PARTICLE PHYSICS
How Do Gluons Bind Matter?

MEDICINE
Lifting the Curse of Alzheimer's

COMPUTING
Innovating Beyond Moore's Law

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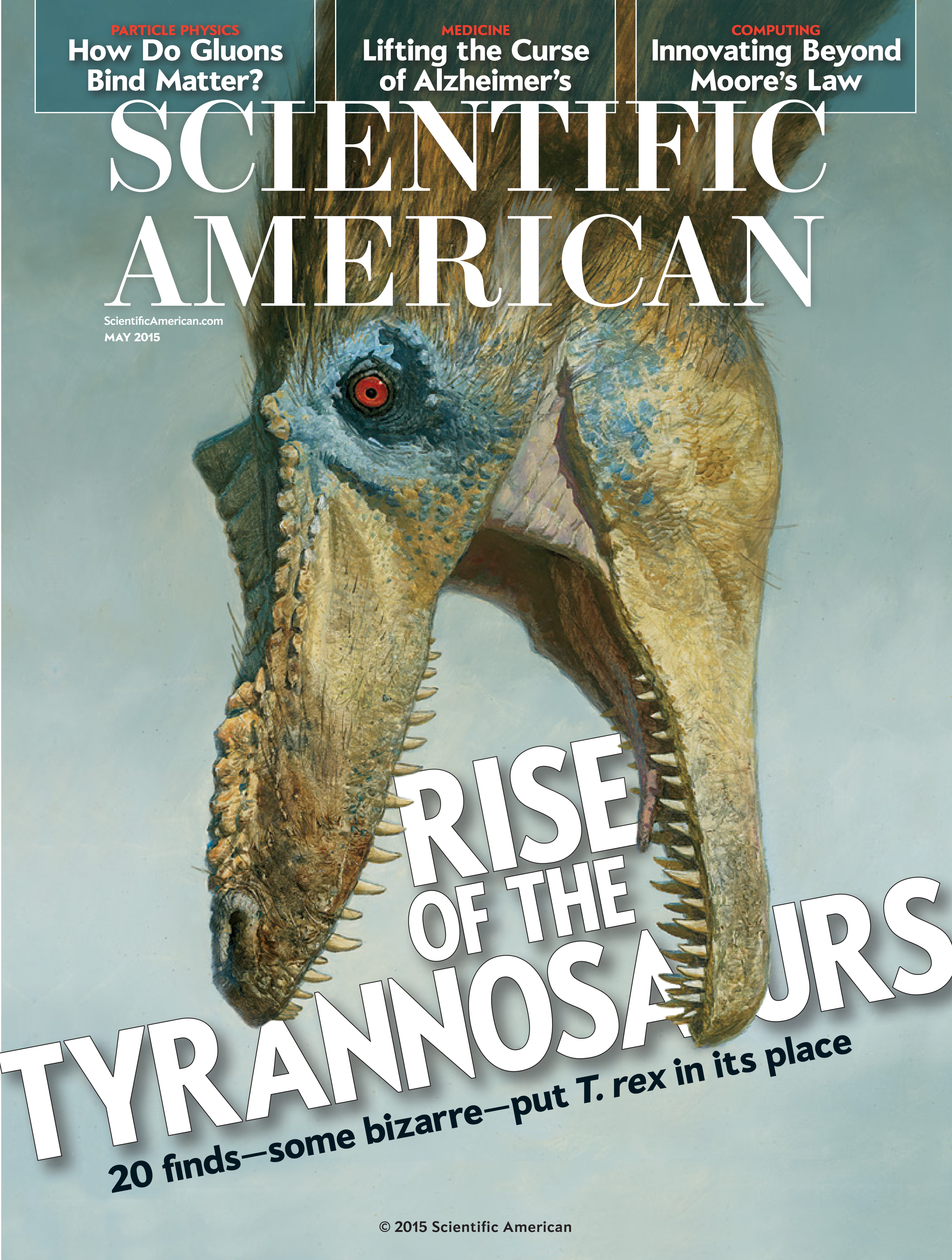
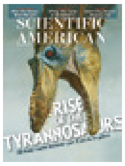


RISE OF THE TYRANNOSAURS

20 finds—some bizarre—put *T. rex* in its place



Qianzhousaurus, which was discovered at a Chinese construction site, is one of the most recent additions to the family tree of tyrannosaurs. Such finds are revolutionizing paleontologists' understanding of the origin and evolution of this group. They reveal that a startling variety of tyrannosaurs roamed the earth right up until the end of the Age of Dinosaurs. Illustration by James Gurney.

SCIENTIFIC AMERICAN

May 2015 Volume 312, Number 5

PIM VUIK *Gallery Stock*

FEATURES

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DEPARTMENTS

ON THE WEB

Deepwater Horizon Oil Spill: Five Years Later
Our In-Depth Report revisits the environmental disaster half a decade on, covering what became of the missing oil, how microbes helped to clean up the spill and what the long-term effects on marine life are.
Go to www.ScientificAmerican.com/may2015/bp-anniversary

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CHRISTOPHER MARLEY (*insects*)

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

Rise of the Tyrants

"Go ahead and pick one up if you like." It was 1996. In front of me was a box of fossils, many millions of years old. I was visiting the laboratory of Paul Sereno, a University of Chicago paleontologist, while reporting a feature article. Reaching in, I lifted a sepia-tinted bone, about six inches long and blade-shaped. It was oddly heavy in my hand from the mineralization that had occurred over millennia. I ran my thumb along one side. Oops—still quite sharp! Instantly my mind conjured a mouthful of these remorseless fangs in a human-sized skull owned by a *Tyrannosaurus rex.* A chill ran up my spine.

How did *T. rex* become the towering predator of the Cretaceous? As paleontologist Stephen Brusatte writes in this issue's cover story, "Rise of the Tyrannosaurs," starting on page 34, in the past 15 years nearly 20 new finds have been remaking our understanding of this theropod ("beast-footed") dinosaur. "The king of the dinosaurs," Brusatte asserts, "far from belonging to a dynasty of giant predators, actually had rather humble roots and was merely the last survivor of a startling variety of tyrannosaurs that lived across the globe right up until the asteroid impact 66 million years ago that brought the dinosaur era to a close and ushered in the Age of Mammals."

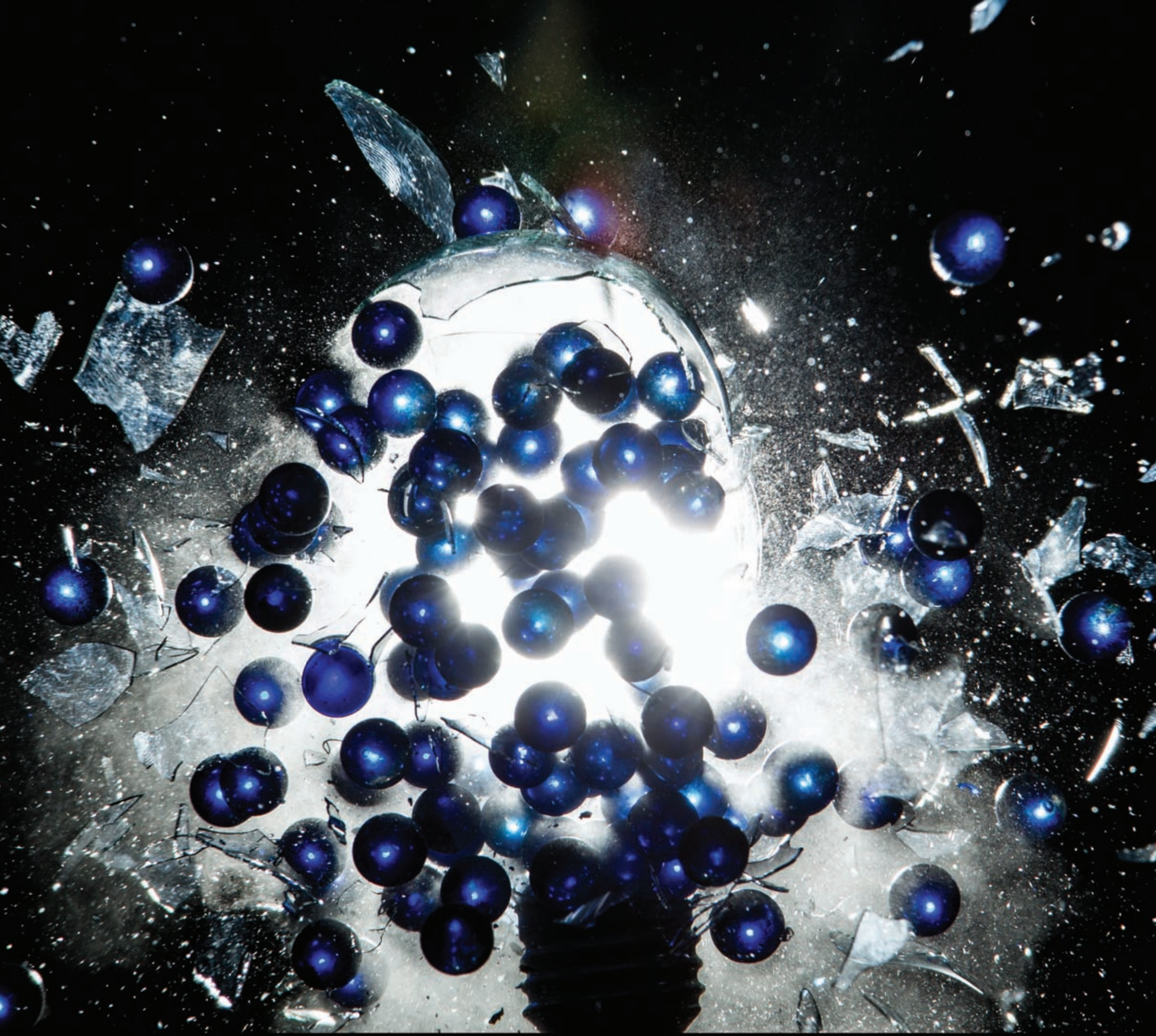
Considering the rise and fall of the "tyrant lizard," I suppose I will not be the only one to recall Romantic poet Percy Bysshe Shelley's famous sonnet "Ozymandias," which is about an ancient king whose once great works have all been erased over the passage of a vast span of time. In light of the monumental achievements and current challenges of our own species, it does make me thoughtful. SA

CITIZEN SCIENCE

Entries Due Soon

The Google Science Fair is open until May 19 for entries by individuals or teams of up to three students ages 13 through 18. As I have done every year since the global competition began in 2011, I am honored to serve as chief judge. *Scientific American* is a founding partner and this year is funding two prizes: the $25,000 Innovator Award for projects in biology, chemistry, physics, or the behavioral or social sciences and the $10,000 Community Impact Award to recognize research that makes a practical difference by addressing an environmental, health or resources challenge; winners also get a year's worth of mentoring to further their endeavors. As always, I am looking forward to seeing the inspiring work of our world's fine young minds. *—M.D.*

Illustration by Nick Higgins



editors@sciam.com

January 2015

"Humanity has always busied itself resolving rather than avoiding problems."

MATT TOBLER *FORT COLLINS, COLO.*

CLIMATE GEOENGINEERING

I believe that in "A Hacker's Guide to Planet Cooling" [Science Agenda], the editors support the wrong approach to fixing our climate woes when they argue for experiments involving geoengineering methods such as fertilizing the ocean with iron to stimulate plankton growth.

Iron fertilization seems a bad idea: it alters the food chain and water chemistry, whereas the sequestration of carbon dioxide is only temporary. An "all hands on deck" approach will most certainly be warranted, but I find geoengineering and similar heavy-handed or fanciful solutions to climate change counterintuitive. Humanity has always busied itself resolving rather than avoiding problems.

Maybe an equal or greater focus should be on limiting population growth, reducing consumption, fostering clean energy, increasing science education, electing scientifically literate politicians, living closer to the earth and fostering an environmental value set in our society.

Matt Tobler
Fort Collins, Colo.

Environmentalists opposed to geoengineering our planet's atmosphere should welcome a recent paper in *Science* that shows that iron fertilization is both natural and effective.

The March 21, 2014, study by Alfredo Martínez-García of the Swiss Federal Institute of Technology in Zurich and his colleagues shows that during the last ice age, iron-rich dust blowing off the Southern Hemisphere's continents maintained high plankton levels in the Southern Ocean, which explains a large reduction of atmospheric carbon dioxide.

Bernie Masters
Peppermint Grove Beach, Western Australia

ARCHIPELAGO WORLDS

"Better Than Earth," René Heller's article on habitable super-Earths—planets up to 10 Earth masses larger than our planet with radii between Earth and Neptune—states that a planet with a higher mass, and therefore a flatter surface, and oceans could be an "archipelago world" of island chains more conducive to biodiversity. But this flatter solid surface, having less distance between its highest and lowest points, would also reduce how much water the planet could harbor without becoming a total water world devoid of any exposed land. Therefore, such a planet's biodiversity could be more sensitive than Earth to its ocean volume and to its climate.

J. Carlos Kuruvilla
via e-mail

HELLER REPLIES: Indeed, the flatter a planet with a given radius, the less water it could have without becoming an ocean world. In an extreme case of a perfectly smooth planet with high surface gravity, a single glass of water could cover the whole world with a nanometer-deep "ocean."

Even so, by virtue of their larger size, super-Earths could support both large oceans and flat topographies. A 1.4-Earth-radii planet with an average ocean depth of two kilometers would have a total ocean volume of two billion cubic kilometers—nearly twice that of Earth's oceans—even with flattened landmasses. Archipelago worlds could have larger ocean volumes than Earth's.

