial hand that enables its user to open jars, for example, or to touch-type on a computer keyboard. Since 2006 and the launch of the Revolutionizing Prosthetics program of the Defense Advanced Research Projects Agency, researchers have made impressive strides in creating sophisticated artificial upper limbs as well.

Part of the challenge in designing highly functional upper limbs is the need to replicate (at least in part) the hand's exquisite fine-motor control. The effort requires being able to tap into the brain's own mental maps, which it uses to transmit nerve signals to specific muscle fibers controlling the forearm, and to know when it receives nerve signals about pressure, position, tension, momentum, and force from the arm and hand, from whence those messages originate. This sensory feedback helps the brain to determine just how many muscle fibers should be recruited to power any given effort.

In an intact limb, these motor and sensory signals work together to create, among other things, the sense known as proprioception—the awareness of where the various parts of the body exist in space and in relation to one another without having to actually look at them. Without proprioception, even what appear to be simple tasks, such as writing with a pen, would be nearly impossible. Thanks to a symphony of nervous system signaling from the brain to the extremities and back again, you are able to move your hand exactly to the pen, gently lift it while seamlessly shifting it into position and lightly touch it down to write.

To date, robotic hands have been developed that permit varying, indirect levels of motor control. In some cases, for example, repeated contracting and relaxing of muscles in the limb stump or in the chest can activate specialized relays that trigger different movements in the artificial limb. Ideally, however, bioengineers would like to build a prosthetic that is linked to, and controlled by, the original motor nerves—which do not die after amputation but merely retreat a bit from the edge of the stump.

Use of motor neurons is just part of the vision, however. Many simple tasks still prove difficult even with today's very advanced prosthetic devices because no sensory signals travel from the artificial limb back to the brain. Amputees have to consciously direct every discrete movement of their prosthesis, relying on what their eyes see for feedback rather than on their natural sense of proprioception. This level of effort results in clumsy and slow movements that leave people exhausted by the concentration and time needed to accomplish such tasks as buttoning a shirt.

A critical goal, then, is to engineer an interface between the nervous system and the prosthesis that allows direct two-way communication of both motor and sensory information. Such a "neuromechanical" interface would permit the development of prosthetic hands that can be controlled by intuitive thought and that feel real. Several research laboratories, including our own, are now pursuing this objective. Although we have each adopted somewhat different approaches with their own advantages and challenges, success will probably depend on some combination of everyone's insights and technological innovations.

TWO MAIN APPROACHES

THE FIRST STEP in creating a useful interface between the body and a prosthetic limb is deciding where in the nervous system to position it. Designers have two main options—interact with the central nervous system (linking to either the brain or the spinal cord) or work further out, in what is known as the peripheral nervous system, with nerves that stretch primarily between the spinal cord and the rest of the body.

To date, most researchers have focused on the brain as a starting point. The least invasive approaches listen in on its neural activity via external electrodes on the scalp or just under the skull on the surface of the brain itself. The electrodes pick up electrical signals from the brain, which a computer then analyzes to signal the desired movement. These methods have the advantage of not poking holes into the brain, but they are susceptible to interference from other electronics. The electrical signals are also rather coarse representations of what the brain is actually doing, which makes it difficult for the computer to predict which movements should occur.

The most invasive approach inserts arrays of microelectrodes directly into the outer layers of the brain. (The microelectrodes used are typically high-density silicon probes, each generally less than a human hair's width in diameter.) As a di-

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How to Plug into the Nervous System

Researchers have built a kind of adapter plug in rats that allows them to connect living nerves on one end with electrically conductive filaments on the other. If all goes well, they will eventually use such biohybrid bridges to link up the severed nerves in a human being in such a way that a prosthetic device can move and feel like a natural hand.

Foreseeable Future

Creating a "living bridge" between the peripheral nervous system of a human being and a prosthetic device will require several steps. First, scientists will direct laboratory-grown nerves (*green*) to grow at the edge of electrically conductive microfilaments (*gray*). Then the neurons will be gently pulled apart, causing the axons to stretch. After the bridge is placed near the stump, the host axons (*red*) will extend across the bridge, allowing signals to flow back and forth between the brain, spinal cord and artificial limb.

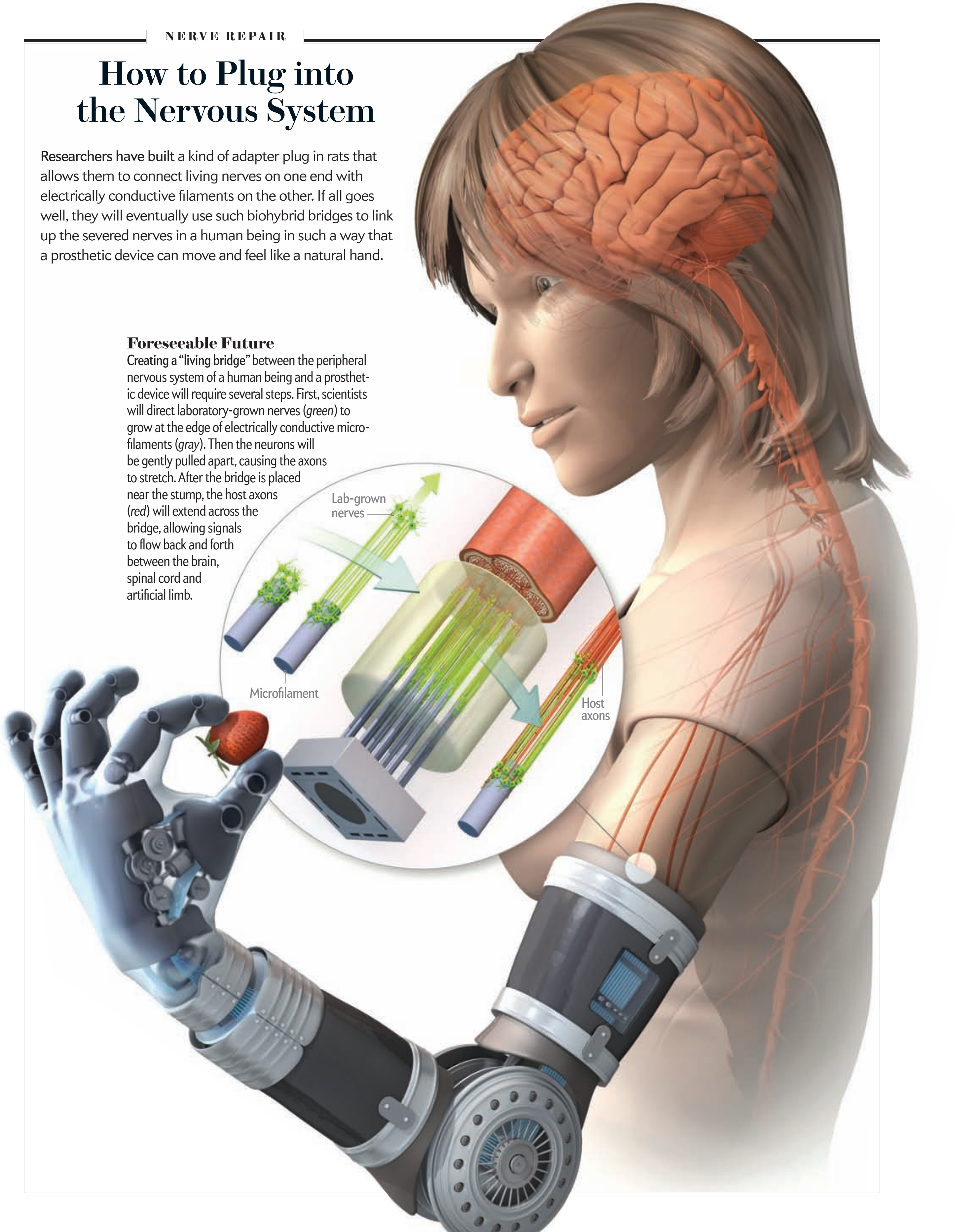


Illustration by Emily Cooper

rect interface, this approach offers the tremendous advantage of providing extremely precise and rich data—including the strength and frequency of "firing" for individual nerve cells. The idea is to use specially designed software to decode or translate this information into the appropriate action. Such highly detailed information would, in theory, permit exquisitely fine control of an artificial limb.

Direct brain linkages are already being tested in dozens of humans. In one case, a woman who had been paralyzed by a stroke was able to use a robotic arm to drink coffee from a container using just her thoughts to guide the device. And in 2012 DARPA launched an initiative that, for the first time, will use brain-penetrating electrodes to control state-of-the-art prosthetic arms in a few individuals who have lost upper limbs. In both cases, the neuron-recording electrodes are connected to wires that emerge from the skull. The signal is then decoded by a powerful computer, which in turn relays instructions to the robotic arm. Ultimately researchers hope to transmit the information wirelessly so that a recipient does not have to be tethered to a computer to use the synthetic arm. Unfortunately, the necessary computer power does not yet come in a package small enough to be internalized, as would be desirable in a real-world setting.

Another drawback is that the brain tissue treats the penetrating electrodes as foreign invaders and launches an inflammatory response that eventually leads to the buildup of minute scar tissue around the electrodes. The scar tissue, in turn, exponentially decreases the number of nerve cells that can be monitored, which causes the signal to grow weaker and less informative over time. In some patients, electrodes have reportedly continued recording from one or more neurons for several years after implantation, but these cases are the exception. Investigators are now searching for ways to minimize the body's intense reaction against foreign objects in the brain.

PERIPHERAL ADVANTAGES

SUCH CHALLENGES prompted the two of us to try to tap into the peripheral nervous system. Whereas the central nervous system consists of up to 100 billion nerve cells, the peripheral nervous system is mostly made up of fibers, known as axons, which are bundled together to form nerves. These axons are, in essence, very long projections—sometimes up to one meter in length—from nerve cells that transmit electrical signals between the central nervous system and the rest of the body.

Some of these peripheral nerve fibers connect the spinal cord to the muscles and hence allow the brain to control motor functions by sending signals down to the spinal cord. Other peripheral nerve fibers relay sensory information—such as limb position, temperature or touch—from the body to the spine, which then passes it on to the brain for further processing.

Because the remaining sensory nerves in a limb stump often continue emitting signals as if they were receiving inputs from the missing arm or leg, many amputees have a feeling that their lost appendage is still there—a condition known as phantom limb syndrome. If you could hook up those misfiring sensory axons to an artificial prosthetic that would send strong signals to the nerves, the brain would readily interpret the incoming signals as coming from a forearm, a hand and fingers.

Similarly, the motor axons of the peripheral nervous system are still capable of directing movement. Because the brain retains the ability to coordinate and match these varying motor signals to different motions, it would command a properly connected artificial limb to move in a natural way.

The problem is that peripheral axons will not grow longer unless they have a biological target with which they can make contact. Moreover, as is true in the central nervous system, the body tends to react badly to wires implanted into peripheral nerves.

Todd Kuiken of Northwestern University and his group have demonstrated, in human volunteers, an ingenious work-around to this problem: they use muscles in the chest as a kind of bridge between the stump from an amputated arm and the internal electronics of a prosthetic device. First, the Northwestern scientists cut the motor nerves to a handful of superficial muscles in the chest so that they do not receive any competing signals from the brain. Then they carefully redirect the motor axons that once connected the spinal column and the severed part of the arm so that they now connect to the superficial chest muscles instead. Within a matter of weeks, the rerouted nerves completely connect up with (or innervate) the chest muscles. Commands from the brain that are meant to stimulate the no longer existent arm now travel to the chest instead, thus causing those muscles to contract.

The nervous system's inborn ability to adapt allows scientists to create "living bridges" between nerves in a stump and the electronics of prostheses.

At this point, electrodes are placed on the skin of the chest to record the electrical activity of the individual muscles as they contract. Such recordings, in turn, indirectly reveal the signaling coming from the brain. After a few weeks of training, patients can move the prosthetic devices simply by thinking about what they want the device to do. For example, thinking about clasping a cup leads to a specific pattern of contractions in the chest that in turn "tells" the electronics in the prosthesis to bend the fingers in the artificial hand.

Kuiken and his group have now used this approach, known as targeted muscle reinnervation, on dozens of amputees. Yet whether this technology can provide the fine control needed to re-create all the natural moves of a real hand and arm remains to be seen.

NEURAL BRIDGES

WE BELIEVE that fine-motor control of an artificial arm will ultimately require a different kind of link between living tissue and the prosthesis. Fortunately, muscles are not the only tissue that severed nerves will innervate. Nerves will also grow toward other nerves and will even accept transplanted nerves as part of the family, so to speak. Thus, about six years ago we decided to explore the possibility of using transplanted nerve fibers instead of muscle as the intermediary between the severed axons in a stump and the electrical wiring of a prosthetic device.

To create such a neural bridge, one first has to figure out how to grow nerve fibers that are long enough to span the gap between the host axons and the electronics. One of us (Smith) has developed a technique for stretching axons grown in cell culture to help them to achieve the required lengths. This process exploits the natural ability of nerves to elongate during normal growth spurts. One of the most extreme examples of this kind of "stretch growth" occurs in axons in the blue whale's spinal cord, which can elongate more than three centimeters a day and reach up to 30 meters in length.

In essence, we take a cell culture of neurons and start dividing it into two—pulling the halves a little farther apart each day. The axons in the middle get stretched and thus must grow in both directions to release the tension. Taking advantage of this natural mechanical process, we have developed devices we call axon elongators that can stretch-grow bundles of axons at the unprecedented experimental rate of one centimeter a day, which causes them to become as long as 10 centimeters and eventually probably even longer.

One of our first applications of these stretch-grown axons was to serve as a living bridge to repair severed peripheral nerves, such as occurs during trauma or surgery. When we implanted such axon bundles so that one end was close to the tip of a severed nerve in rats, the axons in the nerve reached out and grew along the length of the bridge. In fact, many of the axons inched their way so far into the previously paralyzed limb that the nerve was completely restored and the rats were able to regain function.