FREE WILL DEBATE

Eddy Nahmias's article "Why We Have Free Will" is oddly devoid of support for the existence of free will. Instead Nahmias argues for a distinction between conscious and unconscious thought and then conflates conscious thought with free will.

If you produced an exact physical duplicate of a time slice of the universe, then everything that is true about what is going on in that first chunk would be true of the duplicate chunk. This concept, rather than any variation on the interaction between conscious and unconscious thought, is what makes free will an illusion.

Victor Likwornik
University of Toronto

Nahmias argues that neuroscientific findings are consistent with our having free will. Yet "free will" is a vague and ambiguous term that is used in diverse ways in law, theology, artificial intelligence and philosophy. And in using it, Nahmias silently shifts around from a concept of self-control to one of consciousness to one of responsibility to one that depends on an opinion poll. What's more, he neglects to address the relativity of free will: our will is free from certain forces and not free from others, and it is free to do certain things and not others.

Paul Saka
McAllen, Tex.

I would suggest the conscious mind is much like an executive of a large organization, delegating the power to make decisions and take action to subordinate "subconscious" neural modules that report back to the executive.

Suppose I tell a student to perform an experiment and bring me the results. The actual results may be known to the student days before they are finally reported to me, but the decision to initiate said experiment was still my decision.

Anthony M. Castaldo
San Antonio, Tex.

SWANK DIVING SUIT

In reporting on a surface-air-pressure diving suit called the Exosuit in the article

"In Search of Sunken Treasure," Philip J. Hilts leaves the reader to view it as new, golly-gee technology.

I am surprised that Hilts does not recognize the JIM suit, an atmospheric-pressure diving suit that was deployed more than 40 years ago and perhaps best known to the general public for its appearance in the James Bond 1981 movie *For Your Eyes Only*. Several other suits followed it.

Ted Agon
Houston, Tex.

HILTS REPLIES: The Exosuit is the latest and most sophisticated in a long line of atmospheric diving suits made to allow people to dive and do work in the deep while at surface pressure. The first one was built in 1715—out of oak. It was essentially a barrel with armholes that were cuffed, and it went to 60 feet.

Phil Nuytten, creator of Nuytco Research's Exosuit, has been developing such suits since the 1970s. He says the difference between the JIM suit and the Exosuit is enormous. For most of its life, the JIM suit had no thrusters to make it mobile. It also had joints on the arms and legs that were difficult to move in deep water, and the electronics were very primitive.

The Exosuit has gyros and sensors so the pilot and the people onboard the surface ship can know its exact position, and it has thrusters that can be controlled by the pilot or from the ship. The Exosuit has many other advances as well, and Nuytten says there are more developments coming, such as a model that swims with fins, completely independent of the surface boat.

ERRATUM

The "Plant Vasculature" section of "Living Large," by Kate Wong, erroneously describes the accompanying micrograph as a section of the stem of a *Ranunculus* plant, with chloroplasts in white. It instead shows a root, and the white objects are food-storing plastids.

CLARIFICATION

Clara Moskowitz's review of "Finding Zero: A Mathematician's Odyssey to Uncover the Origins of Numbers," by Amir D. Aczel [Recommended], referred to mathematics depending on "the numerals 0 through 10." It should have referred to "0 through 9."

LETTERS TO THE EDITOR

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Wooing the Fence-sitters

To get measles vaccine coverage for all, try small nudges to hesitant parents

Powerful measles protection rests on numbers: 92 to 94 percent. That is the portion of people in a community that must be vaccinated to prevent outbreaks of a disease that killed more children around the world in 2013 than car accidents or AIDS. At that immunization level, the virus has trouble finding victims, even the unvaccinated, as shown by both direct experience and models of disease. Libya and Tanzania, for instance, have passed that bar, with vaccination rates of 99 percent. The U.S., dragged down by parents who refuse to vaccinate their kids, has not. Coverage is as low as 86 percent in states such as Colorado and Ohio, and the national average is 91 percent. Last year, as a consequence, 644 people in the U.S. were sickened by measles—more than in any year since 2000. What is to be done to keep things from getting even worse?

Some policy makers have called for new laws that would require MMR (*m*easles, *m*umps and *r*ubella) shots for all school-age children. Eight out of 10 Americans would support such laws, one CNN poll found. But strong-arm tactics would probably backfire and reinforce the antivaccine movement, which is driven by fears that shots cause autism and other side effects. A better way, highlighted by behavioral science research, is to change other parents' hesitant attitudes with little nudges.

Parents who vehemently oppose the shots become even *less* likely to vaccinate when confronted by insistence on vaccine safety, researchers have found. Fortunately, such opponents make up only about 9 percent of adults, according to a recent Gallup poll. Their fear of a vaccine-autism link usually stems from a fraudulent and retracted 1998 *Lancet* study. But experts say there are many more people who do not vaccinate their kids because they are just unsure. For example, 52 percent of adults in the Gallup poll have not made up their mind about vaccines and autism. These fence-sitters could be prodded toward getting shots.

The best route to reach these parents is through their pediatricians, whom surveys show to be one of the most important sources of information about vaccines. When doctors do not stand strongly behind vaccines, refusal rates go up. A 2013 study in *Pediatrics,* for example, found that presenting vaccines as a vague choice (saying, "What do you want to do about shots?") rather than the standard of care ("Well, we have to do some shots") increased the odds of parents refusing almost 18-fold. And informing parents that their child would receive a vaccine at their next scheduled appointment made them more likely to go through with it than if they were merely asked which vaccines they wanted their child to receive.

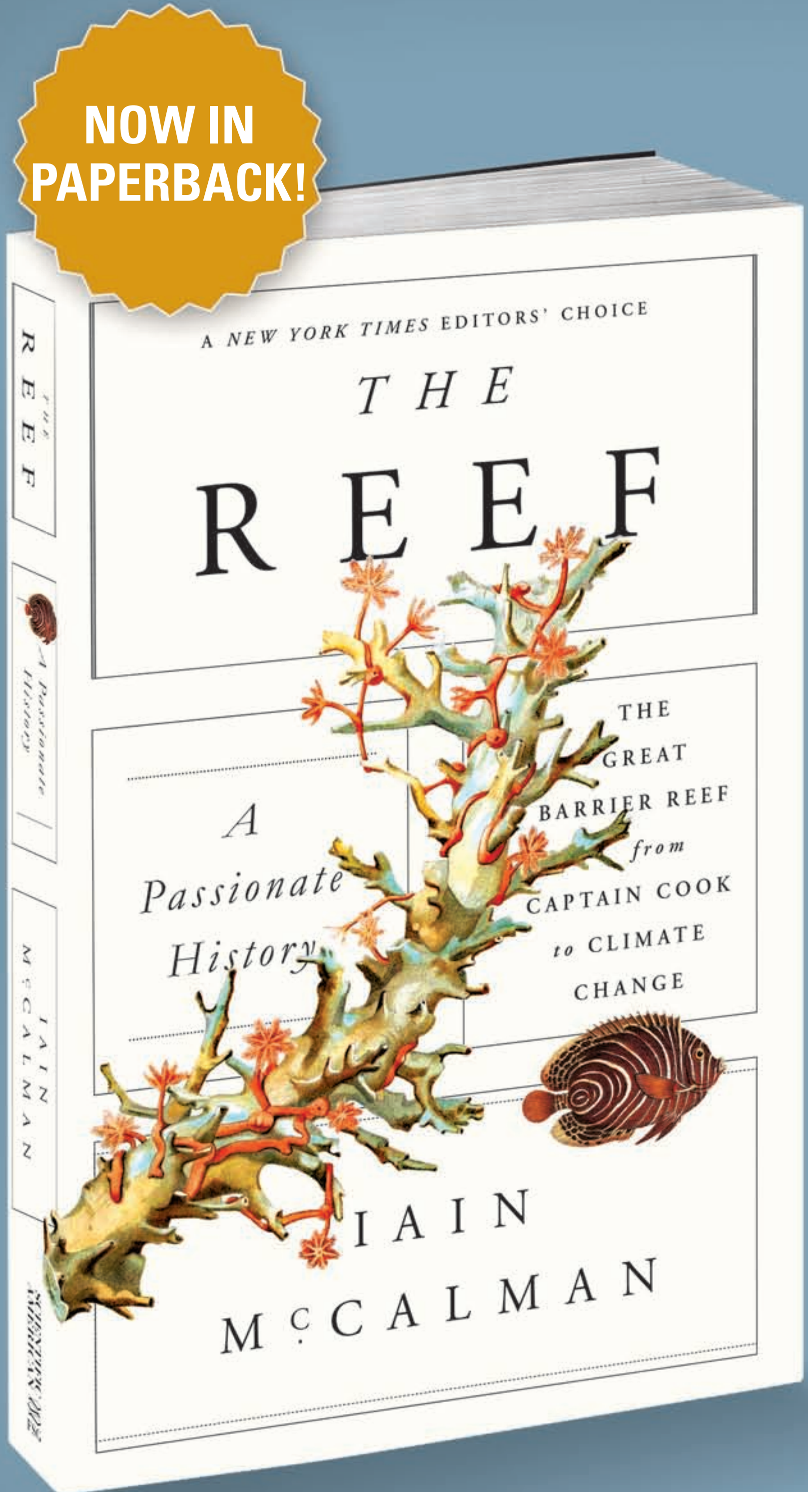
For parents whose distrust of the medical establishment fuels hesitancy about vaccines (roughly 23 percent of the reluctant group), recruiting friends and peers to pass on the message could be more effective. Peer pressure and social norms are one of the strongest influences on the decision to vaccinate or not, scientists reported in 2014 in the *Proceedings of the Royal Society B.* To take advantage of this fact, in Washington State, a public-private pilot program trains provaccine parents to be advocates in their communities. These parents spread the message on social media and speak directly to their neighbors at schools and community events.

Simply asking people to plan ahead is another way to get more of those who are waffling to vaccinate. In a 2011 study, for example, employees at a midwestern utilities firm were sent a letter reminding them that they were eligible for a free flu vaccine. If the letter prompted them to write down both a date and a time for the shot, they were 4.2 percent more likely to get vaccinated than other employees were. (Flu shots are not as controversial as MMR shots, but the important factor is the change in compliance.)

If states begin implementing such interventions and search for new strategies, we can push past the safety threshold. Otherwise, we will fail to prevent a very preventable disease. SA

SCIENTIFIC AMERICAN ONLINE
Experts on how to raise vaccine rates: ScientificAmerican.com/may2015/parents-vaccines

Illustration by Steven P. Hughes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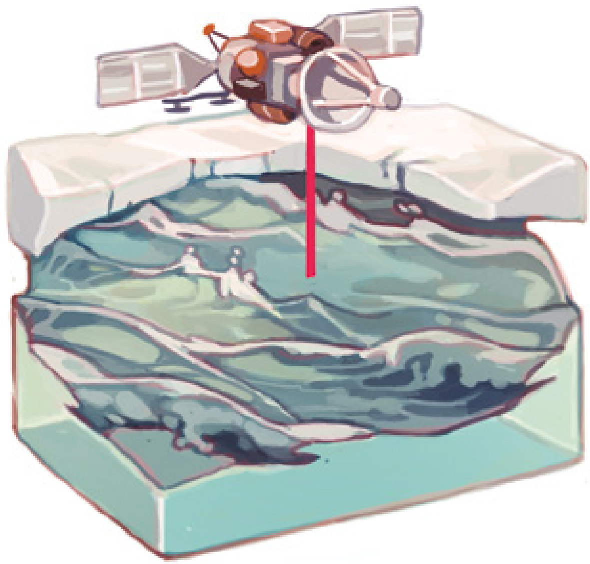
IAIN McCALMAN

Commentary on science in the news from the experts

Van R. Kane writes about the policy and technology of future interplanetary exploration missions for the Planetary Society.

Time to Go to Europa

A mission to Jupiter's icy moon is our best shot at finding extraterrestrial life in our solar system



In the 4.6 billion years since our solar system formed, life could have emerged on several of its worlds. Aside from Earth, however, Jupiter's moon Europa seems to be the most likely to host it today. Early Venus and Mars probably had abundant liquid water, the essential elixir for life as we know it, but one became a hot hell and the other a frozen globe. Saturn's moon Enceladus also has a substantial reservoir of liquid water, but the U.S. scientific community, in its most recent decadal survey, prioritized studying Europa, which is nearer. Europa's ocean, with perhaps twice the water of Earth's oceans, is believed to have been liquid since the moon's formation. On Europa, life might have had time to evolve.

Scientists believe that Europa's ocean lies directly atop a sizable rocky world, putting water in contact with the other elements and minerals essential for life. As the moon orbits Jupiter, tidal flexing heats the world from within, keeping the vast ocean liquid and likely powering volcanic activity. Rich ecosystems exist on our own planet's seafloor, where volcanic rifts create hydrothermal vents. The same might be true on Europa.

We have sent probes to Europa before. During its mission to Jupiter in the late 1990s, NASA's Galileo spacecraft observed the moon, all but confirming that Europa harbored a 100-kilometer-deep ocean covered by a relatively thin, icy shell. Tidal forces regularly break the ice, allowing water from the depths to well onto the surface, leaving stains that provide evidence of the ocean's chemistry. Observations by the Hubble Space Telescope in 2012 suggest that water plumes periodically erupt from Europa's surface. If such plumes are present, a spacecraft could sample the chemistry of this potentially life-bearing ocean by flying through them.

Galileo's vintage instruments (designed at the same time as the Apple II computer) could not determine what exactly stains Europa's surface or just how thick its icy crust may be—crucial for learning whether Europa is habitable. NASA crashed Galileo into Jupiter in 2003, and ever since, scientists and groups such as the Planetary Society have been urging NASA to send a follow-up mission. NASA's proposed Europa Clipper mission could do the job. It would orbit Jupiter, not Europa, and would dip into the planet's intense radiation belts 45 times to fly just above the moon's surface, retreating each time to safer locales to transmit its data home. The Clipper would characterize Europa's ocean, explore its chemistry and study its geologic processes. It would also scout locations for a future mission to land.

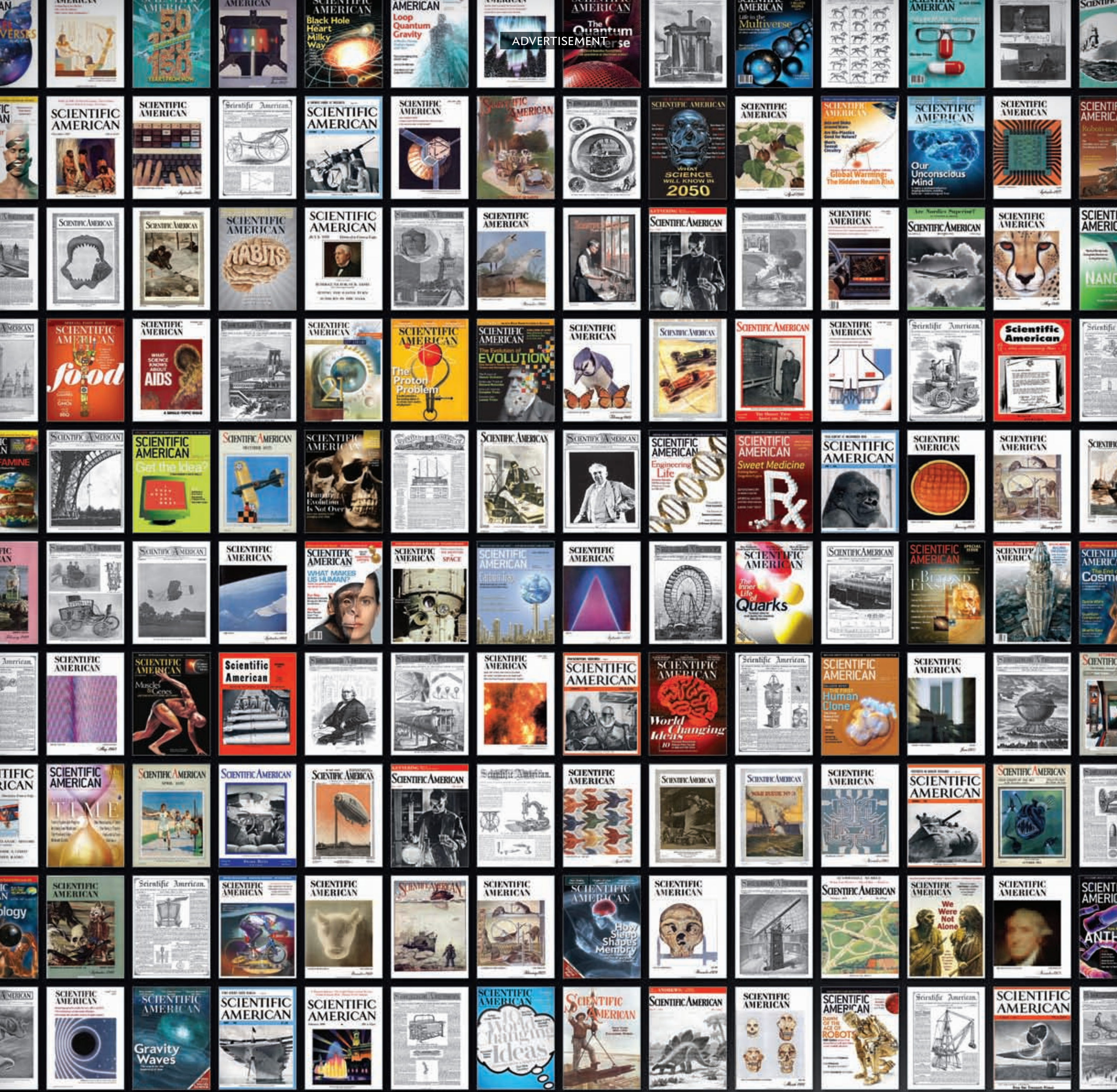
For most of the past 15 years, a mission to return to Europa has lingered in a perpetual early-study phase, trapped between the shifting and often conflicting priorities of successive Congresses and presidents. This year that changed, as both Congress and President Barack Obama officially endorsed a mission. This nascent plan, though, comes without a firm launch date or target cost. The Clipper mission would cost approximately $2 billion, but the White House is proposing just $185 million to fund the first four years of developmental work.

By comparison, when NASA began work two years ago on its next Mars rover, the project had a firm launch date (2020), a target budget ($1.5 billion) and substantial funding ($775 million for its first four years). Although the Clipper's engineering team members believe they could be ready to launch in 2022, the White House speaks of a mid-2020 launch. The proposed Europa funding stream punts the commitment to develop and launch a mission to a future president and Congress.

Europa is a compelling target, but a dedicated mission to deeply study it is at risk of slipping into the indefinite future. NASA has a credible mission concept that addresses the key scientific questions at an affordable cost. The White House and Congress should commit funding to move this mission toward launch as soon as possible. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/may2015

Illustration by Sachin Teng



SCIENTIFIC AMERICAN
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The Proton Problem

HEALTH

Teen Dispirit

Income levels are driving a wedge in adolescent well-being

Wealth typically begets health, as researchers have known for decades. Lower-income families have more medical issues during early childhood and adulthood than wealthier families do. Infants are more likely to be born premature and underweight. Children have higher rates of asthma. Adults are at higher risk of diabetes and cardiovascular disease.

Such disparities among teenagers, however, whose health problems tend to be subtler, had been harder to pin down. According to a new study by researchers at McGill University's Institute for Health and Social Policy, the socioeconomic fault line divides adolescents, too. Increasingly, low-income youths suffer from more physical and psychological issues than their more affluent peers, which could reverberate well into adulthood.

The trends emerged from data in the Health Behavior in School-Aged Children study, a survey-based analysis conducted every four years and led by the World Health Organization. Using surveys completed in 2002, 2006 and 2010, the McGill team examined reports of physical well-being, psychological health and family affluence among nearly 500,000 students—ages 11, 13 and 15—in 34 countries in Europe and North America. Entries were matched with the Gini index, an estimate of national income inequality.

Published online in February in the *Lancet,* the analysis uncovered a growing health gap between teenagers in wealthier and poorer households. Disadvantaged adolescents reported less physical activity and more bodily aches and pains, sleep-

Illustrations by Thomas Fuchs

lessness, and emotional difficulties, such as nervousness and irritability, compared with more advantaged teenagers. The gulf grew wider in countries with more economic inequality. "The U.S. was consistently one of the most unequal countries in terms of health," says psychologist Frank Elgar, lead author of the study.

Potential solutions to this escalating problem cover a wide swath. Karen Matthews, who studies adolescent health at the University of Pittsburgh, recommends more sleep—with earlier bedtimes or later school starts—in light of studies linking diminished shut-eye with a higher risk of obesity in teens. Because physical activity improves weight control, mental alertness and grades, schools should also consider reversing the trend of cutting gym time.

Other experts lobby for the integration of "social medicine"—treatments that recognize the social factors contributing to disease and illness—into physician training. Harvard Medical School now has a semester-long course in that vein. Similarly, the American Academy of Pediatrics issued a policy report in 2012 on the need to halt poverty-driven health disparities during childhood, before they fester and lead to life-threatening adult diseases.

The earliest interventions may be most effective. Research by James Heckman, an economist at the University of Chicago, found that programs for ages younger than three years, such as nurse home visits to assist new parents, yielded the greatest dollar-to-dollar return on investment in terms of helping disadvantaged youth attain the education and employment levels necessary to improve their socioeconomic status later in life, in comparison with fixes such as job training after high school.

Any and all approaches may be warranted, considering the high stakes for individuals and society. "If you are unhealthy as a teen, it's very likely you'll be unhealthy as an adult," Matthews says. And we can all agree that adolescence is already tough enough. —*Jessica Wapner*

MEDICINE

Switching Sides

A dual hemispheric fix for stroke

It's best to treat the good with the bad, new medical insights into brain attacks suggest. Doctors are beginning to think the side of the brain *opposite* to a clot in stroke patients is just as important a target for treatment as the damaged tissue when it comes to a faster recovery.

Only in the past few years have researchers discovered that the uninjured side of the brain becomes more active after a stroke to help its fallen neighbor. In some instances, it pumps out proteins that induce damaged neurons to begin repairs and others that trigger new blood vessels to form. It can even extend its own neurons across hemispheres to restore function.

Current stroke treatments largely target the damaged tissue. "I think everyone thought, 'The other side of the brain is working pretty well,'" says Stanford University neurologist Gary Steinberg. "'Why don't we leave that alone?'" In light of the growing evidence that the healthy hemisphere provides aid naturally, however, doctors are now investigating how to boost its healing actions. One such drug, shepherded by Adviye Ergul of Georgia Regents University and Susan Fagan of the University of Georgia, activates receptors on uninjured tissue that trigger pathways to reduce harmful inflammation and support the growth of neurons and blood vessels on the side of the brain with the clot. The drug increases repair rates in rats that have experienced stroke—results described recently in the *Journal of Hypertension*—and Ergul and Fagan say the therapy could become available to humans in the next five years. —*Rebecca Harrington*

IN THE NEWS

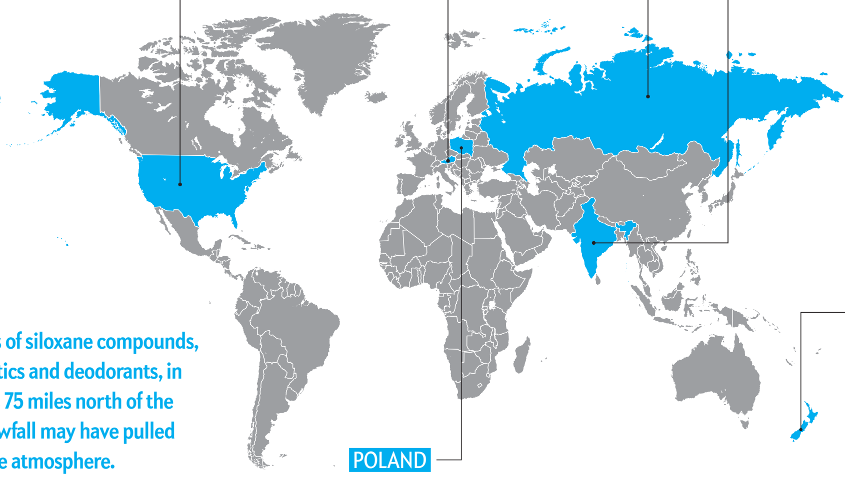
Quick Hits

U.S.
The National Institutes of Health designated $41.5 million to study human placentas and the ways pollution, medications and diet influence how they develop.

RUSSIA
The Russian Federal Space Agency says it will separate the nation's modules from the International Space Station when the mega satellite's mission ends in 2024 to construct a base of its own.

AUSTRIA
Architects in Vienna revealed plans to build a 25-story wood skyscraper next year.

INDIA
The Ministry of Health and Family Welfare announced that it will give free pills to 400 million people every year in a campaign to prevent elephantiasis, a disease caused by microscopic worms and characterized by grotesquely swollen body parts.



ANTARCTICA
Researchers found traces of siloxane compounds, which are used in cosmetics and deodorants, in soil and plants on islands 75 miles north of the Antarctic Peninsula. Snowfall may have pulled the compounds out of the atmosphere.

POLAND
An atomic clock the size of four rooms began ticking at the National Laboratory of Atomic, Molecular and Optical Physics in Toru. Once calibrated, the instrument will err by only one second after tens of billions of years.

NEW ZEALAND
Personalized jet-pack maker Martin Aircraft Company debuted on Australia's stock exchange, its share rising by 272.5 percent over five weekdays. The jet packs cost around $200,000 each and are intended for tricky emergency rescues.

For more details, visit www.ScientificAmerican.com/may2015/advances

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HEALTH CARE POLICY

Global Role Model

A successful malaria program enters its second phase

In an era when partisan squabbling threatens to bring the U.S. government to a halt, one of America's most successful global health programs, begun under President George W. Bush in 2005, is about to enter a second phase. Known as the President's Malaria Initiative, or PMI, the program is considered by many to be one of the best run and most effective of the U.S.'s worldwide health efforts.

The initiative is one of the largest players in the international effort to combat malaria, which kills more than half a million people a year. An estimated 4.3 million fewer malaria deaths occurred between 2001 and 2013, according to the World Health Organization, which is about a 47 percent reduction in the number of deaths if malaria patterns in 2000 had gone unchecked.

PMI accounted for a substantial part of this success. The program is based on four interventions: insecticide-treated mosquito nets, indoor spraying, testing and treatment with artemisinin-based drugs, and preventive treatment of pregnant women. The next phase of the strategy, under the Obama administration, will build on the gains, seeking to reduce malaria deaths by 30 percent between 2015 and 2020 in 19 target countries in sub-Saharan Africa and in the Greater Mekong region in Asia. (There were 198 million malaria cases globally in 2013.) Efforts will even aim to eliminate the disease in some countries. The program will also address drug and insecticide resistance to malaria, along with each country's capacity for its own treatment, monitoring and surveillance.