In addition, we determined that our neural bridges survived for at least four months after transplantation—all without triggering an immune reaction. Indeed, our neural bridges worked so well in rats that we are now trying them out in pigs. And if those experiments are successful, we will begin trials in people who have recently suffered major nerve damage.

Having demonstrated a way to direct and stimulate severed axons to regrow significantly, we next attempted to make a more complicated bridge that would allow the axons to communicate with the electronics in a prosthesis. Our vision was to find thin, conductive filaments that the body would not perceive as foreign. After some trial and error, we decided to create our filaments using various conductive polymers, one of which is polyaniline, a nitrogen-based organic compound that has long been known to carry electric current and that research by others had indicated might be tolerated by the body. So far, at least in studies of rodents, such specialized polymers do not appear to provoke a strong reaction from the immune system.

The next step was to induce a bundle of lab-grown neurons to grow around one end of those microfilaments and then stretch-grow the axons toward the host nerve. (The other end of the microfilaments would connect with the prosthesis via a wireless transmitter.) Ideally, axons from a stump would grow along our stretched axons and make contact with the filaments, which would pick up electrical signals from the stump's motor axons and convey them to the electronics; likewise, sensory signals sent from the electronics would travel up the filaments, depolarizing the sensory axons that had grown into the bridge and thereby relaying information to the spine and brain.

Using this approach in rats, we have found that the stretch-grown neural tissue provides a pathway that guides the host's regenerating axons to within a few tens of microns of the polymer filaments. That is close enough for different filaments to be able to record the signals of the nerves going in one direction (down the limb) and to stimulate the nerves going in the other direction (toward the brain). In essence, we have created a simple adapter cord that connects devices with two different kinds of plugs. Our hybrid of biological tissue (the neurons and their stretch-grown axons) and a nonbiological conductor would allow electronics in a prosthesis to plug in at one end and axons from the stump to plug in at the other end. So far these biohybrids have survived and maintained their integration with the host nerve for at least one month following transplantation, which suggests the immune system readily tolerates them because it would otherwise have destroyed them in a matter of days. Further tests at longer time points are ongoing.

NEXT STEPS

WHILE PROMISING, our biohybrid approach to neural engineering is still in its infancy. We do not yet know how long these bridges will last. Nor do we know whether the immune system will tolerate the polymer-based components over the long run. Moreover, we need to minimize interference from other electrical devices as well as improve the sensitivity of the individual nerve signals that are transmitted from the bridge to the prosthesis. Even if we can connect the neurons from a limb stump to a prosthesis, we still have no guarantee that the brain will be able to interpret the signals that originate in the prosthesis in a meaningful way.

Experience with hand transplants provides reason to believe that the brain might be up to the task. In performing such transplants, surgeons cannot possibly connect every last nerve fiber correctly from the host to the transplanted hand. Such precision turns out to be unnecessary, however. The brain essentially redraws its own internal map of which motor neurons do what, allowing it to eventually gain control of the new hand. Similarly, driving a robotic hand that is linked to the nervous system will probably require extensive retraining of the brain.

Further progress in the control of prosthetic limbs may well require a combination of advances in research on both the central and the peripheral nervous systems. Yet forming direct connections between the brain and advanced prosthetics—by tapping directly into the cerebrum, through repurposed chest muscles or linking across biohybrid bridges—offers the best chance of having an artificial arm that moves as gracefully and feels as natural as the original one. Although the interface between Luke Skywalker and his new arm was never revealed in *The Empire Strikes Back,* scientists are well on the way to figuring out how it must have been constructed. SA

MORE TO EXPLORE:

Stretch Growth of Integrated Axon Tracts: Extremes and Exploitations. Douglas H. Smith in *Progress in Neurobiology,* Vol. 89, No. 3, pages 231–239; November 2009.

Neural Tissue Engineering and Biohybridized Microsystems for Neurobiological Investigation in Vitro, Part 1. D. Kacy Cullen, John A. Wolf, Varadraj N. Vernekar, Jelena Vukasinovic and Michelle C. LaPlaca in *Critical Reviews in Biomedical Engineering,* Vol. 39, No. 3, pages 201–240; 2011.

Neural Tissue Engineering for Neuroregeneration and Biohybridized Interface Microsystems in Vivo, Part 2. D. Kacy Cullen, John A. Wolf, Douglas H. Smith and Bryan J. Pfister in *Critical Reviews in Biomedical Engineering,* Vol. 39, No. 3, pages 241–259; 2011.

SCIENTIFIC AMERICAN ONLINE
Listen to an interview with Cullen, as he discusses biohybrid bridges and the future of prosthetic devices, at **ScientificAmerican.com/jan2013/bionic-limb**

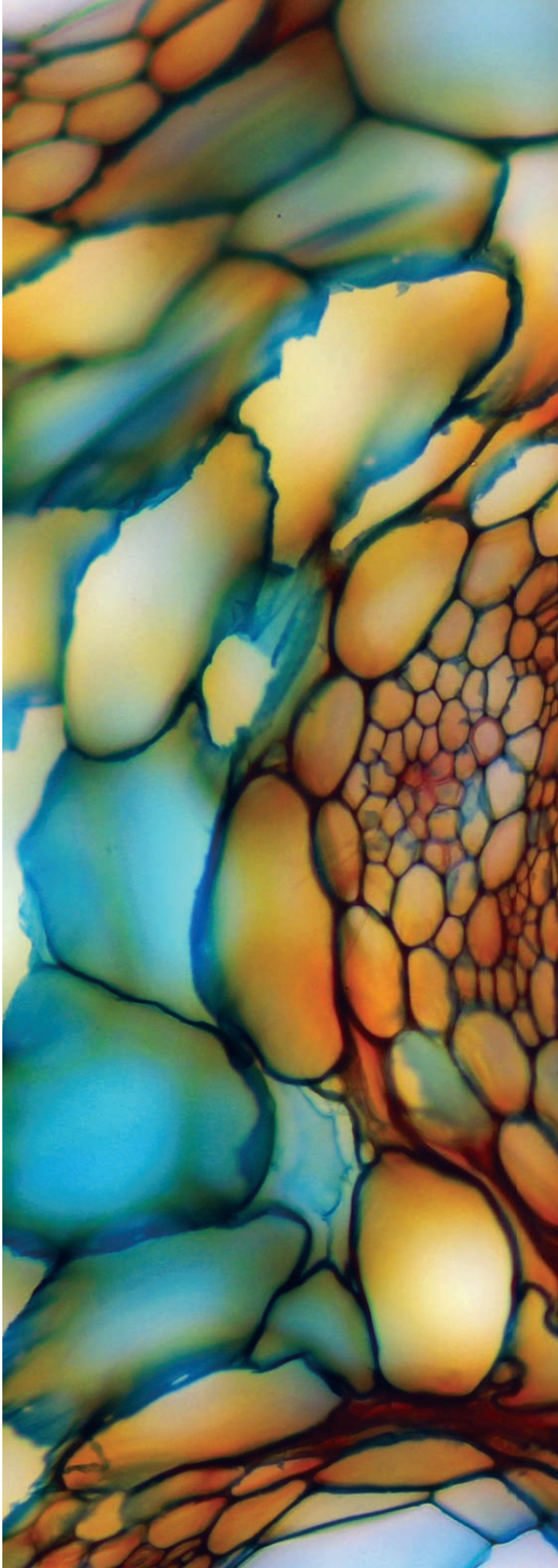
LIFE SCIENCE

SMALL WONDERS

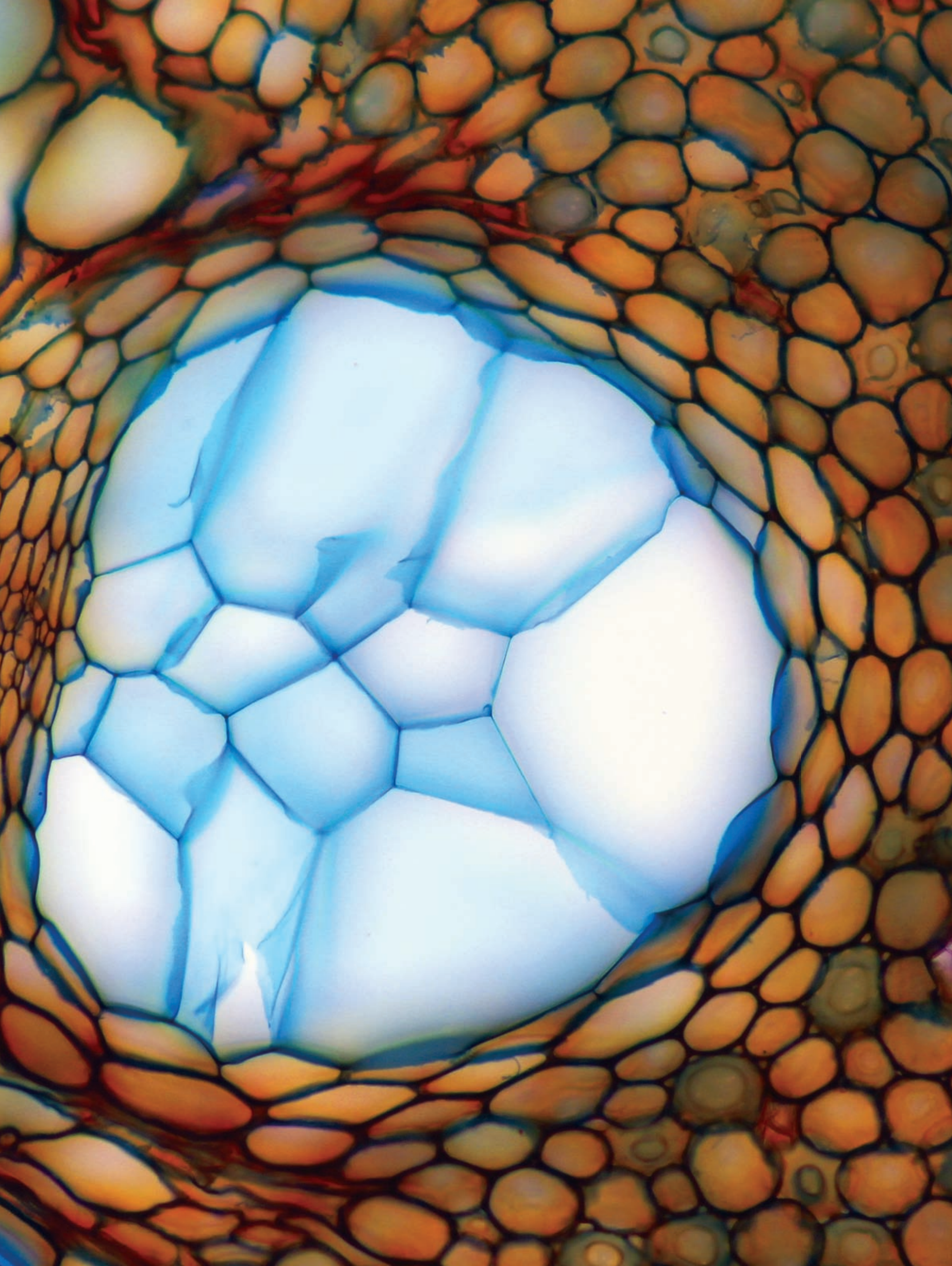
Light microscopy reveals hidden marvels of the natural world

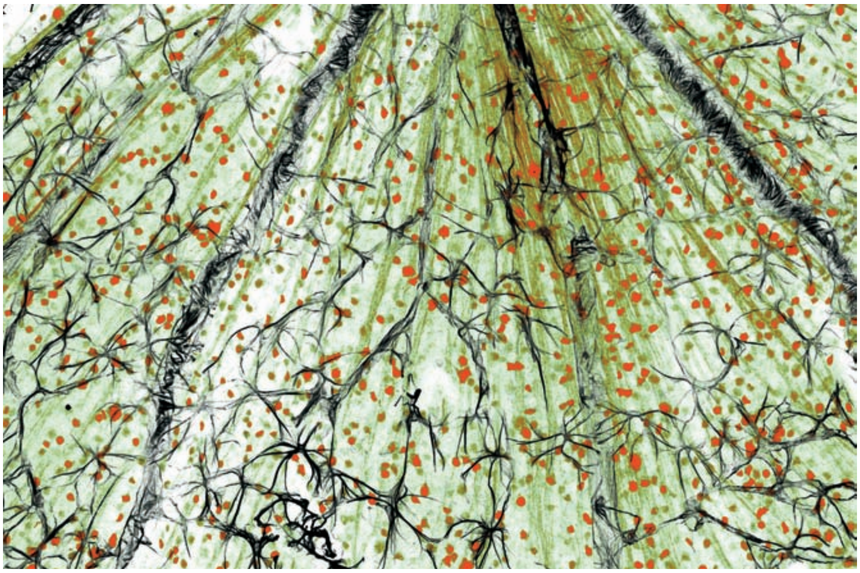
By Kate Wong

A STAINED-GLASS SPIRAL OF CELLS FROM AN ALOE PLANT, AN old-growth forest of neural cells in the retina of a mouse, a starry sea of leaf hairs on a garden shrub—organisms have a way of reinventing themselves rather spectacularly under the microscope, giving observers a new appreciation for what Charles Darwin termed nature's "endless forms most beautiful." In these tiny worlds, beauty arises from both the brilliance of evolution's small-scale solutions to life's challenges and the techniques microscopists use to visualize biological structures and processes. To peer through the eyepiece is to discover a universe in an embryo, an organ, a cell. As Igor Siwanowicz of the Howard Hughes Medical Institute [*see photographs on pages 61 and 63*] puts it, "microscopy allows me to see beyond the cuticle, explore the baroque arrangement of muscle fibers or intricate fractal-like network of neurons, and appreciate that beauty (probably in the most subjective sense possible) isn't only skin deep." Siwanowicz is among the winners of the 2012 Olympus BioScapes International Digital Imaging Competition, which welcomes entries from scientists and hobbyists alike. His images and other entries that caught SCIENTIFIC AMERICAN's eye grace the pages that follow. We hope you enjoy this armchair safari into miniature realms where science and art converge. SA

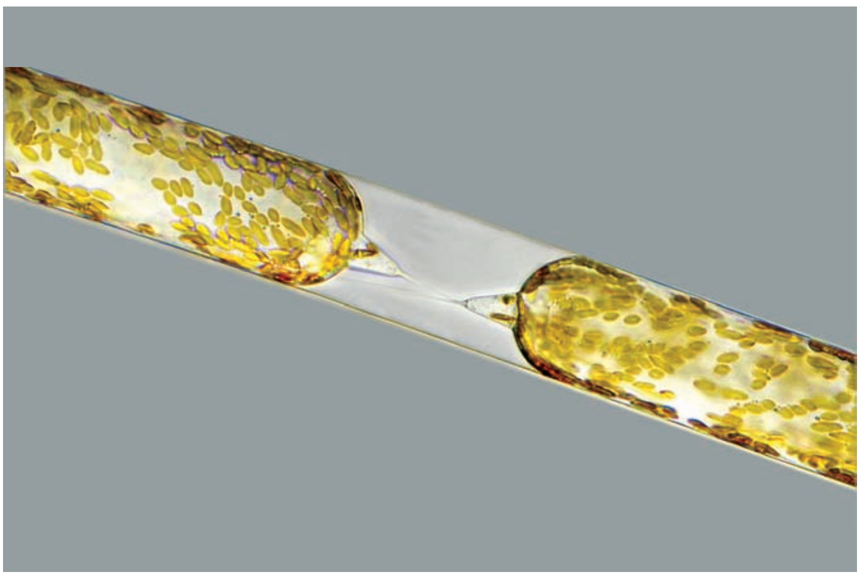


ALOIN CELLS: Botanist Anatoly I. Mikhaltsov of the Children's Ecological and Biological Center in Omsk, Russia, was studying the anatomy of *Aloe erinacea*, an endangered species of aloe endemic to Namibia, when he captured this image of the plant's aloin cells (*blue*)—which secrete a component of the gel-like sap that oozes from an aloe's severed leaf—using a coloring method that he developed. The cluster of aloin cells is 300 microns wide.



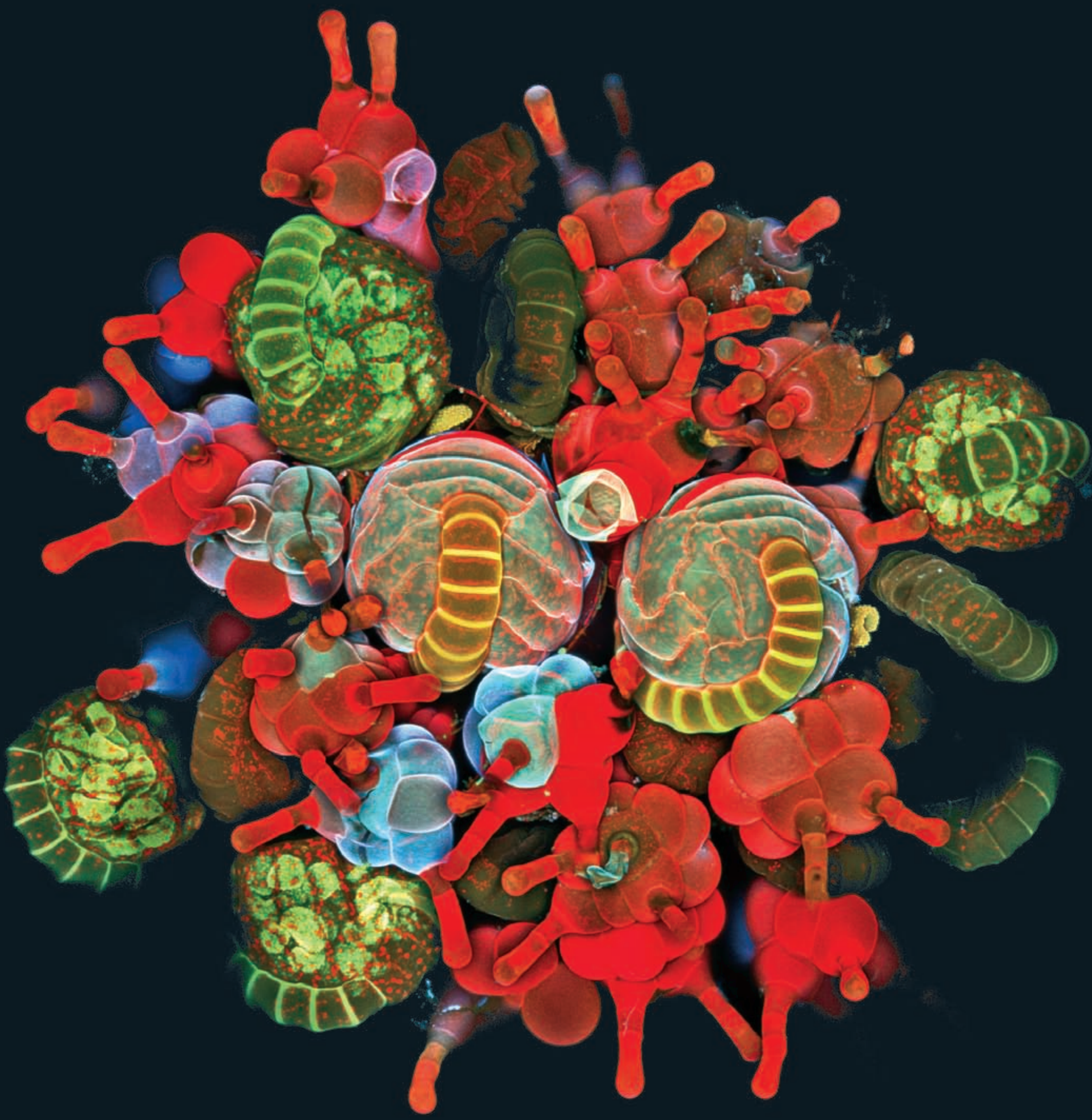


RETINAL ASTROCYTES: A tapestry of cells in a mouse retina reveals a network of spidery astrocytes (*black*) that balances the amounts of ions and water in the space around neurons (*orange*) and their axons (*green*). The arms of the astrocytes wrap around blood vessels, which appear as vertical black "roads," creating a physical and chemical barrier that determines which molecules reach the neurons. Neurobiologist Alejandra Bosco of the University of Utah produced this image of the retina, which was 0.1 millimeter by five millimeters when flattened, as part of her research on the role of astrocytes in diseases such as glaucoma.

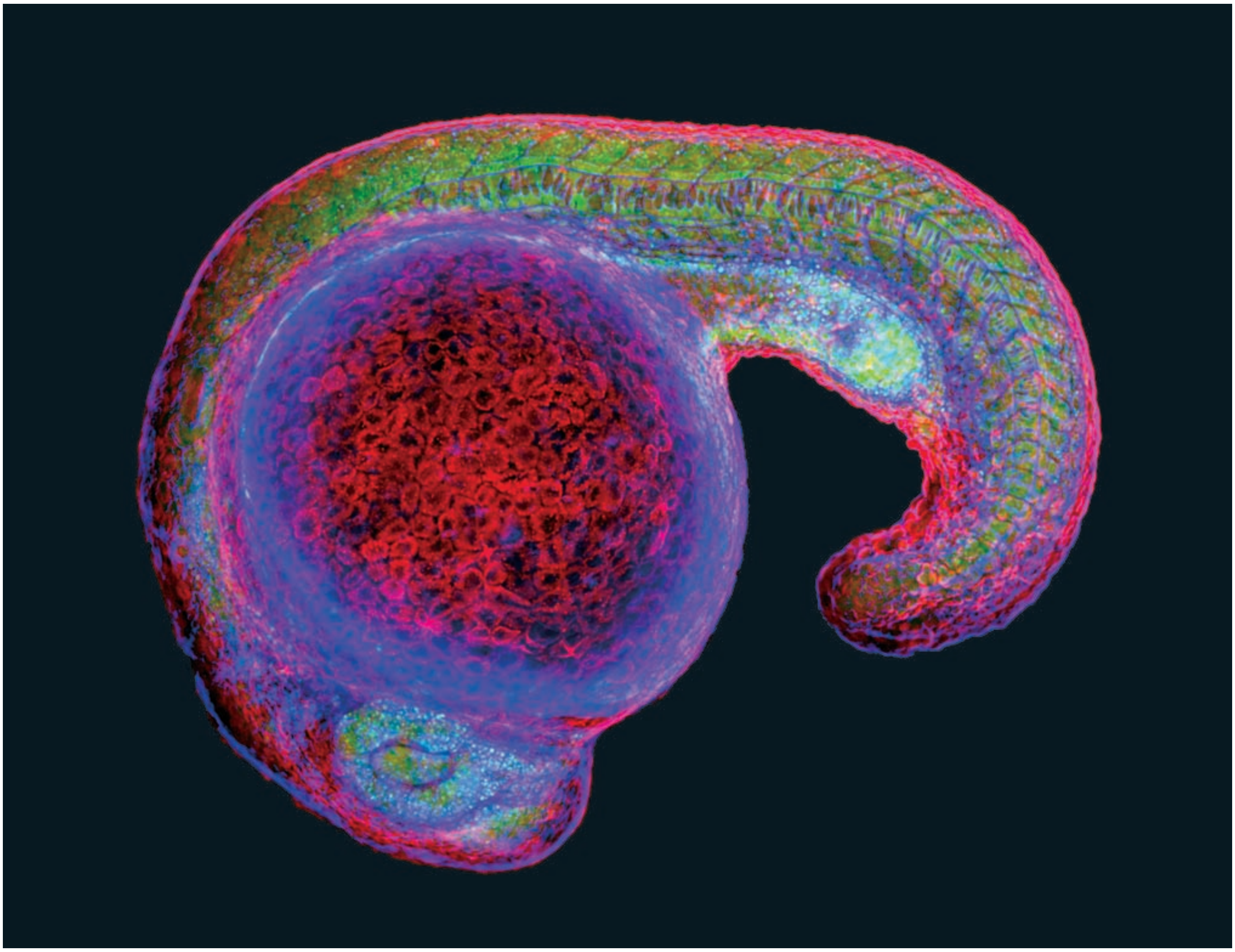


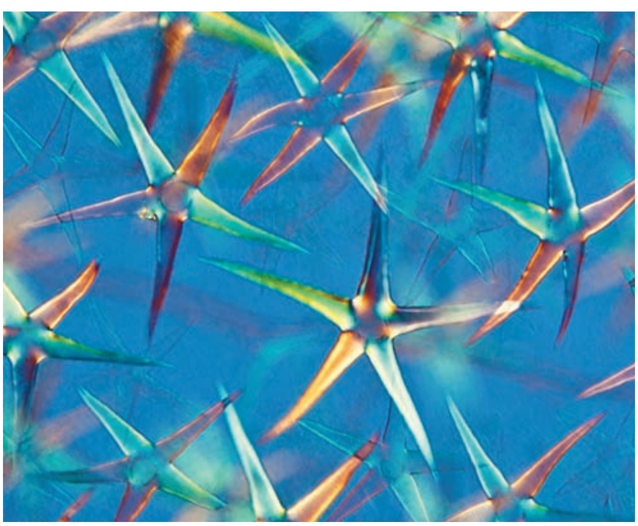
DIATOM REPRODUCTION: The marine diatom *Rhizosolenia setigera* undergoes binary fission, a type of asexual reproduction in which a mother cell divides into two daughter cells. The golden structures are chloroplasts, bodies that carry out photosynthesis. The organism's clear shell consists of silica glass. Hobbyist Wolfgang Bettighofer of Kiel, Germany, stacked 15 photomicrographic frames to create the image, which shows about 300 microns of the recently divided cells.

BUTTERFLY WING: The abstract beauty of a butterfly wing is revealed in this image by Sahar Khodaverdi, who is earning a master's degree in plant biology at the University of Tabriz in Iran. Butterfly wings are covered with delicate scales. The color and iridescence of the wings arise from both the pigments in the scales and the way light interacts with the nanostructure of those scales.



FERN SPORANGIA: Inspect the underside of a fern frond, and you may find it covered with dark spots known as sori. Each sorus is made up of clusters of structures called sporangia that contain spores for reproduction. Here sporangia from the fern *Polypodium virginianum* (*multicolored structures*) mingle with specialized hairs termed paraphyses (*red*) that are believed to protect the spores from the elements. Neurobiologist Igor Siwanowicz of the Howard Hughes Medical Institute campus in Ashburn, Va., visualized the cluster, which measures nearly a millimeter across, using the same fluorescent dyes he applies to invertebrate animals.





ZEBRA FISH EMBRYO: Karen W. Dehnert, Scott T. Laughlin, Holly Aaron and Carolyn R. Bertozzi of the University of California, Berkeley, obtained this image of a live zebra fish embryo, 19 hours old (*above*), using 10× magnification while studying how the distribution of a class of carbohydrates containing a sugar known as fucose changes during development. The addition of fucose to certain molecules is essential for proper embryonic development.

LEAF HAIRS: Star-shaped hairs cover the leaves of the ornamental shrub *Deutzia scabra* (*left*). The hairs, which measure around 0.25 millimeter across, defend against grazing animals, wind, frost and ultraviolet radiation. In Japan, woodworkers use the abrasive leaves for fine polishing. To get these dense hairs of varying height in focus, freelance microphotographer Steve Lowry took a series of images at different foci and then combined the in-focus information using a computer program to create a single, stacked image.