The secret to the initiative's success seems to be that it takes on mundane but often overlooked management issues that can trip up global health programs. PMI's approach is holistic: it takes responsibility for every link in the chain, from procurement to quality control. U.S. global health officials in other fields say it is a model particularly for its sustained focus on a limited number of targeted interventions

COMMENT AT ScientificAmerican.com/may2015

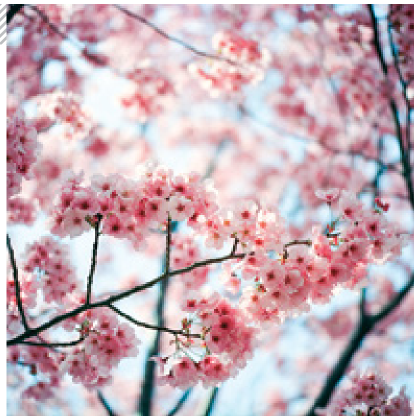
The President's Malaria Initiative supports indoor insecticide spraying in 19 countries, including Ethiopia (*left*), to control malaria. The program also helps target areas conduct regular insect screens (*above*) to identify problematic mosquito species (*below*).

in countries with a high burden of disease.

The recent accomplishments of antimalaria programs may have the unintended consequence of creating a sense of complacency at a time when efforts need to be amplified. Despite increases in the past decade, the overall global budget for malaria control is still projected to lag by more than $2 billion a year compared with what the mission requires, according to the Henry J. Kaiser Family Foundation. And a new PMI strategy document warns of "waning country and donor attention" as malaria rates drop. At the launch of the second phase of the initiative at the White House in February, Bernard Nahlen, deputy coordinator, warned: "The minute you take your foot off the pedal, malaria will come back with a vengeance." —*Sam Loewenberg*

ECOLOGY

May Flowers Bring Leaf Showers



The timing of spring determines autumn's onset

Flowers bloom and buds pop to herald the arrival of spring, but it is much harder to mark the natural start of autumn. The spectacular color changes in fall foliage take place gradually and vary geographically. Ecologists struggle to model the timing of current autumn seasons, let alone forecast onsets a century from now. But achieving the latter goal could enable predictions about seasonal shifts expected to have an effect on future climate.

The customary approach to predicting autumn's start date relies on two variables: temperature and day length. Trevor Keenan of Macquarie University in Sydney, Australia, and Andrew Richardson of Harvard University knew the model was too simple, however, because ecologists frequently obtain poor results from it. So they analyzed approximately 20 years of tree foliage observations from the Harvard Forest in Massachusetts and the Hubbard Brook Experimental Forest in New Hampshire in combination with 13 years of foliage satellite data for the eastern U.S. The data revealed a new trigger for fall's arrival: the timing of spring. The analysis, published online in *Global Change Biology,* found that if spring began one day earlier for a particular tree, defined as when leaves emerged, then autumn arrived 0.6 day earlier on average for that same tree, defined as when leaves changed color. "It's quite an unexpected finding," says Boston University ecologist Richard Primack, who was not involved in the study.

Keenan and Richardson do not know why autumn's arrival would depend on the onset of the preceding spring. "What's actually happening underneath the hood—the processes that initiate autumn—are quite complicated and not well understood," Keenan says. Leaves may be programmed to drop once they reach a certain age, causing their senescence to shift earlier in the year if spring arrives sooner. Or perhaps an early spring means trees siphon more groundwater from soil, which could stress the water supply later in the growing season and kill leaves prematurely.

The spring-autumn link most likely is bad news for humans. Under the old model, ecologists had predicted that a century from now, autumn would start two weeks later given a seven degrees Celsius warmer climate—an outcome that would mitigate global warming because a longer summer allows trees to capture more carbon dioxide from the atmosphere. But Keenan and Richardson's model indicates spring's earlier arrival on a warmer planet will tug fall's start date forward. In such a scenario, autumn would be delayed only a few days, so trees would not capture much more carbon.

This new thinking is hardly the final word on autumnal alterations, but the study paves a route for future research. "This paper is going to stimulate a lot of interest," Primack says. "People all over the world will read it and immediately go back to their own data sets and start reanalyzing them." —*Annie Sneed*

TECH

The Retiarius Bot

It's a dog-eat-dog world—and now a drone-eat-drone one, too. At a February demonstration in La Queue-en-Brie, France (*left*), Malou Tech showed off the Interceptor MP200 and its "antidrone strategy"—capturing smaller unmanned copters with a net. The remote-controlled, defensive ambusher could be law enforcement's airborne answer to an emerging security threat. Earlier this year personal flying bots were spotted hovering suspiciously over cultural and diplomatic landmarks in central Paris. Since October 2014 officials have recorded more than 60 incidents of drone activity near France's capital and its nuclear plants. In 2012 the nation adopted civilian drone legislation that has begun to go into effect, including a requirement for permissions to fly over populated areas. Here in the U.S., laws and regulations that govern flight of unmanned aircraft are still evolving. —*Bryan Lufkin*

YOSHIKA SAKAI *Getty Images (flowering tree)*; FRANCOIS MORI *AP Photo (drones)*

COMMENT AT ScientificAmerican.com/may2015

FOOD SCIENCE

Popcorn Physics 101

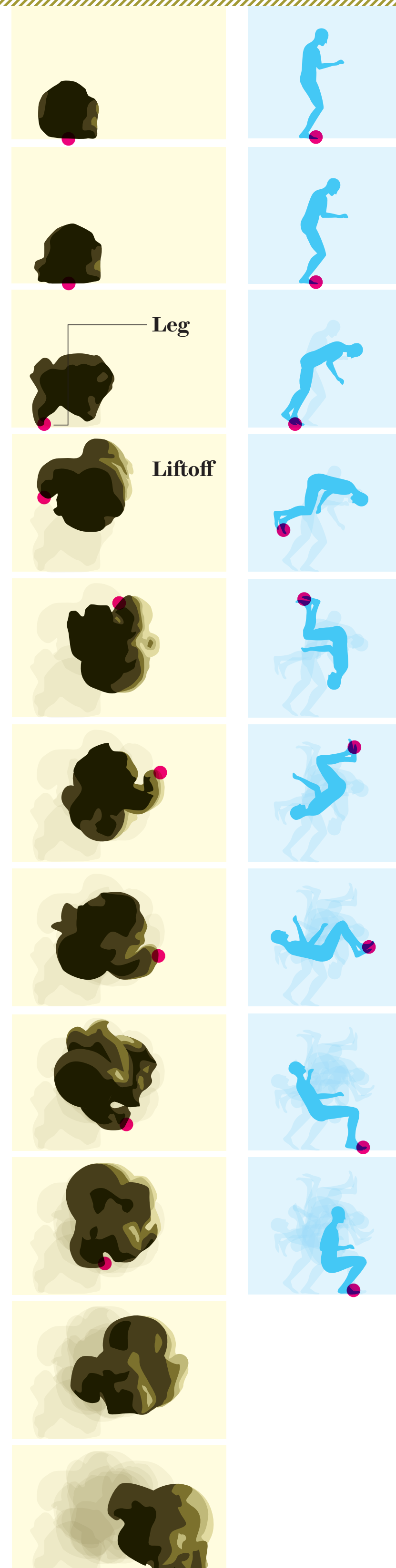
Grab some butter and salt

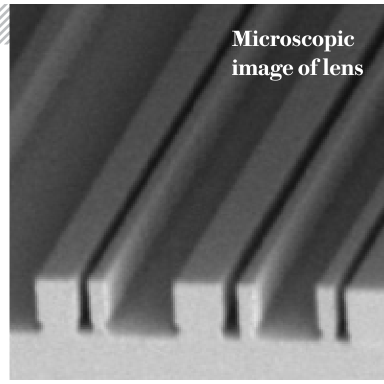
Americans eat more than 17 billion quarts of popcorn every year, yet some of the biomechanics of this deceptively simple treat still escape science. Most existing popcorn trivia—that 96 percent of kernels pop at 356 degrees Fahrenheit, for example—originated from commercial research, so a French physicist and aeronautical engineer took it on themselves to meticulously investigate the thermodynamic and acoustic properties of popcorn popping.

The basic journey of hard kernel to fluffy morsel is straightforward. Heat causes water inside the kernel's starchy interior to boil, building up pressure until the vapor bursts through the shell. But with high-speed cameras in hand, this team discovered something new: starch inside heated kernels first forms a leglike appendage (*right*). As the scientists described in the *Journal of the Royal Society Interface,* after the leg comes into contact with the bottom of a pan or bag, it compresses and releases like a spring, vaulting the kernel into the air and causing it to somersault. "It's quite similar to when we humans jump because we also compress our muscles and release them," says co-author Emmanuel Virot, an aeronautical engineer then at École Polytechnique.

The researchers also monitored the motions of the classic movie snack with supersensitive microphones and found that the characteristic "pop" sound typically occurs about 100 milliseconds after the kernel cracks open. Thus, the kernel's splitting is not the source of the sound. The researchers suspect instead that the pockets of heated water vapor within cause the noise as they burst through their starchy cages. These delicious results could help clarify tough physics ideas for students. As co-author Alexandre Ponomarenko, a physicist now at the French National Institute for Agricultural Research, puts it: "The aim of this research was really to provide physics teachers with a fun way to show all of these concepts in the classroom."

—*Rachel Nuwer*





MATERIALS SCIENCE

The Lens Descends

Optics, reimagined

The gently curved lentil served as the namesake for the similarly shaped lens. Future cameras, however, may focus light by relying on *flat* lenses. Physicists are making major advancements with planar lenses that can scatter and bend rays of light, sans bulge.

As we dream of smartphones that could roll up or slip into a wallet, laboratory researchers have made inroads with flexible circuits, batteries and displays. The millimeters-thick camera lens, however, stands in the way, especially in cases where corrective lenses are necessary to overcome imperfections that would otherwise yield blurry images.

A leap ahead came in 2012, when physicist and engineer Federico Capasso and his colleagues at Harvard University introduced a rudimentary flat, ultrathin lens. Despite its lack of curvature, the glass sliver could focus light via microscopic silicon ridges densely and precisely arranged to bend incoming waves in specific, calculated directions (*above*). But the lens worked on wavelengths of only one color—and not precisely at that.

The latest rendition, detailed online in February in the journal *Science,* has moved beyond proof of concept: it perfectly focuses red, green and blue light, which can be combined to yield multicolor images. The team has since crafted a larger prototype, and it "works exactly like the prediction," Capasso says. Such lenses could reduce the bulk and cost of photography, microscopy and astronomy equipment. And they could one day be printed on flexible plastic for thin, bendable gadgets. The scientists are in talks with Google and other technology companies. Such low-profile lenses would be useful for new kinds of compact, lightweight displays and imaging systems, says Bernard Kress, principal optical architect at Google[x].

The question is, If it doesn't look like a lentil, can it still be called a lens?

—*Prachi Patel*

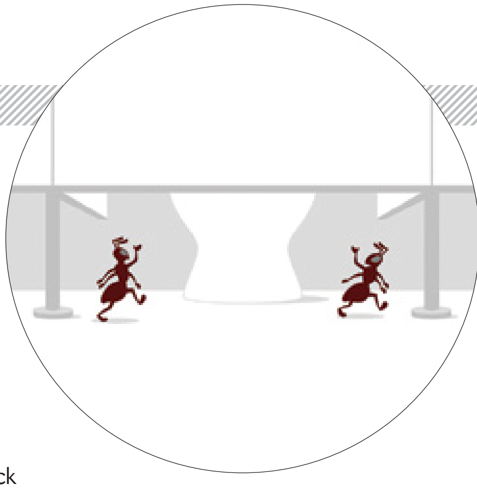
SOURCE: "POPCORN: CRITICAL TEMPERATURE, JUMP AND SOUND," BY EMMANUEL VIROT AND ALEXANDRE PONOMARENKO, IN *JOURNAL OF THE ROYAL SOCIETY INTERFACE*, VOL. 12, NO. 104; MARCH 2015 (*popcorn and somersaulting person*); COURTESY OF PATRICE GENEVET, FEDERICO CAPASSO AND FRANCESCO AIETA *Harvard School of Engineering and Applied Sciences* (*lens image*)

Graphic by Jen Christiansen

ANIMAL BEHAVIOR

Tiny Toilets

Some ants build latrines within their nests



Other than dung beetles, most animals try their best to avoid poop. Humans typically build entire rooms designed to flush the stuff away. The ick factor evolved for good reason: fecal matter is a great place for microorganisms to live and grow, some of which can lead to serious infection and illness.

Like us, many insects that live in colonies have evolved ways of keeping their nests and hives sanitary. Honeybees perform so-called defecation flights, in which they leave the nest to do their business. Some ants, like leaf-cutters, use their feces as manure for gardens that grow fungal food, but only certain "sanitation workers" are permitted to handle it. Ants in general are well known for their cleanliness—disposing of the dead outside the nest and leaving food scraps and other waste in special refuse chambers.

Thus, University of Regensburg biologist Tomer J. Czaczkes was surprised when he noticed dark patches accumulating in the corners of the white plaster nests in which his black garden ants, *Lasius niger,* lived. Over seven years of observations, he became convinced the dark patches were made of feces.

To confirm his suspicion, Czaczkes added artificial coloring to the ants' food for 21 colonies. Sure enough, the dark patches started showing up in brilliant shades of red and blue. Because the piles of ant poo never contained food scraps, corpses or other debris, Czaczkes and his colleagues conclude that referring to these spots as "toilets" is apt. The results were detailed in the February issue of *PLOS ONE.*

No one is sure why black garden ants keep their feces inside the nest, especially given that Formicidae are otherwise fastidious housekeepers. Perhaps it is used for defense, for territory demarcation or as a building material. Or it could serve as a source of salt or other nutrients. Another possibility, according to Czaczkes, is that the waste is stored precisely because it is stinky. "Ants tell friend from foe apart by their smell," he explains. "Perhaps newly emerged ants go to the toilet and sort of 'bathe' in it, to pick up the colony smell quickly." Each explanation is plausible, so more research will be necessary to determine the best one.