MOTH CATERPILLAR: In a second micrograph made by Siwanowicz (*opposite*), a slug moth caterpillar prepares to bundle up in a silk cocoon for the last phase of its metamorphosis into the adult moth form. Each of its simple eyes has six dome-shaped lenses. Adults, in contrast, have large, multifaceted compound eyes. To compensate for the poor vision afforded by their simple eyes, caterpillars are covered with receptors for other senses. The caterpillar's head is roughly 0.5 millimeter wide.

MORE TO EXPLORE

For more information about the Olympus BioScapes competition, visit www.olympusbioscapes.com

SCIENTIFIC AMERICAN ONLINE
To see a slide show of additional images, go to ScientificAmerican.com/jan2013/bioscapes

DROWNED: A 43-day atmospheric-river storm in 1861 turned California's Central Valley region into an inland sea, simulated here on a current-day map.

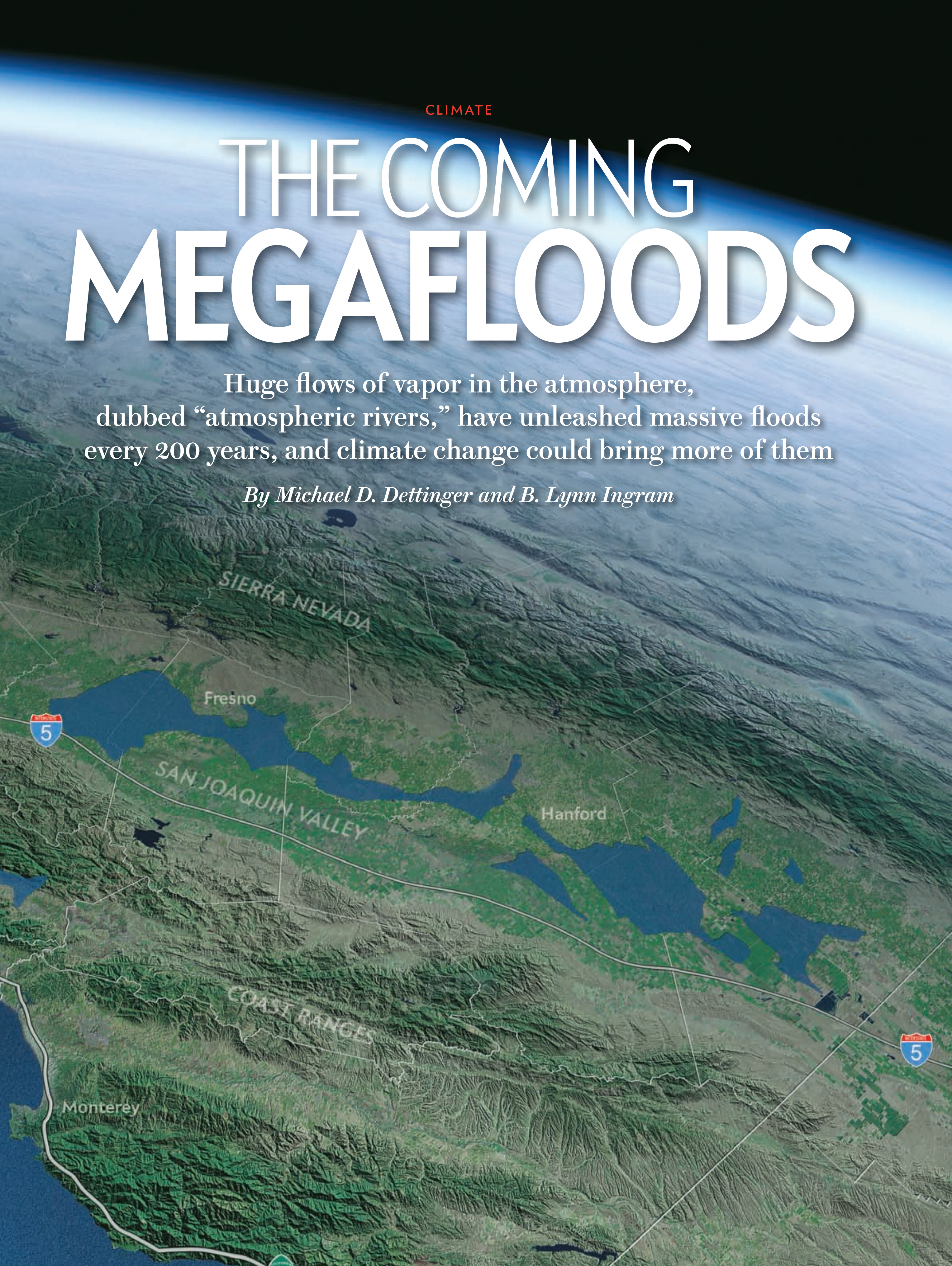
Illustrations by Don Foley

CLIMATE

THE COMING MEGAFLOODS

Huge flows of vapor in the atmosphere, dubbed "atmospheric rivers," have unleashed massive floods every 200 years, and climate change could bring more of them

By Michael D. Dettinger and B. Lynn Ingram



Michael D. Dettinger is a research hydrologist for the U.S. Geological Survey and a research associate at the Climate, Atmospheric Sciences and Physical Oceanography Division at the Scripps Institution of Oceanography in La Jolla, Calif.

B. Lynn Ingram is a professor of earth and planetary science at the University of California, Berkeley, and co-author of *The West without Water* (University of California Press, Spring 2013).

THE INTENSE RAINSTORMS SWEEPING IN FROM the Pacific Ocean began to pound central California on Christmas Eve in 1861 and continued virtually unabated for 43 days. The deluges quickly transformed rivers running down from the Sierra Nevada mountains along the state's eastern border into raging torrents that swept away entire communities and mining settlements. The rivers and rains poured into the state's vast Central Valley, turning it into an inland sea 300 miles long and 20 miles wide. Thousands of people died, and one quarter of the state's estimated 800,000 cattle drowned. Downtown Sacramento was submerged under 10 feet of brown water filled with debris from countless mudslides on the region's steep slopes. California's legislature, unable to function, moved to San Francisco until Sacramento dried out—six months later. By then, the state was bankrupt.

A comparable episode today would be incredibly more devastating. The Central Valley is home to more than six million people, 1.4 million of them in Sacramento. The land produces about $20 billion in crops annually, including 70 percent of the world's almonds—and portions of it have dropped 30 feet in elevation because of extensive groundwater pumping, making those areas even more prone to flooding. Scientists who recently modeled a similarly relentless storm that lasted only 23 days concluded that this smaller visitation would cause $400 billion in property damage and agricultural losses. Thousands of people could die unless preparations and evacuations worked very well indeed.

Was the 1861–62 flood a freak event? It appears not. New studies of sediment deposits in widespread locations indicate that cataclysmic floods of this magnitude have inundated California every two centuries or so for at least the past two millennia. The 1861–62 storms also pummeled the coastline from northern Mexico and southern California up to British Columbia, creating the worst floods in recorded history. Climate scientists now hypothesize that these floods, and others like them

IN BRIEF

Geologic evidence shows that truly massive floods, caused by rainfall alone, have occurred in California about every 200 years. The most recent was in 1861, and it bankrupted the state.

Such floods were most likely caused by atmospheric rivers: narrow bands of water vapor about a mile above the ocean that extend for thousands of miles. Much smaller forms of these rivers regularly hit California, as well as the western coasts of other countries.

Scientists who created a simulated megastorm, called ARkStorm, that was patterned after the 1861 flood but was less severe, found that such a torrent could force more than a million people to evacuate and cause $400 billion in losses if it happened in California today.

Forecasters are getting better at predicting the arrival of atmospheric rivers, which will improve warnings about flooding from the common storms and about the potential for catastrophe from a megastorm.

in several regions of the world, were caused by atmospheric rivers, a phenomenon you may have never heard of. And they think California, at least, is overdue for another one.

TEN MISSISSIPPI RIVERS, ONE MILE HIGH

ATMOSPHERIC RIVERS are long streams of water vapor that form at about one mile up in the atmosphere. They are only 250 miles across but extend for thousands of miles—sometimes across an entire ocean basin such as the Pacific. These conveyor belts of vapor carry as much water as 10 to 15 Mississippi Rivers from the tropics and across the middle latitudes. When one reaches the U.S. West Coast and hits inland mountain ranges, such as the Sierra Nevada, it is forced up, cools off and condenses into vast quantities of precipitation.

People on the West Coast of North America have long known about storms called "pineapple expresses," which pour in from the tropics near Hawaii and dump heavy rain and snow for three to five days. It turns out that they are just one configuration of an atmospheric river. As many as nine atmospheric rivers hit California every year, according to recent investigations. Few of them end up being strong enough to yield true megafloods, but even the "normal" storms are about as intense as rainstorms get in the rest of the U.S., so they challenge emergency personnel as well as flood-control authorities and water managers.

Atmospheric rivers also bring rains to the west coasts of other continents and can occasionally form in unlikely places. For example, the catastrophic flooding in and around Nashville in May 2010—which caused some 30 deaths and more than $2 billion in damages—was fed by an unusual atmospheric river that brought heavy rain for two relentless days up into Tennessee from the Gulf of Mexico. In 2009 substantial flooding in southern England and in various parts of Spain was also caused by atmospheric rivers. But the phenomenon is best understood along the Pacific Coast, and the latest studies suggest that these rivers of vapor may become even larger in the future as the climate warms.

SUDDEN DISCOVERY

DESPITE THEIR INCREDIBLE DESTRUCTION, atmospheric rivers were discovered only relatively recently and in part by serendipity.

In January 1998 the National Oceanic and Atmospheric Administration's Environmental Technology Laboratory began a project called CALJET to improve the forecasting of large storms that hit the California coast. The lab's research meteorologist Marty Ralph and others flew specially outfitted aircraft over the North Pacific into an approaching winter storm to directly measure the conditions. That storm was described as a "jet"—a zone of high winds. The researchers found that the single storm, for several days running, was carrying about 20 percent of the atmosphere's moisture that was moving poleward at middle latitudes. The jet was concentrated at about a mile above the ocean's surface, high enough to have been difficult to identify using traditional meteorological observations from the ground.

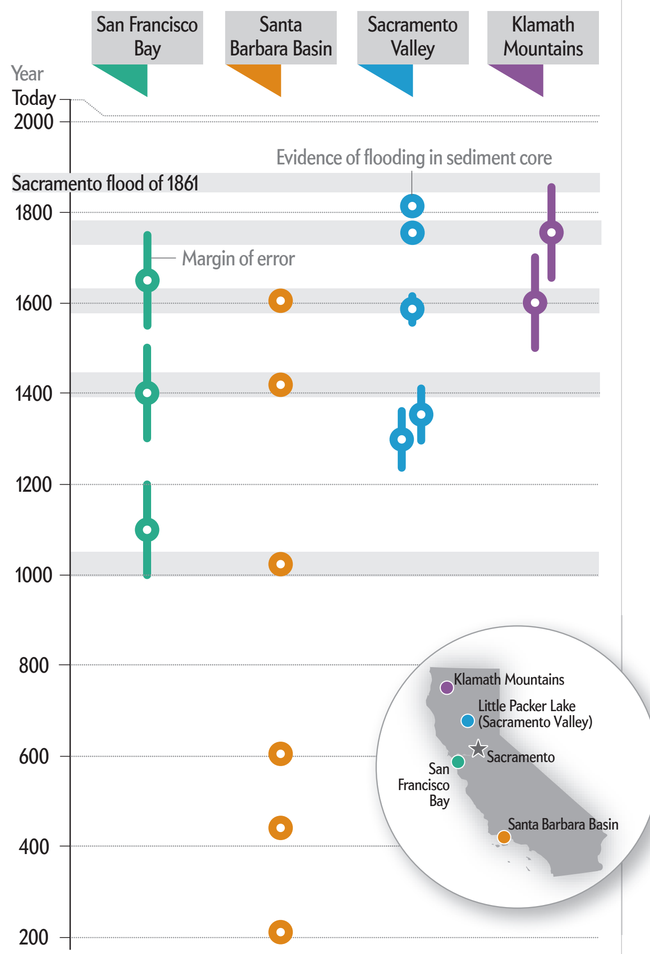
Also in 1998 researchers Yong Zhu and the late Reginald Newell, then at the Massachusetts Institute of Technology, noticed an odd feature in simulations of global wind and water-vapor patterns that had been made by the European Center for Medium-Range Weather Forecasts. They found that, outside of the tropics, an average of about 95 percent of all vapor transport toward the poles occurred in just five or six narrow bands,

TIMELINE

California Megafloods, Every Two Centuries

Massive floods have struck California every 200 years or so, according to analysis of sediment deposits left by the torrents in four widely separated locations. Different dating methods used at the sediment sites have varying margins of error, but the midpoints align fairly well. If the pattern holds, the state could be due for another catastrophe; the most recent megaflood was in 1861, and it left Sacramento underwater for six months (*photograph*).

DAVID JOSLYN COLLECTION/CENTER FOR SACRAMENTO HISTORY



Graphic by Jen Christiansen, Map by XNR Productions distributed somewhat randomly around the globe, that moved west to east across the middle latitudes. To describe these bands, they coined the term "atmospheric rivers."

At about the same time, satellites carrying the new Special Sensor Microwave Imager were for the first time providing clear and complete observations of water-vapor distributions globally. The imagery showed that water vapor tended to concentrate in long, narrow, moving corridors that extend most often from the warm, moist air of the tropics into the drier, cooler regions outside the tropics. The tentacles appeared and then fell apart on timescales from days to a couple of weeks.