"The next obvious step is a lot of boring observation, where I hope to catch the ants using the toilets," he says. To covertly watch them do their business, Czaczkes will have to make nests with see-through lids and work under red light, which the ants cannot see. Onward, entomology. —*Jason G. Goldman*

ASTRONOMY

Small Fry

M dwarf stars hold promise for extraterrestrial life

In the search for habitable worlds beyond our solar system, the biggest, hottest opportunities may be found around the smallest, coolest stars. Called M dwarfs, these stars have a mere fraction of the sun's mass and luminosity but are more than 10 times as numerous. Planets circling an M dwarf must be in a close orbit to the star to be warm enough for life, like campers huddling around a small fire. This proximity makes them relatively easy for planet hunters to find, and the prevalence of M dwarfs means there are plenty nearby to investigate.

Astronomers are now gearing up for such an exploration. Multiple independent projects are already monitoring nearby M dwarfs, and a host of new telescopes and satellites are in the works to spot planets orbiting them, including NASA's Transiting Exoplanet Survey Satellite (set to launch in 2017). These efforts make the imminent discovery of potentially habitable M dwarf planets a near certainty. Whether all those bodies will actually prove to be habitable, however, is much less clear: the same sunny properties that make promising M dwarf planets so easy to find may also preclude the possibility for life on those worlds.

—Lee Billings

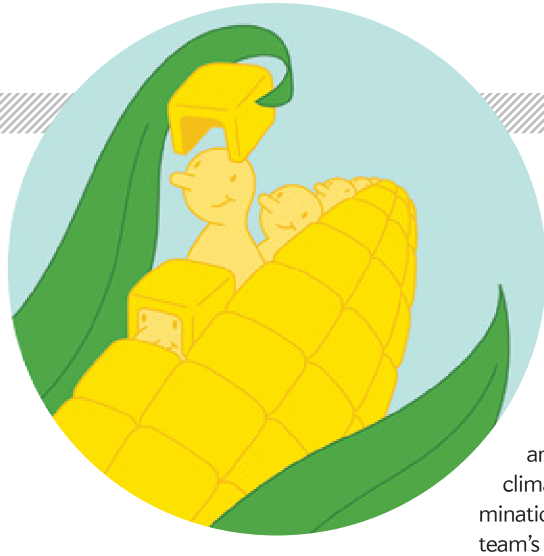
3 REASONS M DWARF PLANETS ARE EASY TO FIND BUT DIFFICULT FOR LIFE

WOBBLES AND TIDES Astronomers find some planets by looking for wobbling stars, a periodic back-and-forth motion caused by the gravitational tugging of unseen worlds. An Earth-size planet in a habitable orbit around an M dwarf would shift its motion through space at a detectable meter per second, and the wobble would recur every few weeks or months—much more frequent than the sun's nearly indiscernible wobble. But at such close proximity, tidal forces could sap energy from the planet's spin, causing it to rotate only once per orbit, always presenting the same hemisphere to the star, just as the moon does to Earth. In worst-case scenarios, such a planet's water and air could freeze out and accumulate as a giant ice cap on its cold nightside, rendering the surface uninhabitable.

SHADOWS AND FLARES Another way to locate planets is to look for the shadows of transiting worlds, planets that partially eclipse their stars as seen from Earth. Because of their close-in orbits, transiting M dwarf planets would block a larger fraction of starlight than they would if they orbited larger stars, making their shadows easier to see. There is a downside, however, for potential life. M dwarfs are much less luminous than sunlike stars and far more variable, dramatically dimming and brightening because of star spots and stellar flares, bathing planets in x-rays and ultraviolet radiation. Such unpredictable radiation could wreak havoc on climates and biospheres. And cheek by jowl with a tempestuous M dwarf, an otherwise habitable planet could have its atmosphere eroded by powerful flares.

LONG LIVES AND TROUBLED YOUTHS One reason M dwarfs are so numerous is that they simply live longer than other stars—their numbers growing over time because their small size allows them to slowly, efficiently burn their nuclear fuel. But this longevity comes only after a troubled youth. Somewhat counterintuitively, because of their small size and weaker gravity, M dwarfs can take longer to form than much larger stars. They can spend hundreds of millions of years as protostars, slowly forming from collapsing clouds of gas. Planets, however, may form around such a protostar in only tens of millions of years. In all the intervening time, those worlds would broil in the protostar's light and heat, possibly cooking off most of their life-giving water before the M dwarf was fully formed.

Illustration by Ron Miller



PLANT SCIENCE

The Culture of Germination

Plants make sure their seeds sprout at the perfect time with temperature memories

Mother knows best—even if Mom is a plant. A common flowering plant, *Arabidopsis,* hands down "memories" of recent temperatures to its seeds to prepare them for incoming spring weather conditions, a new study shows.

In an experiment by crop geneticists in Norwich, England, *Arabidopsis* individuals exposed to warmer temperatures produced seeds that sprouted more quickly than plants exposed to cooler temperatures—even if the warmer temperatures had occurred several weeks before the parents made the seeds. The investigators, based at the independent plant research institution John Innes Center, the University of York and the University of Exeter, traced the difference to a protein involved in flowering. In cool weather, the protein levels prompt the mother plant to produce more tannin in its fruit. Tannin is a compound that makes seed casings strong, so higher levels make those shells harder for seedlings to break through, delaying germination. "The mother defines how hard the seed coat is to break free from, and in this way it's controlling what the seed does," says Steven Penfield, a geneticist at John Innes and a co-author of the study, published in the *Proceedings of the National Academy of Sciences USA*. In warmer weather, the parent plant tweaks protein levels to make sure its offspring sprout immediately to take advantage of the heat.

Penfield notes that the finding has attracted interest from scientists and agricultural companies alike. As climate change shifts the timing of germination for many botanical species, his team's work suggests that modifying the genes involved in sensing the seasons could change when seeds sprout regardless of the weather outside.

Coaxing plants to relinquish control of their seeds' sprouting times may be a crucial step toward making sure food grows consistently, says Kent Bradford, an agricultural researcher at the University of California, Davis, who is eager to see if lettuces have a similar process for regulating germination. "We're trying to adapt those populations to the environment we expect to be here 10, 20 years down the road." *—Sarah Lewin*

INSTANT EGGHEAD

Right on Schedule

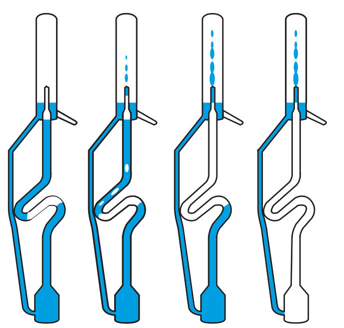
How do geysers erupt over and over?

Strokkur Geyser in Iceland

Yellowstone National Park's Old Faithful mystifies and delights tourists with its recurrent eruptions. But because of its popularity, it is heavily protected: the government limits access to curious scientists and restricts experiments on its plumbing. At least 80 smaller but equally percussive geysers also burst forth in Chile's Atacama Desert, offering an analogous opportunity to probe the earth's inner workings. Geologists laden with temperature and pressure sensors, GoPro cameras and a host of other gadgets recently observed one such geyser, nicknamed El Jefe, over the course of five days and more than 3,500 eruptions—one every 132 seconds. The result? The most detailed data set yet on the explosive choreography between water and steam.

El Jefe's flare-ups occur more regularly than those at many other geysers, but the plumbing is largely the same: a deep underground reservoir of water feeding a narrow channel that leads to the surface. As heat from the earth's core transfers to the reservoir, bubbles of steam rise through the water and up through the channel until they are caught in a small side chamber, a "bubble trap." When enough steam collects there, it escapes and, with water, overflows the geyser's top. Eventually these escaping bubbles make the water in the channel so hot that it boils and triggers a full eruption; the low pressure from the boiling water at the top of the column starts a downward-propagating reaction that lowers the boiling point of the water underneath so that steam and hot water from the whole column shoot up all at once. (These stages, followed by a recharge stage when the water filters back down into the reservoir to resume cycling, are shown in the group's laboratory model above.) The observations were published in February in the *Journal of Volcanology and Geothermal Research*.

Geysers in the lab



The measurements, taken at a range of depths, will yield a better understanding of the geyser's cycle and boiling patterns, says Michael Manga, a geologist on the El Jefe project at the University of California, Berkeley. Previous studies had captured either pressure or temperature, but both are necessary to gain insights into how heat travels through water below the earth's surface. Steven Ingebritsen, a researcher at the U.S. Geological Survey, is intrigued by what this more complete picture of geysers can tell geologists about other geothermal phenomena, such as volcanoes, which operate primarily underground and are incredibly challenging to probe—instruments would melt, for starters. The same flow of magma below the surface powers both types of eruptions. "They got their probes as deep as was feasible," Ingebritsen says. "But you wonder what's going on down deeper." —*Sarah Lewin*

JONATHAN IRISH *Getty Images (erupting geyser)*; SOURCE: "GEYSER PREPLAY AND ERUPTION IN A LABORATORY MODEL WITH A BUBBLE TRAP" BY ESTHER ADELSTEIN ET AL., IN *JOURNAL OF VOLCANOLOGY AND GEOTHERMAL RESEARCH*, VOL. 285; SEPTEMBER 15, 2014 *(model of geyser cycle)*

Dina Fine Maron is an associate editor at *Scientific American.*

Why Girls Are Starting Puberty Early

As causes become clearer, scientists worry about lasting social effects

For the past two decades scientists have been trying to unravel a mystery in young girls. Breast development, typical of 11-year-olds a generation ago, is now occurring in more seven-year-olds and, rarely, even in three-year-olds. That precocious development, scientists fear, may increase their risk for cancer or other illnesses later in life. Time has not resolved the puzzle. Nor is there any indication that this trend is slowing. More and more families are finding themselves in the strange position of juggling stuffed animals and puberty talks with their first and second graders.

Obesity appears to be the major factor sending girls into these unchartered waters. The rate of obesity has more than doubled in children over the past 30 years. And whereas only 7 percent of children aged six to 11 were obese in 1980, nearly 18 percent were obese in 2012. The latest studies, however, suggest that weight gain does not explain everything. Family stress and chemical exposures in the environment may also play a role, but the data do not yet paint a very clear picture of their contribution. As for boys, the data are murkier, but one 2012 study did suggest that they, too, may be starting puberty earlier than before—perhaps by as much as six months to two years.

Clinicians say that slightly early development of breasts is likely not physically harmful and so does not require medical or pharmaceutical therapy for most girls. (Among the few exceptions are pituitary disorders.) The psychological effects, though, are another matter that warrants more attention from schools and parents; early puberty seems to augment the risk of depression and to promote substance abuse and early initiation of sexual intercourse.

OBESITY'S ROLE

PRECOCIOUS DEVELOPMENT was first thrust into the spotlight in 1997, when a landmark U.S. study declared that at least 5 percent of white and 15 percent of black girls had started to develop breasts by age seven—much earlier than expected. "That finding evoked a lot of passion," says Paul B. Kaplowitz, a pediatric endocrinologist at Children's National Health System in Washington, D.C. Moreover, the 1997 work found that the trend toward early development was not happening only in outliers. Puberty was happening earlier in most girls and again differed by race: instead of age 11, the typical age of breast development by the early 1990s was 8.87 years in African-Americans and 9.96 in white girls, researchers found. Other studies soon reached similar conclusions in Europe as well as the U.S. According to the most recent U.S. data (from 2013), 23 percent of black girls, 15 percent of Hispanic girls and 10 percent of white girls have started to develop breasts by the age of seven. Those findings suggest the proportion of girls with significantly earlier breast development may still be ticking upward.

From a biological point of view, whether puberty begins early or late, it still starts in the brain. Something cues the brain to produce a substance called gonadotropin-releasing hormone, or GnRH. This process activates the pituitary gland, which then signals the ovaries to produce estrogen, which in turn stimulates the breasts to grow and puberty to begin. (Pubic hair forms as the result of a different biological process.) Menstruation usually begins a few years later. Focusing too much on the latter meant researchers tended to overlook the breast trend.

The ovaries are not the only place in the body where estrogen is produced, however. Fat cells manufacture the hormone as well. Thus, with obesity levels on the rise around the world, it is not surprising that earlier puberty would result. Although girls' breasts are developing earlier than before, the age at which they start to menstruate—and at which ovaries start pumping out large amounts of estrogen on a regular basis—has advanced by about only three months compared with decades past. As a result, puberty not only begins earlier but lasts longer than before.

The most obvious physical consequence of early puberty is a prolonged exposure to estrogen. Although excessive amounts of the hormone appear to increase the risk of developing breast

Illustration by Melody Newcomb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> ***"There is really no correlation between age of onset of puberty and one's social or emotional maturation."*** **—Frank M. Biro**

cancer, no data so far indicate that starting one's period a few months earlier than the previous norm exposes a girl to enough extra estrogen to cause a health problem. The potential effect probably is minimal, researchers say—particularly when weighed against myriad other factors—such as genetics, alcohol consumption and exercise—that also affect cancer risk. The much smaller exposure to estrogen that occurs in conjunction with early breast development has not yet been definitively studied.

Against that backdrop, many experts now believe parents should focus on the psychosocial consequences of early puberty rather than the potential physical risks. Frank M. Biro of Cincinnati Children's Hospital Medical Center has spent his career studying puberty. He is also the father of three children. In his estimation, one of the biggest issues with early puberty is social well-being. "We interact with girls as they appear," Biro says. "People relate to an early-maturing girl as if she is older than she is, but there is really no correlation between age of onset of puberty and one's social or emotional maturation." The result can be incredibly confusing for girls—who may face sexual innuendo or teasing long before they (or their parents) are ready for it.