Needless to say, researchers soon put together these three remarkably complementary findings. Since then, scientists have conducted a growing number of studies to better characterize West Coast atmospheric rivers. New observatories with upward-looking radars and wind profilers have been established to watch for them. NOAA's Hydrometeorological Testbed program is peering farther inland to find out what happens when atmospheric rivers penetrate the interior.

Using data from these networks, forecasters are getting better and better at recognizing atmospheric rivers in weather models and at predicting their arrival at the West Coast. In recent years some storms have been recognized more than a week before they hit land. Atmospheric rivers are also appearing in climate models used to predict future climate changes. Forecasters, feeling more confident in their prediction abilities, are beginning to warn the public about extremely heavy rains earlier than they would have in the past. This improvement is providing extra time for emergency managers to prepare.

A MEGAFLOOD EVERY CENTURY?

DESPITE GREATER SCIENTIFIC UNDERSTANDING, the 1861–62 floods are all but forgotten today. Communities, industries and agricultural operations in California and the West have spent the past century spreading out onto many of the same floodplains that were submerged 150 years ago. Residents everywhere are unaware or unwary of the obvious risks to life and property. Meanwhile, though, anxious climatologists worry about the accumulating evidence that a megastorm could happen again and soon.

The concern grows out of research that is looking 2,000 years back in time to piece together evidence revealing the occurrence and frequency of past floods, like detectives returning to a crime scene of long ago. They are sifting through evidence archived in sediments from lake beds, floodplains, marshes and submarine basins. As floodwaters course down slopes and across the landscape, they scour the hills, picking up clay, silt and sand and carrying that material in swollen currents. When the rivers slow on reaching a floodplain, marsh, estuary or the ocean, they release their loads of sediment: first the larger gravels, then the sands, and finally the silts and clays. Nature rebuilds after such events, and over time the flood deposits are themselves buried beneath newer sediments left by normal weather. Scientists extract vertical cores from these sediments and, back at the lab, analyze the preserved layers and date what happened when.

For example, flood deposits have been found under tidal marshes around San Francisco Bay in northern California. Typically the inflowing river waters that spread across the marshes deposit only thin traces of the finest sediments—clays and silts. The more vigorous flows of major floods carry larger particles and deposit thicker and coarser layers. The flood layers can be dated using the common radiocarbon-dating method, which in this application is accurate to within about 100 years. A study of the marsh cores by one of us (Ingram) and geographer Frances Malamud-Roam revealed deposits from massive flooding around A.D. 1100, 1400 and 1650. A distinct layer from the 1861–62 event is difficult to distinguish, however, because hydraulic gold mining in the Sierra Nevada foothills during the decade before and after the flood moved enormous volumes of silt and sand that essentially wiped out whatever traces the floodwaters might have left.

Sediment cores taken from beneath San Francisco Bay itself also indicate that in 1400 the bay was filled with freshwater (as it was during the 1861–62 event), indicating a massive flood.

Geologists have found more evidence in southern California, where two thirds of the state's nearly 38 million people live today, along the coast of Santa Barbara. Sediments there settle to the seafloor every spring (forming a light-colored layer of algae known as diatoms) and again in winter (forming a dark-colored silt layer). Because the oxygen concentrations in the deep waters there are inhospitably low for bottom-dwelling organisms that would usually churn and burrow, the annual sediment layers have remained remarkably undisturbed for thousands of years. Sediment cores there reveal six distinct megafloods that appear as thick gray silt layers in A.D. 212, 440, 603, 1029, 1418 and 1605. The three most recent dates correlate well with the approximate 1100, 1400 and 1650 dates indicated by the marsh deposits around San Francisco Bay—confirming that truly widespread floods have occurred every few hundred years. (In October, Ingrid Hendy of the University of Michigan and her colleagues published a paper based on a different dating method; it found a set of Santa Barbara dates that were offset from the six specific dates by 100 to 300 years, but the same basic pattern of megafloods every 200 years or so holds.)

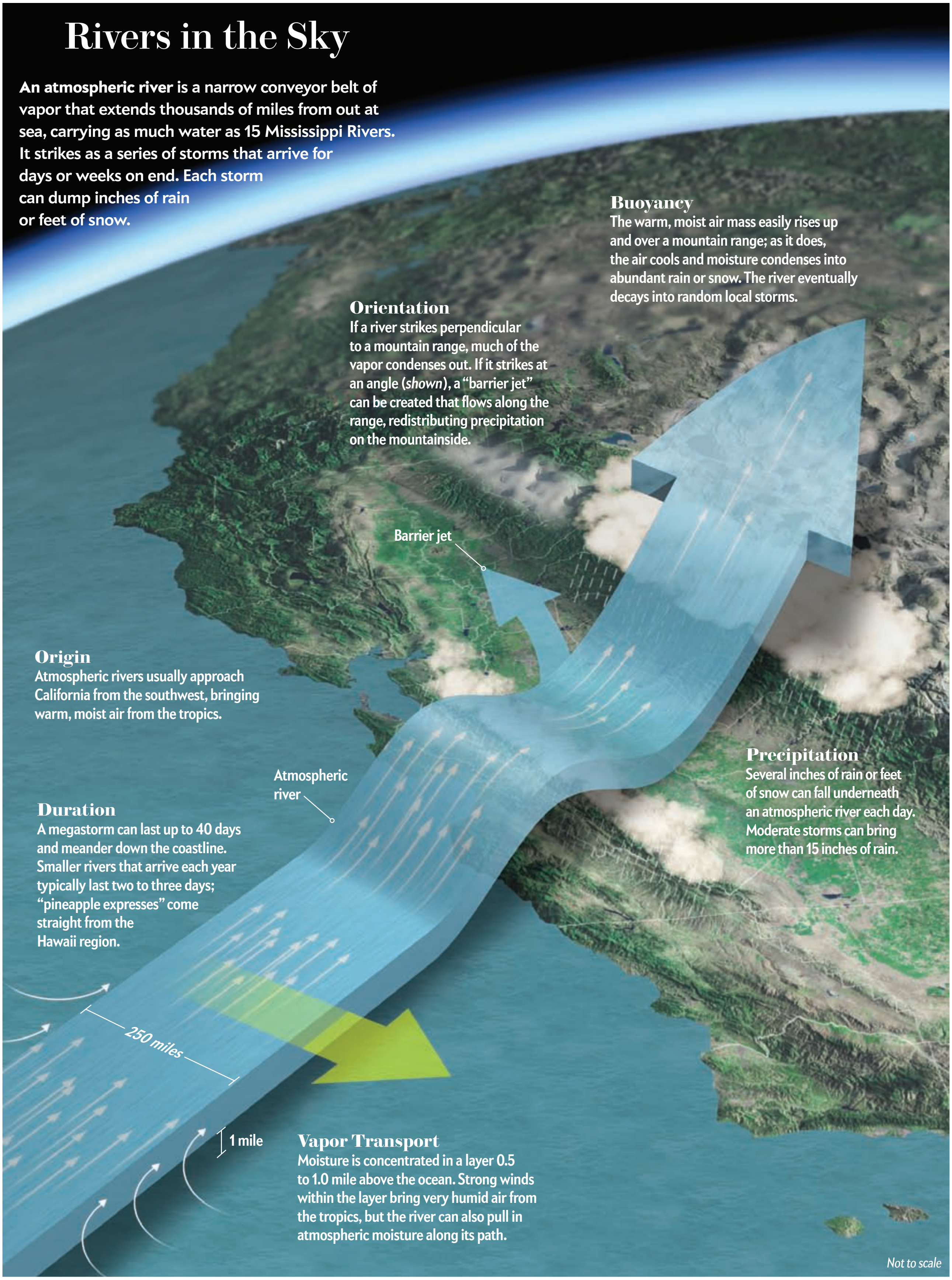
Ironically, smaller atmospheric rivers are not all bad; between 1950 and 2010 they supplied 30 to 50 percent of California's rain and snow—in the span of about 10 days each year.

The thickest flood layer in the Santa Barbara Basin was deposited in 1605. The sediment was two inches thick, a few miles offshore. The 440 and 1418 floods each left layers more than an inch thick. These compare with layers of 0.24 and 0.08 inch near the top of the core that were left by large storms in 1958 and 1964, respectively, which were among the biggest of the past century. The three earlier floods must have been far worse than any we have witnessed.

Evidence for enormous floods has also been found about 150 miles northeast of San Francisco Bay, in sediment cores taken from a small lake called Little Packer that lies in the floodplain of the Sacramento River, the largest river in northern California. During major floods, sediment-laden floodwaters spill into the lake, and the sediment settles to the bottom, forming thick, coarse layers. Geographer Roger Byrne of the University of Cal-

Rivers in the Sky

An atmospheric river is a narrow conveyor belt of vapor that extends thousands of miles from out at sea, carrying as much water as 15 Mississippi Rivers. It strikes as a series of storms that arrive for days or weeks on end. Each storm can dump inches of rain or feet of snow.



ifornia, Berkeley, and his then graduate student Donald G. Sullivan used radiocarbon dating to determine that a flood comparable to the 1861–62 catastrophe occurred in each of the following time spans: 1235–1360, 1295–1410, 1555–1615, 1750–70 and 1810–20. That is, one megaflood every 100 to 200 years.

Certain megafloods have also left records of their passage in narrow canyons in the Klamath Mountains in the northwestern corner of California. Two particularly enormous deposits were laid down around 1600 and 1750, once again agreeing with the other data.

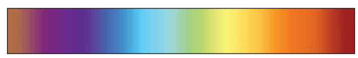
When taken together, all the historical evidence suggests that the 1605 flood was at least 50 percent greater than any of the other megafloods. And although the radiocarbon dates have significant uncertainties and could be reinterpreted if dating methods improve, the unsettling bottom line is that megafloods as large or larger than the 1861–62 flood are a normal occurrence every two centuries or so. It has now been 150 years since that calamity, so it appears that California may be due for another episode soon.

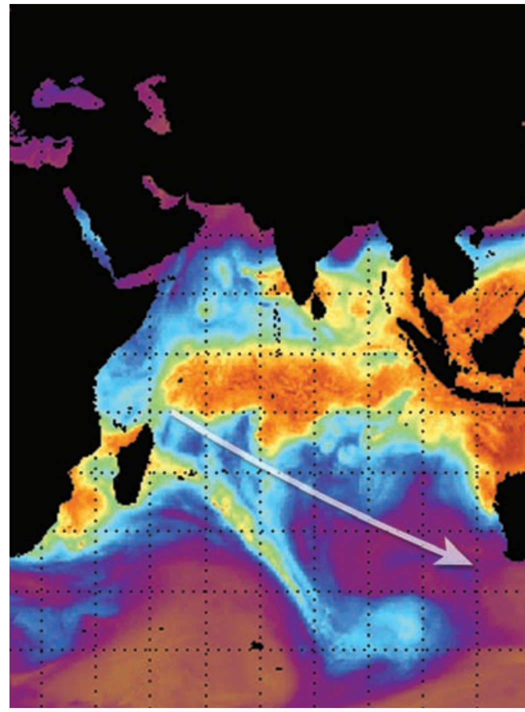
GLOBAL CONCERN

All West Coasts Can Be Hit

Atmospheric rivers form over tropical waters and flow poleward toward the west coasts of many continents (one hit England in November 2009). They are prominent along the U.S. Pacific Coast but can occasionally arise in unusual places, such as the Gulf of Mexico (one flooded Nashville in May 2010). Atmospheric rivers could become larger in the future as the climate warms.

Composite of atmospheric water vapor from December 17–19, 2010





COURTESY OF UNIVERSITY OF WISCONSIN–MADISON/SSEC (*atmospheric moisture base map*); XNR PRODUCTIONS (*landmass and arrow overlays*)

DISASTERS MORE LIKELY

IRONICALLY, ATMOSPHERIC RIVERS that set up over California are not all bad. The smaller ones that arise annually are important sources of water. By analyzing the amount of rain and snow that atmospheric rivers brought to the U.S. West Coast in recent decades, along with records about long-term precipitation, snowpack and stream flow, researchers have found that between 1950 and 2010, atmospheric rivers supplied 30 to 50 percent of California's water—in the span of only 10 days each year. They are finding similar proportions along the rest of the West Coast. In the same time period, however, the storms also caused more than 80 percent of flooding in California rivers and 81 percent of the 128 most well-documented levee breaks in California's Central Valley.

Because atmospheric rivers play such terrible roles in floods and such vital roles in water supply, it is natural to wonder what might happen with them as climate change takes firmer hold. Recall that Zhu and Newell first coined the term "atmospheric river" to describe features they observed in computer models of weather. Those models are closely related to models used to project the future consequences of rising greenhouse gas concentrations. Scientists do not program atmospheric rivers into weather and climate models; the rivers emerge as natural consequences of the way that the atmosphere and the atmospheric water cycle work, when the models are let loose to simulate the past, present or future. Thus, the rivers also appear in climate projection models used in Intergovernmental Panel on Climate Change assessments.