BEYOND OBESITY

ALTHOUGH RESEARCHERS AGREE that obesity plays the central role in the earlier development of puberty, there is evidence implicating other factors as well. Lise Aksglaede and her colleagues at Rigshospitalet in Copenhagen followed more than 2,000 girls and discovered that although heavier individuals were indeed entering puberty earlier, a similar—if slightly less pronounced—trend also existed among normal-weight girls. In a 2009 study published in *Pediatrics,* they concluded that the increases in body mass index (a standard measure of weight in relation to height) between 1991 and 2006 were simply not large enough to account for girls' breast development dropping by a year during that period. "In my view, this is the best study that suggests it may not all be body fat and that there's something else here," Kaplowitz says.

What might that something else include? Researchers have long suspected that exposure to certain compounds known as endocrine disruptors might have a part in triggering early puberty. These substances, among them pesticides, polychlorinated biphenyls and bisphenol A, mimic the effects of estrogen in the body—and so could potentially stimulate early breast growth. Discerning how much of an influence exposure to these chemicals might play is complicated, however, by the obesity epidemic. Because the body often stores chemicals in fat cells, an overweight girl is more likely to be exposed to more chemicals—making it difficult to apportion blame between endocrine disruptors and weight gain. Other investigators have implicated intense stresses in childhood, such as sometimes occurs with the absence of the biological father in the home or if a child is sensitive to conflict around her, as possible causes of earlier puberty—although the biological mechanism of action is not known. What is evident is that there is a symphony of moving parts to make puberty happen instead of a solo actor.

WHAT TO DO?

GIRLS ARE NOT HAPLESS CREATURES, of course, buffeted by the winds of change without any control over their actions. Regular physical activity may prove beneficial to help counteract at least some of the trend toward early puberty by improving mood and combating weight gain. Helping daughters to maintain a healthy diet rich in fruits and vegetables may also offer some protection, psychologist Julianna Deardorff and pediatric endocrinologist Louise Greenspan write in their new book, *The New Puberty: How to Navigate Early Development in Today's Girls.*

One thing mothers can do to try to avoid the problem in the first place is to breast-feed their children. Children who are breast-fed appear to be less likely to enter puberty early, although the reasons are still unclear. A 2015 study that tracked some 1,200 girls and their mothers' breast-feeding habits found that breast-feeding—and longer duration of breast-feeding—correlated with later onset of breast development in daughters in some populations. Parents and communities can also help protect girls from the painful psychological effects of early development. One way, Deardorff says, is preparing girls for puberty by talking about developmental changes in a positive, nonstigmatizing way. Living in a homogeneous neighborhood may also be helpful: early-maturing fifth graders of Mexican descent showed fewer symptoms of depression by seventh grade when they lived in Hispanic neighborhoods compared with similar girls living in more diverse neighborhoods, according to another study. It is unclear, however, why homogeneity may have helped.

Regardless of where girls live, they could well benefit from a change in school curriculums. Schools typically do not offer sexual education classes covering body maturation until fifth grade, when most children are around age 10 or 11. Puberty education should start earlier, Deardorff and Greenspan believe, with age-appropriate materials beginning in the first semester of fourth grade to more closely conform with present reality.

Identifying the triggers that push individual girls into early puberty remains a challenge that leaves parents short of a simple action plan. As Marcia E. Herman-Giddens, lead author of the watershed 1997 early puberty paper, says, "People always want to know the reason, but I don't think people will ever be able to sort out the reason or the fix. It's a lot of things interacting together, and they have different effects on different individuals."

It remains to be seen if the early puberty trends will continue. "You would think at some point you would hit a biologic minimum, but I don't know when that is or when it would be," Biro says. Will every girl start maturing earlier? If obesity trends reverse course, will puberty begin later? As researchers look for answers, it is clear that parents and doctors alike need to be aware of the changes happening right now. SA

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The Agenda Setters

Bringing Science to Life

SXSW Education 2015

Austin, TX | March 9, 2015

SCIENTIFIC AMERICAN is committed to inspiring the next generation of students to pursue science, technology, engineering and math (STEM) careers. We put education at the top of the agenda.

To really change the future of education for the better, we need a combination of creative vision powered by the social entrepreneurship of education leaders and teachers. So at this year's SXSWedu conference, Scientific American and Macmillan Education, co-hosted a "Science of Learning" panel with Harvard University professor Robert Lue and University of Illinois at Urbana-Champaign professor Tim Steltzer to discuss how we can use emerging technology to improve instructional methods in schools. That evening, we partnered with Google for Education to continue the conversation with more teachers, ed-tech visionaries, media people and developers at the Google Fiber Space in Austin.

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

Truth in Digital Advertising

As we consume more and more of our media on mobile devices, advertisers are finding sneakier ways to deliver their messages

The list of gadgets that have been replaced by the smartphone is stunningly long—and growing. Camera, camcorder, music player, GPS unit, scanner, voice recorder, radio, Game Boy. Who buys those anymore, now that a single phone can get the job done?

But small electronics aren't the only entities being displaced in the mobile revolution. Media channels, including newspapers, magazines and television shows, are also suffering. Even Web surfing on our regular computers is taking a hit, as we do more and more of our Internetting on phones and tablets.

So who cares if people watch less regular TV, read fewer printed publications and spend less time on the full-sized Web?

I'll tell you who: advertisers. With all the traditional channels shrinking, how are advertisers supposed to reach customers? Banner ads on our devices are ugly and intrusive.

There are other ways to advertise to an on-the-go digital audience. You can display a full-screen ad while a Web page or app is loading. You can send texts (with permission, of course). And as the mobile era matures, we'll see more product placement in games, free apps (brought to you by sponsors) and ads that respond to your current location. So far, though, advertisers and brands aren't doing much in these realms; they're wary of the technical challenges, haven't studied the effectiveness and don't want to infuriate potential customers.

To overcome these various digital hurdles, the ad industry has been serving up a sneaky solution: make ads look less like ads—and more like the articles, videos and posts around them. An ad that matches the typeface, design and layout of the real articles feels less like a tacky intrusion.

This trend, called native advertising, has taken over the Internet; even the Web sites of journalistic bastions such as the *New York Times* and the *Wall Street Journal* are incorporating it. Social-media companies have signed on as well. On Facebook and Twitter, every 10th item or so is an ad; only the subtle subtitle "Sponsored," appearing in light gray type, tells you which posts are ads.

Overall, native ads have been a huge success. On NYTimes.com, readers spend as much time on the ads as on the articles.

But what about journalistic independence? What about separation of "church and state" (ads and editorial)? Won't dressing up ads to look like reported articles mislead people?

Sometimes, yes. An Interactive Advertising Bureau study found that only 41 percent of general-news readers could tell such ads apart from real news stories.

And it's getting worse. Advertisers worry that the "Sponsored" label dissuades readers from clicking, so Web sites from NYTimes.com to BuzzFeed.com are making the labels smaller and less noticeable. Sometimes the labels disappear entirely.

At a recent panel about the difficulty of advertising in the new, small-screen world, I heard an ad executive tell an impressive story. She had gotten a musical performance—paid for by her soft drink client—seamlessly inserted into a TV awards show, without any moment of blackness before or after. "It looked just like part of the real broadcast!" she recounted happily.

But how, then, could viewers tell the ad apart from independently produced material? A fellow panelist rolled his eyes. "Oh, good grief. People are savvy. They *know!*" he responded.

Look, it's great that native advertising works—publications and programs and free social networks have to stay solvent somehow. But if advertisers truly believe in their material, they should have no problem labeling it as advertising. ("Sponsored post" is already a little vague; "From around the Web" and "More news you may like" are downright deceptive.)

For now native ads will remain all the rage—with no laws governing them and no labeling standard. But that could change; the Federal Trade Commission has begun considering regulation. In other words, if the new generation of digital advertisers don't clean up their act, someone else may clean it up for them. SA

SCIENTIFIC AMERICAN ONLINE
Suggestions for the future of advertising: ScientificAmerican.com/may2015/pogue

Illustration by Lisk Feng

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Mathematics

Speaker: Arthur Benjamin, Ph.D

The Secrets of Mental Math

Dr. Benjamin will demonstrate and explain how to perform amazing feats of mental calculation. You'll improve your ability to manipulate and memorize numbers, learn how to figure out the day of the week of any date in history, and other astounding feats of mind.

The Mathematics of Games and Gambling

What are the best and worst games to play at the casino? When should you hit, split, or double down in blackjack? How much should you bet? Learn the answer to these questions, along with some games you can't lose, once you know the secret.

My Favorite Numbers

What makes the number 9 so magical? Explore the beauty of the Fibonacci Numbers 1, 2, 3, 5, 8, 13, 21, … and the golden ratio 1.618 … Is it irrational to be in love with Pi?

Discrete Mathematics

Learn the mathematics that underlie computer science and cryptography. Topics include combinatorics (the art of counting), number theory, and graph theory. But don't let the names of these topics scare you. You don't need much more than arithmetic and a logical mind to enjoy this lecture.

Psychology

Speaker: Jennifer Crocker, Ph.D.

Does Self-Esteem Matter?

Despite a huge volume of studies, researchers hotly debate whether self-esteem is actually important to well-being. We'll consider some of the major controversies in the field, such as whether high self-esteem people are happier, more successful, or more popular than low self-esteem people, and what factors actually affect our self-esteem.

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

Pursuing Self-Esteem

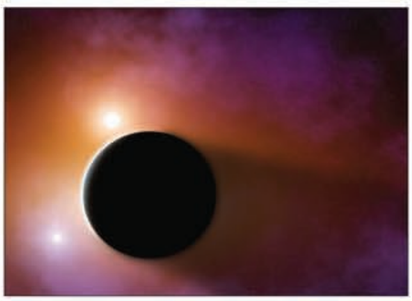
People tend to invest their self-esteem in just a few endeavors, such as academics, appearance or sports. Learn what research tells us about the benefits and pitfalls of pursing self-esteem by striving for success and avoiding failure in these domains, as well as successful strategies for avoiding the downsides of pursuing self-esteem.

Principles of Close Relationships

Many scientists assume that people in relationships are fundamentally self-interested, and aim to promote their own ends. Yet people can also transcend self-interest and care about relationship partners as much as themselves. Learn which relationships are likely to be governed by which set of principles, and what factors prompt these principles to shift.

The Key to Good Relationships

Learn how to create relationships that are good for your health and well-being through positive intentions. Evidence shows that when people strive to be supportive and constructive toward their partners, they tend to become so. Their partners notice and respond in kind, and the relationships tend to improve for everyone.



Astronomy

Speaker: Edwin L. Turner, Ph.D.

Exoplanets: Strange New Worlds

The first planet-sized body orbiting a star beyond the sun was discovered two decades ago. Since then, a torrent of new finds has come. Today we have catalogued and studied a few thousand exoplanets. Take a tour of these strange new worlds and learn about the future outlook for finding more.

The Quest for Earth's Twin

Is life on Earth unique in the universe? If not, our best hope for finding extraterrestrial organisms is to find a planet resembling our own, with the conditions and liquid water we think life probably requires. Learn how we search for Earth twins, and the prospects for detecting alien life from afar.

Life as We Don't Know It

Astrobiologists tend to search for extraterrestrial organisms resembling those found on Earth. But it's quite plausible that the universe contains life that is radically different from ours. Learn how scientists are beginning to study this topic, and how we might eventually hope to recognize life beyond our ability to imagine it.

Abiogenesis: Life's Origins

The biggest mystery about life is how it got started—that is, how it arose from a completely abiotic, or sterile, environment. Scientists have proposed radically different scenarios for this spark, and so far we have no way to discriminate between them. We'll discuss the latest thinking on the perplexing origins of life.

Evolution

Speaker: Spencer C.H. Barrett, Ph.D.

The Evolution Revolution

Evolution provides an explanation for all biodiversity on Earth, including human origins. Learn how and why evolution occurs, and why understanding the process of evolution is not only of profound biological importance but is also crucial for many contemporary issues affecting society.

Plant Sex for Grown-ups

The reproductive strategies of plants exhibit greater variety than those of any other group of organisms. Why should this be so? We'll address a variety of fundamental questions about plant sex, highlight some of the bizarre floral adaptations associated with pollination, and discuss how experimental studies can yield insight.

Evolution On Islands

Islands can act as "evolutionary laboratories," providing some of the clearest evidence for natural selection. We'll contrast the case histories of Australia and New Zealand, highlighting the similarities and differences between the floras and faunas of the two regions, and discuss why islands provide such a rich source of biological novelty.

Biological Invaders

Invasive species can cause huge economic losses and threaten biodiversity and ecosystem function. We'll discuss the fascinating new field of applied science known as invasion biology. Learn why some invasive species have the capacity to evolve rapidly in response to local environmental conditions in their adopted homes, whereas others are characterized by genetic uniformity.

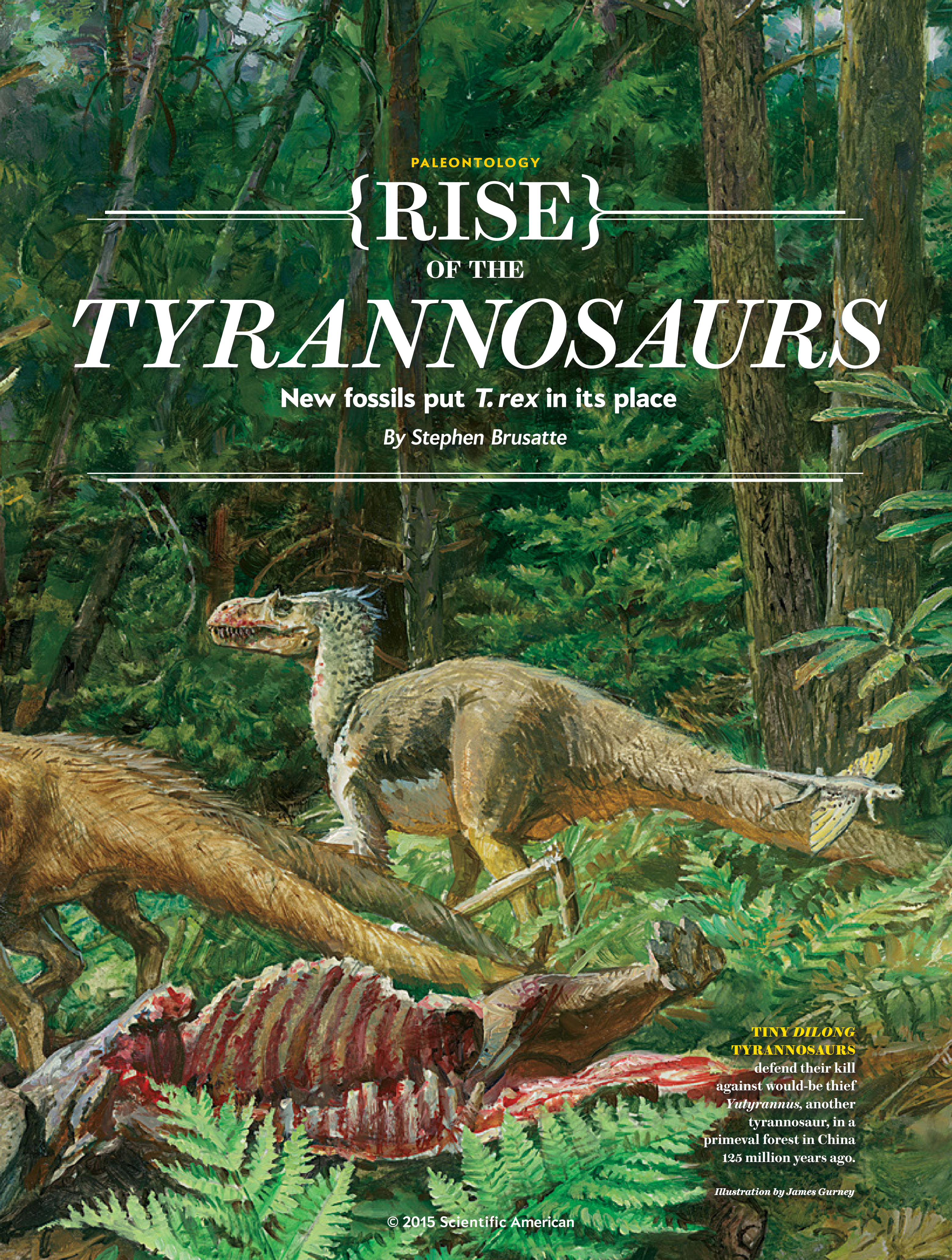

GURNEY

PALEONTOLOGY

{RISE} OF THE TYRANNOSAURS

New fossils put *T. rex* in its place

By Stephen Brusatte



TINY *DILONG* TYRANNOSAURS defend their kill against would-be thief *Yutyrannus*, another tyrannosaur, in a primeval forest in China 125 million years ago.

Illustration by James Gurney

Stephen Brusatte is a paleontologist at the University of Edinburgh in Scotland. His research focuses on the anatomy and evolution of dinosaurs. Brusatte is author of more than 70 technical articles and five books on dinosaurs, and he serves as the "resident paleontologist" for the BBC's *Walking with Dinosaurs* program.

ON A SWELTERING SUMMER DAY IN 2010, A CONSTRUCTION WORKER IN THE southeastern Chinese city of Ganzhou was digging the foundation for a building when his backhoe smashed into something hard. Climbing down to see what it was, he probably expected the worst—impenetrable bedrock, an old water main or some other nuisance that would inevitably delay completion of the sprawling industrial park his crew was racing to finish. But when the dirt and smoke cleared, a very different culprit came into focus: bones—lots of them, some enormous.

Construction did indeed stop that day because the bones turned out to be a major discovery. The worker had stumbled on a nearly complete skeleton of a bizarre new dinosaur species related to *Tyrannosaurus rex*. A few years later my Chinese colleagues invited me to help study the specimen, and in May 2014 we unveiled it as the latest addition to the tyrannosaur family tree: *Qianzhousaurus sinensis*. The formal name is something of a tongue twister, so we gave it a cheeky nickname, "*Pinocchio rex,*" in reference to its peculiar long snout.

Qianzhousaurus is part of a surge of new tyrannosaur discoveries over the past decade that is transforming understanding of this group. Ever since *T. rex*'s discovery more than a century ago, the 13-meter-long, five-ton behemoth has dominated the limelight. Yet its evolutionary history has eluded investigators. During the 20th century scientists discovered a few close relatives of *T. rex* that were likewise impressively large and realized that *T. rex* was not a mere oddity: these big predators formed their own branch of dinosaur genealogy. But they struggled to understand when the tyrannosaurs originated, what they evolved from, and how they were able to grow so large and reach the top of the food chain. These questions have remained unanswered until now.

Over the past 15 years researchers have recovered nearly 20 new tyrannosaur species at locations the world over, including the deserts of Mongolia and the frigid wastelands of the Arctic Circle. These finds have made it possible to piece together the tyrannosaur family tree, and the results are surprising: it turns out that tyrannosaurs were mainly marginal, human-sized carnivores for most of their history, achieving huge size and ecological dominance only during the final 20 million years of the Age of Dinosaurs, which began around 250 million years ago and spanned the Triassic, Jurassic and Cretaceous periods. The king of the dinosaurs, far from belonging to a dynasty of giant predators, actually had rather humble roots and was merely the last survivor of a startling variety of tyrannosaurs that lived across the globe right up until the asteroid impact 66 million years ago that brought the dinosaur era to a close and ushered in the Age of Mammals.

A STAR IS BORN

THE TALE OF HOW the tyrannosaur family history was uncovered begins with the discovery of *T. rex,* enabled by a man named Henry Fairfield Osborn. During the early 20th century Osborn was one of the most visible scientists in the U.S. He was president of the American Museum of Natural History in New York City and the American Academy of Arts and Sciences, as well as a *Time* magazine cover star. He used his considerable platform to push pet ideas on eugenics and racial superiority, so today he is often dismissed as just another bigot from years gone by. But Osborn was a clever paleontologist and an even better scientific

IN BRIEF

Paleontologists have known about *T. rex* and other giant tyrannosaurs for decades. But they were unable to piece together when the tyrannosaurs originated and what they evolved from because they lacked the fossils to do so.

Recent fossil finds have gone a long way toward filling those gaps in scientists' understanding of this iconic group.

Together these discoveries reveal that tyrannosaurs have surprisingly deep—and humble—evolutionary roots.

Furthermore, the group encompasses a far greater diversity of forms than experts had anticipated—including some with truly bizarre anatomical features.

administrator, and one of the best calls he ever made was to send a fossil collector named Barnum Brown out to the American West in search of dinosaurs.

Brown himself was an eccentric character, a man who hunted fossils in the dead of summer in a full-length fur coat and made extra cash spying for governments and oil companies. The guy had good instincts, however, and in 1902 he made one of the most famous discoveries in the history of paleontology: a giant, meat-eating dinosaur from the badlands of Montana.

When this dinosaur was described a few years later, Osborn gave it a name whose brand value has stood the test of time: *Tyrannosaurus rex,* the "tyrant lizard king." It was an instant sensation, making headlines across the country. Osborn and Brown had unveiled the biggest, baddest land-living predator ever.

T. rex became the quintessential celebrity dinosaur, the star of movies and museum exhibits around the globe. But this fame masked a puzzle: for nearly the entire 20th century scientists had little idea of how *T. rex* fit into the broader picture of dinosaur evolution. It was an oddball, a creature so much larger and so dramatically different from other known predatory dinosaurs that it was difficult to place in the dinosaur family album.

Over the next few decades, though, other paleontologists discovered a handful of close *T. rex* relatives that lived at about the same time—in the late Cretaceous—at sites in North America and Asia dated to between 84 million and 66 million years ago. These tyrannosaurs—*Albertosaurus, Gorgosaurus, Tarbosaurus*—are quite similar to *T. rex:* humongous apex predators that thrived during the last gasp of dinosaur history. Although the fossils were impressive, they did little to illuminate the origins of the group.

MODEST BEGINNINGS

A NUMBER OF THE RECENT discoveries that are helping to fill the considerable gaps in our knowledge of tyrannosaurs have come from unexpected locales. The stereotypical dinosaur find involves intrepid paleontologists trekking to some far-flung corner of the desert in western North America, Argentina, the Gobi or the Sahara and braving the heat, dust and snakes to hack fossils out of their rocky tombs. But dinosaurs, including tyrannosaurs, are turning up across the world now, even in the far northern reaches of Russia, where paleontologists instead need to cope with bone-chilling cold in winter and humid, mosquito-infested summers.

Alexander Averianov, my colleague from the Zoological Institute of the Russian Academy of Sciences in St. Petersburg, is one of these paleontologists. In 2010 his team announced a provocative discovery from the vast Krasnoyarsk region of central Siberia: a jumble of bones from a small, meat-eating dinosaur that lived well before *T. rex*—about 170 million years ago in the Middle Jurassic period—and would have been about the size of a human. They named it *Kileskus,* based on the word "lizard" in a local language. It turned out to be a vital clue to the rise of tyrannosaurs.

At first glance, *Kileskus* does not appear very impressive. It certainly does not look anything like *T. rex.* If *T. rex* had been living in Russia during the Middle Jurassic, it could have swatted *Kileskus* away like a fly, even with its pathetic little arms. But *Kileskus* exhibits unmistakable similarities to another small carnivore, *Guanlong,* that lived about 10 million years later in China and was described in 2006. For instance, both animals have a gaudy mohawklike crest of bone running along the top of the skull. And *Guanlong,* which is known from much more complete specimens than *Kileskus,* possesses features that are seen only in tyrannosaurs, such as fused nasal bones in the snout. These shared traits are signs of common ancestry: the modest, almost forgettable *Kileskus* and *Guanlong* are the ancestral stock from which the great *T. rex* arose.

These two finds painted a startling picture of the dawning of tyrannosaurs. They revealed that the group did not begin as massive superpredators, as many researchers had thought when the first tyrannosaurs were found, but rather as second- or third-tier carnivores living in the shadow of giant predators from distantly related groups such as allosaurs and ceratosaurs. In addition, tyrannosaur roots run far deeper than anyone expected. They lived at a time when the supercontinent Pangea had not yet fully broken apart, so that animals could disperse relatively easily across landmasses. This geography explains why early tyrannosaurs have since turned up in Russia and China, and slightly later species have emerged from the U.S., U.K. and perhaps even Australia (the taxonomic affiliation of some Australian predatory dinosaurs is a matter of debate). Together the specimens also show that it took an amazingly long time for tyrannosaurs to rise to power: there was a greater separation in time between the ancestral tyrannosaurs and *T. rex* (at least 100 million years) than between *T. rex* and humans (66 million years).

If the tyrant king was not fearsome enough already, just imagine it as an energetic, intelligent, Big Bird from Hell.

WARM AND FUZZY

ALTHOUGH THE TYRANNOSAURS were slow to reach truly gigantic proportions, that delay does not mean their evolution stagnated in the interim. Mounting evidence indicates that the group underwent considerable diversification long before the likes of *Tarbosaurus* and *T. rex* appeared. Striking examples of this proliferation have come from Liaoning Province in northeastern China.

Liaoning is not the most beautiful place in the world. Even though I grew up in the boring plains of the American Midwest, I find it difficult to keep my eyes open during the three-and-a-half-hour train ride from Beijing through kilometer after kilometer of hilly countryside draped with haze and dotted with farms and billowing smokestacks. But this is a holy land for fossil hunters.

Over the past two decades farmers all around this region have collected thousands of dinosaur skeletons. Repeated volcanic eruptions around 120 million to 130 million years ago quickly buried the ill-fated creatures in ash and mud, preserving their remains in exquisite detail. Among the many beasts found in this Cretaceous Pompeii are two intriguing species of tyrannosaurs. My col-

All in the Family

A rash of fossil discoveries in recent years has filled in the tyrannosaur family tree. The finds show that tyrannosaurs were a surprisingly diverse bunch yet slow to evolve the gigantic proportions associated with mighty *T. rex.*

The Cast

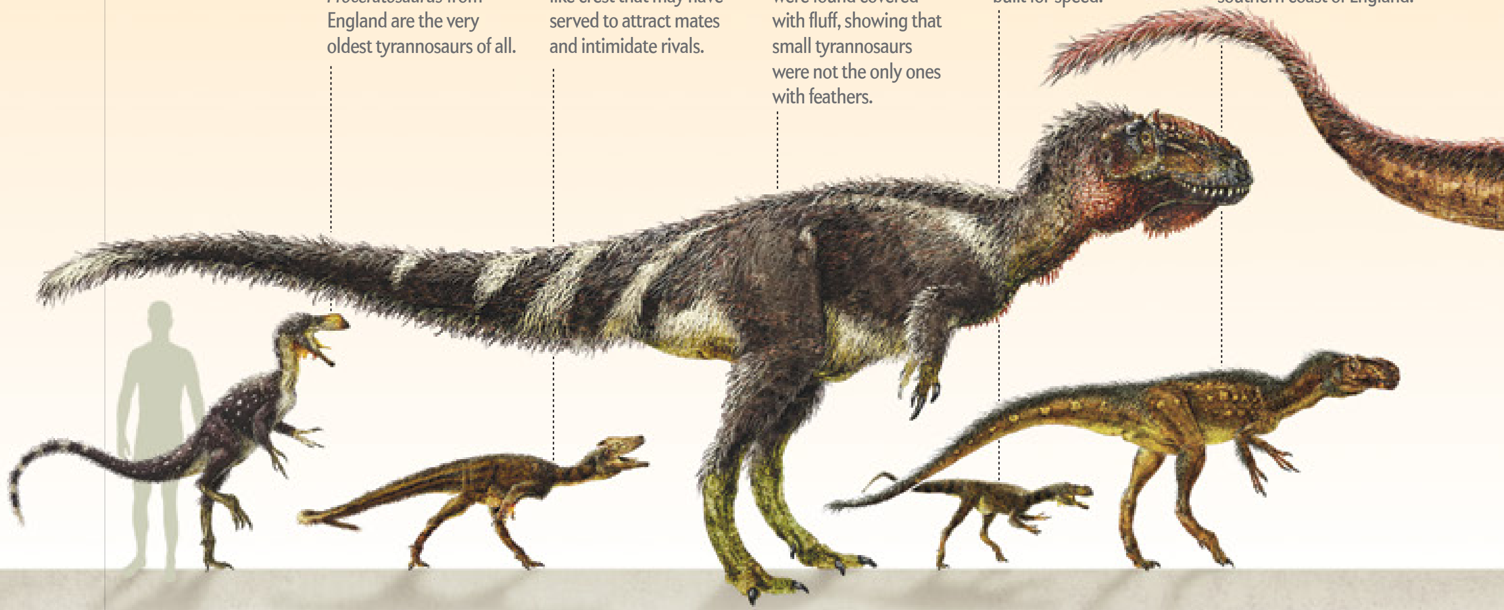
❶ ***Kileskus*** Discovered in central Siberia, this bantam species and *Proceratosaurus* from England are the very oldest tyrannosaurs of all.