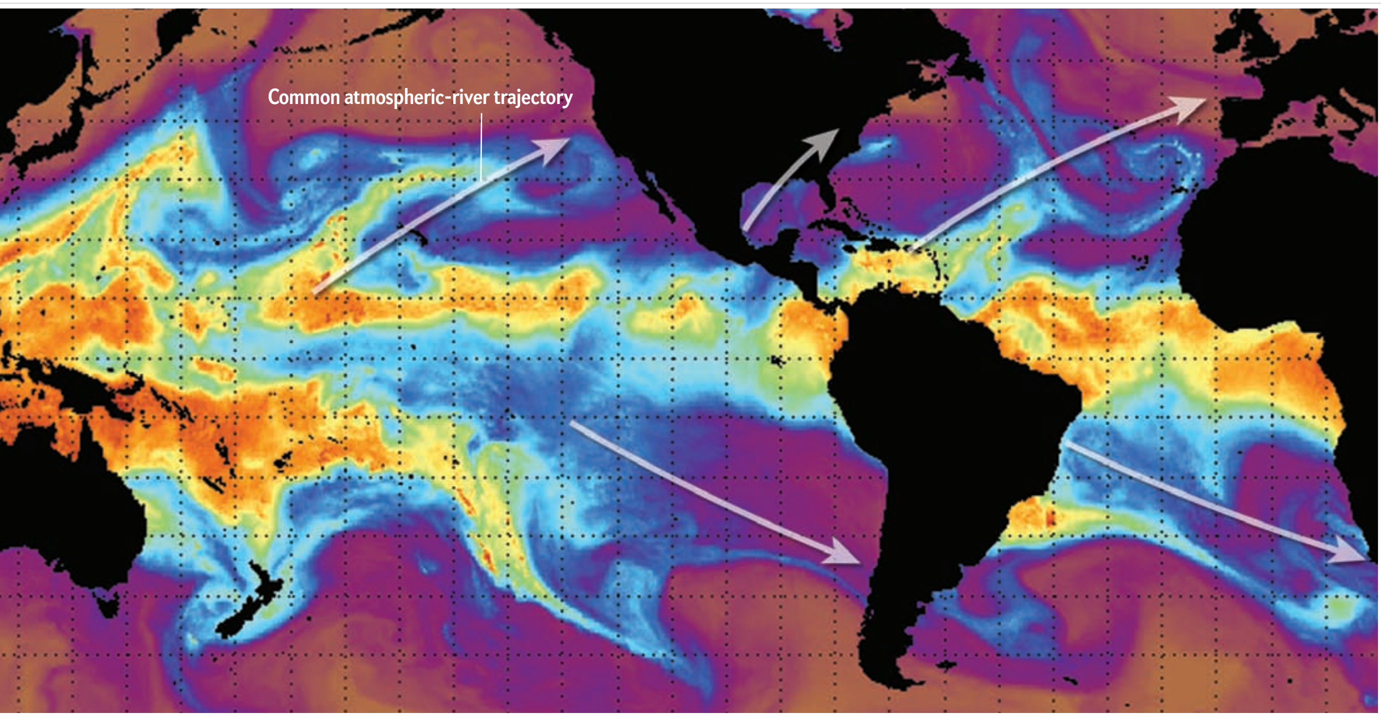
A recent review by one of us (Dettinger) of seven different climate models from around the world has indicated that atmospheric rivers will likely continue to arrive in California throughout the 21st century. In the projections, air temperatures get warmer by about four degrees Fahrenheit on average because of increasing greenhouse gas concentrations. Because a warmer atmosphere holds more water vapor, atmospheric rivers could carry more moisture.

On the other hand, because the tropics and polar regions are projected to warm at different rates, winds over the midlatitude Pacific are expected to weaken slightly. The rain that atmospheric rivers produce is primarily a product of the amount of vapor they hold and how fast they are moving, and so the question arises: Will moister air or weaker winds win out? In six of the seven climate models, the average rain and snow delivered to California by future atmospheric rivers increases by an average of about 10 percent by the year 2100. Moister air trumps weaker winds.

All seven models project that the *number* of atmospheric rivers arriving at the California coast each year will rise as well, from a historical average of about nine to 11. And all seven climate models predict that occasional atmospheric rivers will develop that are bigger than any of the historic megastorms. Given the remarkable role that atmospheric rivers have played in California flooding, even these modest increases are a cause for concern and need to be investigated further to see if the projections are reliable.

TIME TO PREPARE

WITH ATMOSPHERIC RIVERS likely to become more frequent and larger and with so many people now living in their paths, society would be wise to prepare. To provide an example that California emergency managers could use to test their current plans and methods, scientists at the U.S. Geological Survey



recently developed the scenario mentioned at the start of this article: a megastorm that rivaled the 1861–62 storm in size but lasted 23 days instead of 43 (so no one could claim that the scenario was unrealistic). To further ensure that the scenario, which was eventually dubbed ARkStorm (Atmospheric River 1000 Storm), was as realistic as possible, scientists constructed it by stitching together data from two of the largest storm sequences in California from the past 50 years: January 1969 and February 1986.

When project leaders ran the events of ARkStorm through a variety of weather, runoff, engineering and economic models, the results suggested that sustained flooding could occur over most lowland areas of northern *and* southern California. Such flooding could lead to the evacuation of 1.5 million people. Damages and disruptions from high water, hundreds of landslides and hurricane-force winds in certain spots could cause $400 billion in property damages and agricultural losses. Long-term business and employment interruptions could bring the eventual total costs to more than $700 billion. Based on disasters elsewhere in recent years, we believe a calamity this extensive could kill thousands of people (the ARkStorm simulation did not predict deaths).

The costs are about three times those estimated by many of the same USGS project members who had worked on another disaster scenario known as ShakeOut: a hypothetical magnitude 7.8 earthquake in southern California. It appears that an atmospheric-river megastorm—California's "Other Big One"—may pose even greater risks to the Golden State than a large-magnitude earthquake. An ARkStorm event is plausible for California, perhaps even inevitable. And the state's flood protection systems are not designed to handle it. The only upside is that today, with improved science and technology, the megastorms could likely be forecasted anywhere from a few days to more than a week in advance. Proper planning and continuing efforts to improve forecasts could reduce the damage and loss of life.

The same promise, and warning, holds true along the western coasts of other continents. Scientists have studied atmospheric rivers in more depth along California's coast than anywhere else in the world, but they have little reason to expect that the storms would be less frequent or smaller elsewhere. The next megaflood could occur in Chile, Spain, Namibia or Western Australia.

Californians, as well as people all along the West Coast, should be aware of the threats posed by atmospheric rivers and should take forecasts of storms and floods very seriously. Planners and city and state leaders should also take note as they decide on investments for the future. He who forgets the past is likely to repeat it. SA

MORE TO EXPLORE

Holocene Paleoclimate Records from a Large California Bay Estuarine System and Its Watershed Region: Linking Watershed Climate and Bay Conditions. Frances P. Malamud-Roam et al. in *Quaternary Science Reviews,* Vol. 25, Nos. 13–14, pages 1570–1598; July 2006.

Storms, Floods, and the Science of Atmospheric Rivers. Michael D. Dettinger and F. M. Ralph in *Eos,* Vol. 92, No. 32, page 265; 2011.

Design and Quantification of an Extreme Winter Storm Scenario for Emergency Preparedness and Planning Exercises in California. Michael D. Dettinger et al. in *Natural Hazards,* Vol. 60, No. 3, pages 1085–1111; February 2012.

NOAA atmospheric river page: **www.esrl.noaa.gov/psd/atmrivers**

USGS ARkStorm page: **http://urbanearth.gps.caltech.edu/winter-storm-2**

SCIENTIFIC AMERICAN ONLINE
For a historical account that details how extensively the 1861–62 megaflood devastated California, see **ScientificAmerican.com/jan2013/atmospheric-rivers**

NEUROSCIENCE

A Confederacy of Senses

Our many different senses collaborate even more than previously realized. What we hear depends a lot on what we see and feel

By Lawrence D. Rosenblum

IN THE LATE 1970S THE FBI HIRED SUE THOMAS, ALONG WITH EIGHT OTHER DEAF INDIVIDUALS, TO ANALYZE fingerprint patterns. Deaf people, the agency reasoned, might have an easier time staying focused during the notoriously meticulous task. From the first day, however, Thomas found the job unbearably monotonous. She complained to her superiors so often that she was prepared to walk away unemployed when her boss summoned her to a meeting with other agents in his office.

But Thomas was not fired—she was, in a sense, promoted. The agents showed her a silent video of two criminal suspects conversing and asked her to decipher their conversation.

In their own interactions with Thomas, the agents had noticed how deftly she read their lips. As her co-workers anticipated, Thomas easily interpreted the suspects' dialogue, which implicated them in an illegal gambling ring. So began Thomas's career as the FBI's first deaf lipreading expert.

A lifetime's dependence on lipreading to communicate had honed Thomas's skill, but we all rely on the same talent more than we know. In fact, our ability to understand speech is diminished if we cannot see the lips of the speaker, especially in a noisy environment or when the speaker has a thick accent that is foreign to us. Learning to perceive speech with our eyes, as well as our ears, is an important part of typical speech development; as a consequence, blind infants—who cannot see the mouths of speak-

IN BRIEF

Neuroscientists used to think of the brain as a Swiss Army knife with different regions dedicated exclusively to different forms of sensory perception, such as sight, hearing, smell, taste and touch.

In the past three decades studies in psychology and neuroscience have revealed that the brain is an extensively multisensory organ that constantly melds information from the various senses.

The multisensory revolution has not only changed the way scientists understand the function of the brain, it has also suggested new ways to help the blind and deaf and has improved speech-recognition software.

Illustration by Kyle Bean

ers around them—often take longer than average to learn certain aspects of speech. We simply cannot help but integrate the words we see on another's lips with the words we hear. In recent years research on multisensory speech perception has helped bring about a revolution in our understanding of how the brain organizes the information it receives from our many different senses.

Neuroscientists and psychologists have largely abandoned early ideas of the brain as a Swiss Army knife, in which many distinct regions are dedicated to different senses. Instead scientists now think that the brain has evolved to encourage as much cross talk as possible between the senses—that the brain's sensory regions are physically intertwined.

Our senses are always eavesdropping on one another and sticking their noses in one another's business. Although the visual cortex is primarily concerned with vision, for example, it is perfectly capable of interpreting other sensory information as well. Within 90 minutes of being blindfolded, a seeing person becomes extra sensitive to touch via the visual cortex; likewise, brain scans have shown that blind people's visual cortices rewire themselves for hearing. When we snack on potato chips, the crispness of our crunching partially determines how good we think the chips taste—and researchers can bias the results of taste tests by tweaking what people hear. Where we look when we stand still, and what we see, shapes our whole body posture. Put simply, research in the past 15 years demonstrates that no sense works alone. The multisensory revolution is also suggesting new ways to improve devices for the blind and deaf, such as cochlear implants.

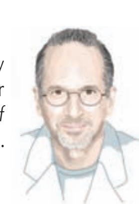
SILENT SYLLABLES

ONE OF THE EARLIEST and most robust examples of multisensory perception is known as the McGurk effect, first reported by Harry McGurk and John MacDonald in 1976. If you watch a video clip of someone silently and repeatedly mouthing the syllable "ga" while you listen to a recording of the same person speaking the syllable "ba," you will hear them pronouncing "da." The silent "ga" syllables change your perception of the audible "ba" syllables because the brain integrates what the body hears and sees. The McGurk effect works in all languages and continues to work even if you have been studying it for 25 years—I can vouch for that myself.

The speech you hear is also influenced by the speech you feel. In 1991 Carol Fowler, then at Dartmouth College, and her colleagues asked naive volunteers to try something called the Tadoma technique, in which you interpret someone's speech by placing your fingers on their lips, cheek and neck. Before cochlear implants, many deaf-blind individuals (including Helen Keller) relied on Tadoma. The syllables the volunteers felt changed how they interpreted syllables coming from nearby loudspeakers.

In 1997 Gemma Calvert, then at the University of Oxford, mapped the areas of the brain that are most active during lipreading. Volunteers with no formal lipreading experience silently lipread a face that slowly articulated the numbers one through nine. Calvert and her colleagues found that lipreading fired up the auditory cortex—the region of the brain that processes sounds—as well as related brain regions known to be active when someone hears speech. This was one of the first demonstrations of cross-sensory influences on an area of the brain thought to be dedicated to a single sense. More recent studies have contributed further evidence of sensory synthesis. For example, scientists now know that the auditory brain stem responds to aspects of

Lawrence D. Rosenblum is a professor of psychology at the University of California, Riverside, and author of *See What I'm Saying: The Extraordinary Power of Our Five Senses* (W. W. Norton, 2010).



seen speech, whereas before they thought it was involved only in more rudimentary processing of sounds. Neuroimaging studies have shown that during the McGurk effect—hearing "da" even though the recorded sound is "ba"—the brain behaves as though the syllable "da" were falling on that person's ears.

These findings suggest that the brain may give equal weight to speech gleaned from the ears, the eyes and even the skin. This is not to say that these distinct modalities provide an equal amount of information: clearly, hearing captures more articulatory detail than sight or touch. Rather the brain makes a concerted effort to consider and combine all the different types of speech information it receives, regardless of modality.

WRITTEN ALL OVER YOUR FACE

IN OTHER INSTANCES, distinct senses help one another process the same type of information. The specific manner in which a person speaks, for example, provides information about who they are, regardless of whether their speech is seen or heard. My colleagues and I film people speaking and manipulate the resulting videos to remove all recognizable facial features—transforming faces into patterns of glowing dots that dart and bob like fireflies where someone's cheeks and lips would have appeared. When we play the videos, our volunteers can lipread these faceless cluster of dots and recognize their friends.

Simple sounds derived from speech can also clue us in to a person's identity. Robert Remez of Columbia University and his colleagues reduce normal speech recordings to sine waves that sound something like the whistles and bloops emitted by R2-D2 in *Star Wars*. Despite missing the typical qualities that distinguish voices such as pitch and timbre, these sine waves retain speaking-style information that allows listeners to recognize their friends. Most strikingly, volunteers can match these sine waves to glowing dot videos of the same person talking.

The fact that stripped-down versions of both heard and seen speech preserve similar information about speech style suggests that these distinct modes of perception are entangled in the brain. Neuroimaging research supports this connection: listening to the voice of someone familiar induces neural activity in the fusiform gyrus, an area of the human brain involved in recognizing faces.

These findings inspired an even more outlandish prediction. If these forms of perception are mingled, then learning to read someone's lips should simultaneously improve one's ability to hear his or her spoken words. We asked volunteers with no lipreading experience to practice lipreading silent videos of someone speaking for one hour. Afterward, the volunteers listened to a set of spoken sentences played against a background of random noise. Unbeknownst to them, half the participants listened to sentences spoken by the same person they had just lipread, whereas the other half heard sentences from a different speaker. The volunteers who lipread and listened to the same person

PAGE 72: PHOTOGRAPHY BY VICTORIA LING

were more successful at picking out the sentences from the noise.

PROMISCUOUS PERCEPTION

RESEARCH ON multisensory speech perception has helped inspire scientists to investigate all kinds of previously unstudied interactions between the senses. For example, most of us know that smell is a big component of taste, but some research shows that sights and sounds also change flavor. In a particularly striking example, scientists found that an orange-flavored drink will taste of cherry if it is tinted red, and vice versa. In 2005 Massimiliano Zampini of the University of Trento in Italy and his teammates showed that altering the timbre of a crunching sound played to volunteers as they ate potato chips partially determined how fresh and crisp the chips tasted. Looking at a continuously descending visual texture—such as a waterfall—convinces people that certain textured surfaces they feel with their hands are ascending. Other evidence shows that cross-sensory input unconsciously changes our behaviors. Tom Stoffregen of the University of Minnesota and his colleagues asked volunteers to stand straight and shift their gaze from a nearby target to a distant one. This simple shift in visual focus induced subtle but systematic changes in body posture.

Similar findings have become so prevalent that many researchers now think of the sensory regions of the brain as inherently multisensory. This revised model of the brain is also consistent with evidence of the brain's incredible plasticity—it can switch up a region's primary function when faced with even short-term or subtle sensory deprivation. For example, imaging research in the past four years has confirmed that blindfolding a person for as little as one and a half hours primes their visual cortex to respond to touch. In fact, the visual cortex's involvement actually heightens sensitivity to touch. In a related example, nearsightedness often enhances people's auditory and spatial skills even if they wear glasses (which leave a good part of the visual periphery blurry). In general, cross-sensory compensation is much more prevalent than we previously thought.

The multisensory revolution has already started to help people who have lost one of their primary senses. Research has shown, for example, that cochlear implants are less effective if someone's brain has had too much time to repurpose the neglected auditory cortex for other forms of perception, such as vision and touch. It is generally recommended, therefore, that congenitally deaf children receive cochlear implants as soon as possible. Similar research has encouraged the practice of having deaf children who have received cochlear implants watch videos of people speaking so that they learn how to integrate the speech they see on someone's lips with the speech they hear.

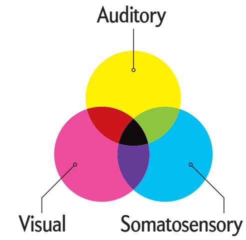
Engineers working on face- and speech-recognition devices have benefited from research on multisensory perception, too. Speech-recognition systems often perform poorly when faced with even moderate levels of background noise. Teaching such systems to analyze video footage of someone's mouth substantially increases accuracy—a strategy that works even with the types of cameras commonly installed in cell phones and laptops.

In some ways, the notion of multisensory perception seems to contradict our everyday experiences. Our instinct is to organize the senses into types because each sense seems to apprehend a very different aspect of our world. We use our eyes to see others and our ears to hear them; we feel the firmness of an apple with our hands but taste it with our tongue. Once sensory information reaches the brain, however, such strict classification crumbles. The brain does not channel visual information from the eyes into one neural container and auditory information from the ears into another, discrete, container as though it were sorting coins. Rather our brains derive meaning from the world in as many ways as possible by blending the diverse forms of sensory perception. ■

PERCEPTION

A Multisensory Makeover

Scientists have known for a few decades that certain brain regions integrate information from distinct senses. One region might, for example, meld visual information with somatosensory perception, such as touch and temperature. It now turns out that multisensory perception is a much more prevalent aspect of the brain's neural architecture than researchers realized, suggesting that the brain evolved to encourage such sensory cross talk.



Traditional Scheme **Emerging Scheme**

These illustrations were extrapolated in part from data on primate brains. Only primary sensory areas are represented.

SOURCE: "IS NEOCORTEX ESSENTIALLY MULTISENSORY?" BY ASIF A. GHAZANFAR AND CHARLES E. SCHROEDER, IN *TRENDS IN COGNITIVE SCIENCES*, VOL. 10, NO. 6; JUNE 2006 (*emerging scheme*); UPDATED PER LAWRENCE D. ROSENBLUM, AARON R. SEITZ AND KHALEEL A. RAZAK

MORE TO EXPLORE

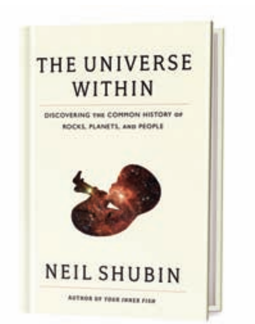
Speech Perception as a Multimodal Phenomenon. Lawrence D. Rosenblum in *Current Directions in Psychological Science,* Vol. 17, No. 6, pages 405–409; December 2008.

The New Handbook of Multisensory Processing. Edited by Barry E. Stein. MIT Press, 2012.

SCIENTIFIC AMERICAN ONLINE
View a demonstration of the McGurk effect and other videos about multisensory perception at **ScientificAmerican.com/jan2013/multisensory-perception**

Illustration by AXS Biomedical Animation Studio

BOOKS



The Universe Within: Discovering the Common History of Rocks, Planets, and People

by Neil Shubin. Pantheon Books, 2013 ($25.95)

Biologist Shubin's grand tour of human origins goes beyond the well-worn Carl Sagan line, "We're made of star stuff." Shubin, whose last best seller discussed how humans evolved from fish, focuses on our molecular composition as it relates to Earth and the cosmos: our bodies are mostly hydrogen, which formed during the big bang; carbon came from the fusion reactions inside stars; algae most likely gave rise to the oxygen we breathe. Even those familiar with the basic underpinnings of how we evolved will find *The Universe Within* engaging. It is laced with Shubin's own fossil-hunting adventures and filled with colorful tales of historical figures, such as Henrietta Leavitt, who discovered a way to measure a star's distance from Earth, and Galileo's lesser-known writings on how gravity dictates an organism's shape.

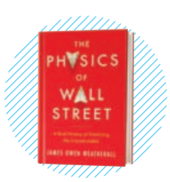
Drawn from Paradise: The Natural History, Art and Discovery of the Birds of Paradise

by David Attenborough and Errol Fuller. Harper Design, 2012 ($45)

British broadcaster Attenborough has narrated some of the most spectacular footage ever captured of the elaborate mating dances of birds of paradise. In this coffee-table book, he and Fuller describe how these ornate birds from New Guinea first came to the attention of Europeans in the early 16th century and how Westerners have studied and depicted them since that time.

Male black sicklebill

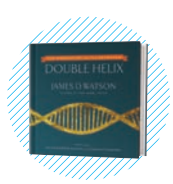
> ***"By weight, we contain such a large amount of oxygen and carbon that we are virtually unique in the known universe."***
> **—From *The Universe Within***



The Physics of Wall Street: A Brief History of Predicting the Unpredictable

by James Owen Weatherall. Houghton Mifflin Harcourt, 2013 ($27)

Weatherall, a doctoral student in physics and math at the time of the 2007–2008 financial crisis, delves into the question of how physics and finance came together. In clear, lively prose, he traces the evolution of the mathematical ideas behind derivatives and hedge funds, from the early papers of a student working on the floor of the Paris Bourse at the end of the 19th century to the late fractal geometry founder Benoît Mandelbrot's thoughts on the randomness of cotton prices. Weatherall argues that the blame for the financial collapse lies not with sophisticated mathematical models but with those who misused them. Economists and physicists must work together to prevent future crises.



The Annotated and Illustrated Double Helix

by James D. Watson. Edited by Alexander Gann and Jan Witkowski. Simon and Schuster, 2012 ($30)

Watson's 1968 account of the race to identify the structure of DNA remains one of the best science memoirs ever written. This new annotated edition features letters, photographs and other documents from the period of Watson, Francis Crick and Maurice Wilkins's Nobel Prize–winning discovery. Among the highlights: letters exchanged by some of the major players, including x-ray crystallographer Rosalind Franklin, who had a famously difficult relationship with Wilkins and Watson, testify to the intense, competitive atmosphere of the time. In one letter, Franklin confides to a friend that she finds many of her colleagues "positively repulsive."

FROM OUR AUTHORS

Mastermind: How to Think Like Sherlock Holmes

by Maria Konnikova. Viking, 2013 ($26.95)

Konnikova, author of the *Scientific American* blog Literally Psyched, has been fascinated by Sherlock Holmes since the days when her father read aloud to her from Conan Doyle's classic mysteries. Now a Ph.D. candidate in psychology, she examines Holmes's powers of perception and problem solving through the lens of her discipline. The book is part literary analysis and part self-help guide, teaching readers how to sharpen the ways they observe the world, store and retrieve memories, and make decisions.

COURTESY OF DAVID ATTENBOROUGH AND ERROL FULLER

COMMENT AT ScientificAmerican.com/jan2013

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

Logic-Tight Compartments

How our modular brains lead us to deny and distort evidence

If you have pondered how intelligent and educated people can, in the face of overwhelming contradictory evidence, believe that evolution is a myth, that global warming is a hoax, that vaccines cause autism and asthma, that 9/11 was orchestrated by the Bush administration, conjecture no more. The explanation is in what I call logic-tight compartments—modules in the brain analogous to watertight compartments in a ship.

The concept of compartmentalized brain functions acting either in concert or in conflict has been a core idea of evolutionary psychology since the early 1990s. According to University of Pennsylvania evolutionary psychologist Robert Kurzban in *Why Everyone (Else) Is a Hypocrite* (Princeton University Press, 2010), the brain evolved as a modular, multitasking problem-solving organ—a Swiss Army knife of practical tools in the old metaphor or an app-loaded iPhone in Kurzban's upgrade. There is no unified "self" that generates internally consistent and seamlessly coherent beliefs devoid of conflict. Instead we are a collection of distinct but interacting modules often at odds with one another. The module that leads us to crave sweet and fatty foods in the short term is in conflict with the module that monitors our body image and health in the long term. The module for cooperation is in conflict with the one for competition, as are the modules for altruism and avarice or the modules for truth telling and lying.

Compartmentalization is also at work when new scientific theories conflict with older and more naive beliefs. In the 2012 paper "Scientific Knowledge Suppresses but Does Not Supplant Earlier Intuitions" in the journal *Cognition,* Occidental College psychologists Andrew Shtulman and Joshua Valcarcel found that subjects more quickly verified the validity of scientific statements when those statements agreed with their prior naive beliefs. Contradictory scientific statements were processed more slowly and less accurately, suggesting that "naive theories survive the acquisition of a mutually incompatible scientific theory, coexisting with that theory for many years to follow."

Cognitive dissonance may also be at work in the compartmentalization of beliefs. In the 2010 article "When in Doubt, Shout!" in *Psychological Science,* Northwestern University researchers David Gal and Derek Rucker found that when subjects' closely held beliefs were shaken, they "engaged in more advocacy of their beliefs ... than did people whose confidence was not undermined." Further, they concluded that enthusiastic evangelists of a belief may in fact be "boiling over with doubt," and thus their persistent proselytizing may be a signal that the belief warrants skepticism.

In addition, our logic-tight compartments are influenced by our moral emotions, which lead us to bend and distort data and evidence through a process called motivated reasoning. The module housing our religious preferences, for example, motivates believers to seek and find facts that support, say, a biblical model of a young earth in which the overwhelming evidence of an old earth must be denied. The module containing our political predilections, if they are, say, of a conservative bent, may motivate procapitalists to believe that any attempt to curtail industrial pollution by way of the threat of global warming must be a liberal hoax.

What can be done to break down the walls separating our logic-tight compartments? In the 2012 paper "Misinformation and Its Correction: Continued Influence and Successful Debiasing" in *Psychological Science in the Public Interest,* University of Western Australia psychologist Stephan Lewandowsky and his colleagues suggest these strategies: "Consider what gaps in people's mental event models are created by debunking and fill them using an alternative explanation.... To avoid making people more familiar with misinformation..., emphasize the facts you wish to communicate rather than the myth. Provide an explicit warning before mentioning a myth, to ensure that people are cognitively on guard and less likely to be influenced by the misinformation.... Consider whether your content may be threatening to the worldview and values of your audience. If so, you risk a worldview backfire effect."

Debunking by itself is not enough. We must replace bad bunk with sound science. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/jan2013

Illustration by Mark Jarman

Anti Gravity by Steve Mirsky

The ongoing search for fundamental farces

Steve Mirsky has been writing the Anti Gravity column since Cheshvan 5756. He is a shver arbeter, according to him, who also hosts the *Scientific American* podcast Science Talk.

Voyage of the Bagel

An interesting effort to insult Darwin uses a cream cheese smear

In late October the *Financial Times* published a report about an interesting pedagogical exercise being perpetrated by creationists in Turkey: "A series of books for primary schoolchildren, describing Charles Darwin as a Jew with a big nose who kept the company of monkeys and other historical figures in anti-Semitic terms, has caused outrage in Turkey amid fears of rising religious intolerance."

This attempt to insult Darwin by categorizing him as Jewish surprised me because I thought everyone always knew Darwin was "a member of the tribe." I attended Hebrew school in preparation for my bar mitzvah, and the classroom featured pictures of our top-three historical figures: Abraham, Moses and Darwin. (There was also a small photograph of Paul Newman, who was half-Jewish.) We learned how Darwin received a fantastic bar mitzvah gift of a five-year ocean cruise on the HMS *Beagle.* I got savings bonds.

Though common knowledge in the Jewish community, Darwin's Judaic background seems to be a shock to many non-Jews. I have only just learned, for example, that most readers of Darwin's many publications do not know that the versions with which they are familiar are highly edited. The great evolutionist wrote in a very particular Jewish style, which his Victorian publisher then revised into highbrow 19th-century English.

For example, Darwin's printed autobiography includes these lines about the captain of the *Beagle:* "Fitzroy's temper was a most unfortunate one. It was usually worst in the early morning, and with his eagle eye he could generally detect something amiss about the ship, and was then unsparing in his blame." But Darwin's original version, written on cocktail napkins during meetings of the Shrewsbury Beth Israel synagogue's building committee, reads: "Don't get me started on Fitzroy and his meshuggaas. This meshuggener had a bed with only a wrong side because that's what he always woke up on. Always looking for tsuris. What a schmuck."

The Voyage of the Beagle, Darwin's account of the cruise, includes this passage: "The different islands to a considerable extent are inhabited by a different set of beings. My attention was first called to this fact by the Vice-Governor, Mr. Lawson, declaring that the tortoises differed from the different islands, and that he could with certainty tell from which island any one was brought." The original writing, scratched out on sheets listing the ship's leisure activities, reads: "I listened to Lawson's whole spiel, and he says if you show him a turtle, abracadabra, he'll tell you its shtetl. I buy it."

Perhaps the most famous passage in all of Darwinia is at the end of the first edition of *On the Origin of Species:* "There is grandeur in this view of life, with its several powers, having been originally breathed into a few forms or into one; and that, whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved."

In his manuscript for the book, which had been entitled *L'Chaim: The Whole Megillah,* Darwin concludes: "Such nachas I get when I wander around and look at turtles and birds, let me tell you. It is not a waste of time that could be spent doing something more productive. What, you think I schlepped up mountains in South America glomming insects for my health? And so the planet spins no matter what plans you had for it, big shot. And you start with a few things that are maybe a little mieskeit, but then, be patient. What, you have somewhere to be? So you wait until genug iz genug, and, guess what, you wind up with new things, some of which are really nice, with a shayna punim. Why that should be a problem, I don't know."

So of course, Darwin was Jewish. Why that fact should in any way diminish the intellectual achievement of his evolution insights is beyond me. His ideas stand on their own merits and would be no less brilliant were he, say, Anglican, or someone who came to hold no religious beliefs at all. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/jan2013

Illustration by Matt Collins

January 1963

Cold War

"Premier Khrushchev, in a note of congratulation on John H. Glenn's orbital flight, had suggested last February that the U.S. and the U.S.S.R. pool some of their space-research efforts. President Kennedy answered by proposing co-operation in space medicine, weather satellites, communications satellites, mapping the earth's magnetic field and tracking space vehicles. Last June, Soviet rocket expert Anatoli A. Blagonravov and Hugh L. Dryden, Deputy Administrator of the National Aeronautics and Space Administration, met and drew up recommendations for specific joint programs in three of those areas. After approval by both governments—and a short delay caused by the Cuban crisis—the agreement was announced during the U.N. debate on the peaceful uses of outer space."

January 1913

Motorcar Musings

"The automobile of the future will look no more like the motor car of to-day than the limousine of 1913 looks like the dos-à-dos of 1896. The limousine or torpedo touring car of the present year is but a link in the gradual transformation of the horse-drawn buggy into the completely enclosed, dust-proof, silent and comfortable 'car of the future.' In outward appearance the car resembles a submarine boat more than it does a carriage. Its long cigar-shaped body encloses everything except the wheels [*see illustration*]."

Piltdown Man

"In Piltdown Common, Sussex, England, an English paleontologist, Mr. Dawson, discovered, about a year ago, a fairly complete human skull representing the most ancient relic of the human race in the British Isles, and one of the oldest found anywhere. The Piltdown skull might be said to stand about half way between the gorilla and modern man—neglecting the fact that the gorilla is more massive in body than man. Nevertheless, the Piltdown skull represents a considerably higher type, it seems, than the Neanderthal race, which has a much more slanting forehead. It appears, therefore, that at least one very low type of man with a comparatively high forehead was in existence in western Europe long before the low-browed Neanderthal man became widely spread in this region."

Doubts lingered about the fossils, and in 1953 three British scientists conclusively proved that Piltdown Man was a hoax.

January 1863

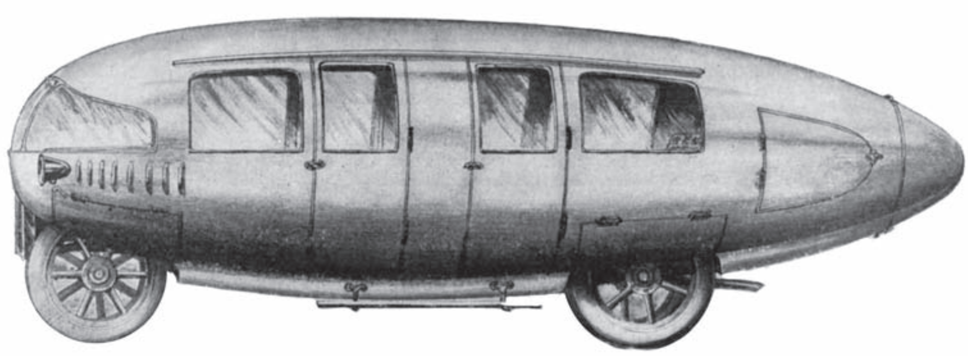
Crime Hysteria

"The *London Daily News* says that the garotte panic is very widespread in that great city, and is driving the citizens to very ridiculous measures for protection. Revolvers and bowie-knives are simple weapons compared with the dangerous arms which some self-defenders carry. Bludgeons that shoot out bayonets and sticks that contain daggers and swords are now sold more openly in the city streets than oranges or chestnuts. Meetings have been held and anti-garotte societies formed for mutual protection. However, despite these precautions, garotte robberies seem to be on the increase, and all London, that is all moneyed London, is in turmoil and alarm."

Information from Light

"Recent scientific discoveries have conferred upon man new powers of investigation, whereby nature has been made to reveal secrets so subtile that they never had been dreamt of before in philosophy. Sir Isaac Newton first dissected a ray of light, and proved that it was composed of several colors, but the subject has recently been elevated into a special science, called 'spectral analysis,' by the splendid discoveries of the two German professors—Kirchoff and Bunsen. Professor Kirchoff used four prisms of very perfect workmanship to examine the solar spectrum through a telescope having a magnifying power of 40. He saw whole series of nebulous bands and dark lines, and a new field of vision, like that first developed by the microscope, was opened up. These dark lines it is conjectured have been made to reveal the chemical composition of the sun's atmosphere."

NOTE: 150 years after Abraham Lincoln's Emancipation Proclamation, take a look at Scientific American's *views back then on the institution of slavery at* ***www.ScientificAmerican.com/jan2013/slavery***

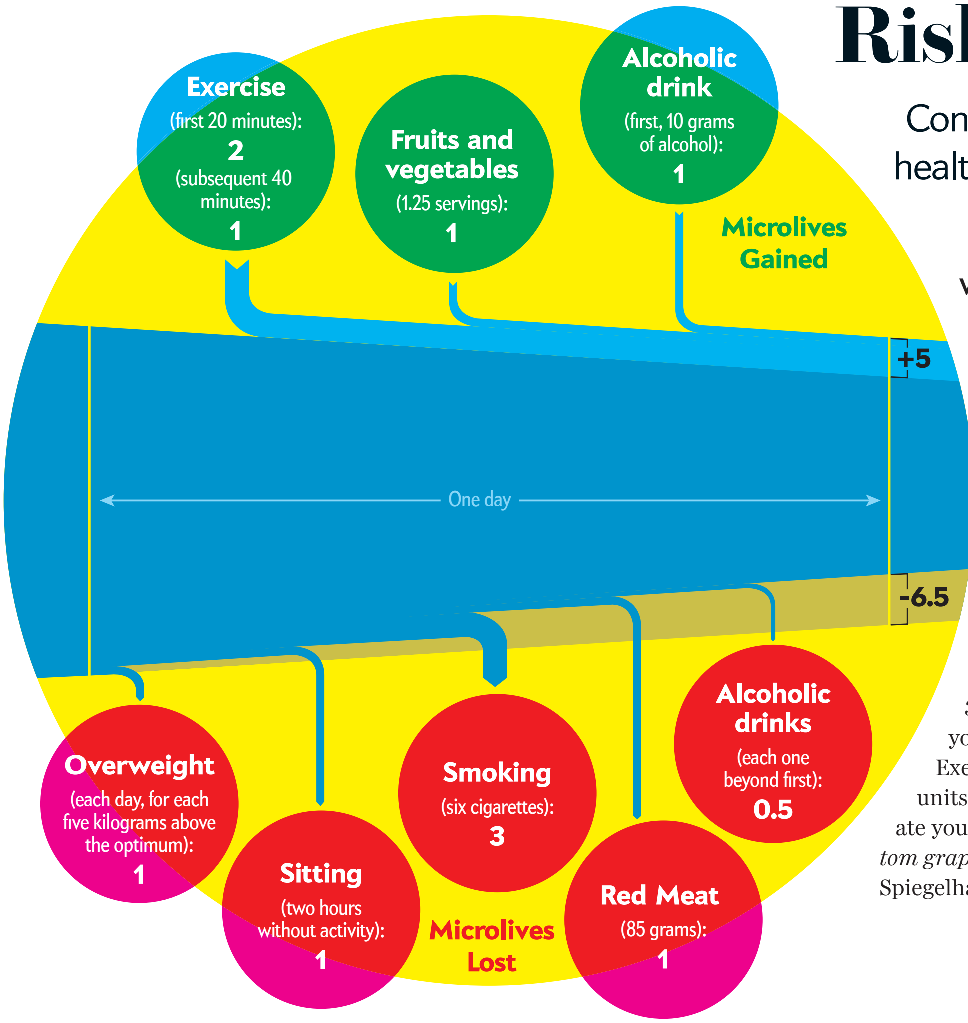


CAR OF THE FUTURE, from the vantage of 1912

SCIENTIFIC AMERICAN, VOL. CVIII, NO. 2; JANUARY 11, 1913

The True Cost of Risky Behavior

Consequences of good and bad health habits are boiled down to 30-minute slices of your life

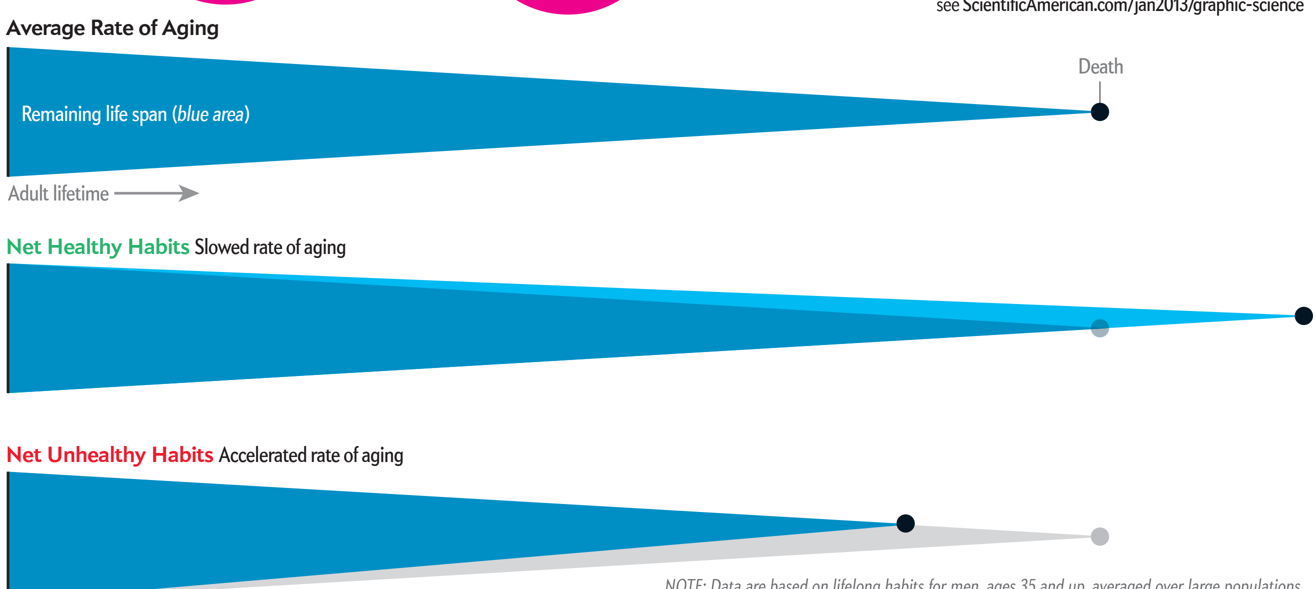


We all know that smoking is bad for our health and that eating vegetables is good for it. Yet *how* bad and *how* good are they? Without a clear notion of threat and reward, it is that much harder to avoid a cigarette or to choke down a serving of broccoli. "I hate when someone tells me that something is risky," says David Spiegelhalter, a professor of risk assessment at the University of Cambridge. "Well, compared to *what?*"

To answer his own question, Spiegelhalter converted reams of statistical risk tables into a simple metric: a microlife—30 minutes. If you smoke two cigarettes, you lose 30 minutes of your life (*top graphic*). Exercise for 20 minutes, and you gain two units of microlife. Over time bad habits accelerate your aging, and good habits slow it down (*bottom graphic*). "That seems to resonate with people," Spiegelhalter says. "No one likes to get older faster."

—*Mark Fischetti*

SCIENTIFIC AMERICAN ONLINE
For a video about your risk of immediate death, see ScientificAmerican.com/jan2013/graphic-science



NOTE: Data are based on lifelong habits for men, ages 35 and up, averaged over large populations. Data for women are similar. No loss or gain can be attributed to a single event, such as one cigarette or one exercise session.

SOURCE: DAVID SPIEGELHALTER *Statistical Laboratory, University of Cambridge*

Graphic by Jen Christiansen