❷ ***Guanlong*** This Chinese tyrannosaur possessed a distinctive mohawk-like crest that may have served to attract mates and intimidate rivals.

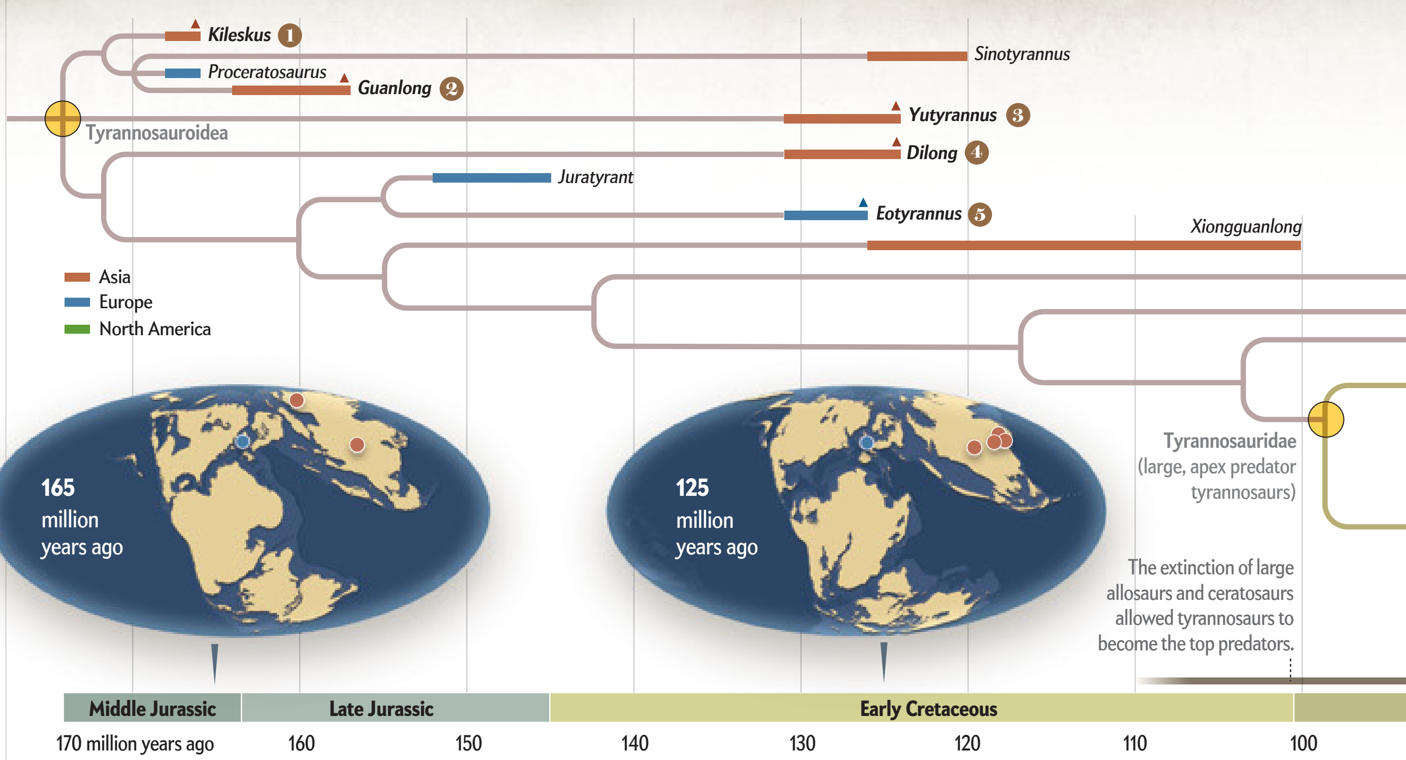
❸ ***Yutyrannus*** Fossils of this large-bodied species from China were found covered with fluff, showing that small tyrannosaurs were not the only ones with feathers.

❹ ***Dilong*** The tiniest tyrannosaur, this leggy Chinese form was built for speed.

❺ ***Eotyrannus*** Fossils of this long-fingered species come from the Isle of Wight off the southern coast of England.



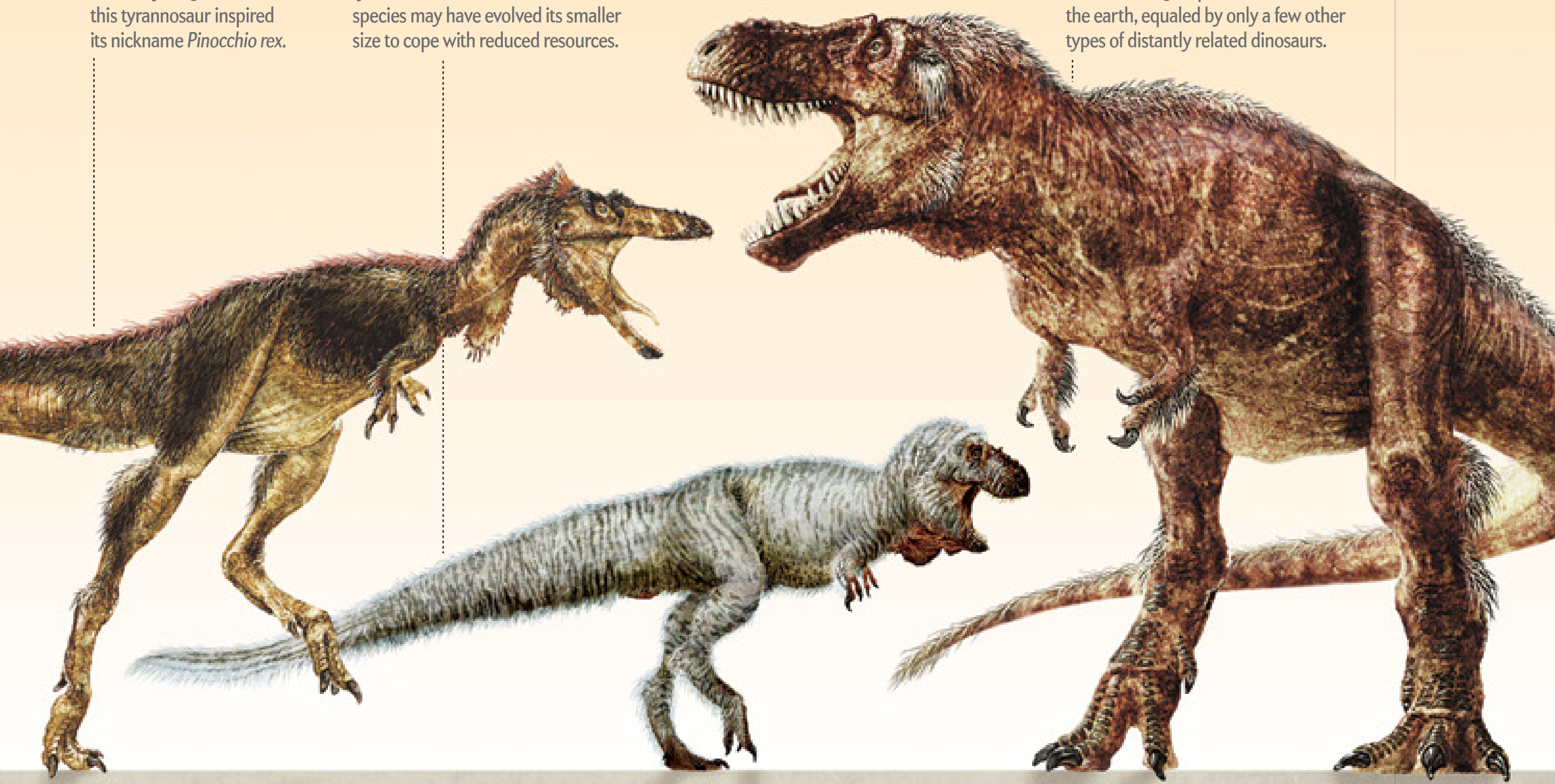
From Humble Beginnings …



6 ***Qianzhousaurus*** The unusually long snout of this tyrannosaur inspired its nickname *Pinocchio rex*.

7 ***Nanuqsaurus*** The most northerly tyrannosaur on record, this Arctic species may have evolved its smaller size to cope with reduced resources.

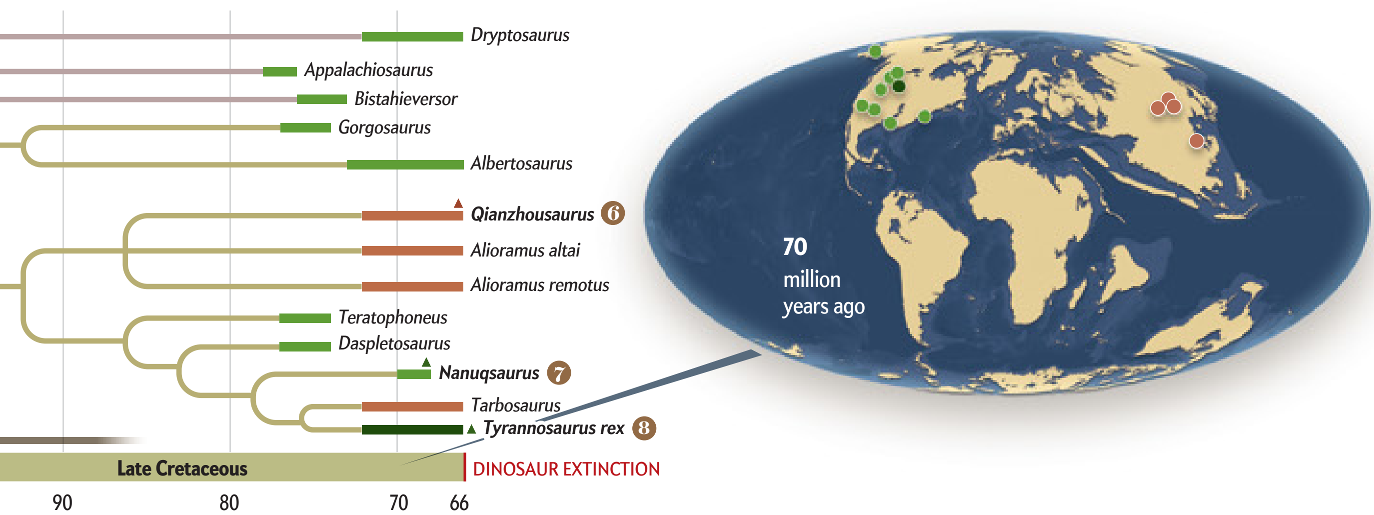
8 ***Tyrannosaurus rex*** The tyrant king was one of the largest predators ever to walk the earth, equaled by only a few other types of distantly related dinosaurs.



... To Apex Predators

Tyrannosaur Biogeography

The growing tyrannosaur fossil record shows that this group was far more widespread than previously thought, with finds emerging from the U.S., U.K., China, Russia and possibly Australia. Tyrannosaurs were able to disperse far and wide because they evolved at a time when the continents had yet to fully break apart, making it easy to cross from one landmass to another.



SOURCE: PLATE TECTONIC AND PALEOGEOGRAPHIC MAPS BY C. R. SCOTESE, PALEOMAP PROJECT, 2009 *(maps)*

Illustration by Todd Marshall (dinosaurs), Graphics by 5W Infographics

LONG-NOSED *QIANZHOUSAURUS,* **found at a construction site in China in 2010, shared ecosystems with much larger-bodied tyrannosaurs, probably by using its stealth and speed to pursue smaller prey.**

league Xu Xing of the Institute of Vertebrate Paleontology and Paleoanthropology in Beijing announced the first of these species, *Dilong,* in 2004. Roughly the size of a golden retriever, it had long arms for catching prey and a lithe, leggy skeleton built for speed. The second species, which Xu described in 2012, is a very different type of animal. At eight to nine meters long and about a ton in mass, this animal—named *Yutyrannus*—probably sat at or near the top of the food chain. Both tyrannosaurs are found in the same rock formation and may have lived side by side approximately 125 million years ago. Together these species, which exhibit the fused nasal bones and other hallmarks of tyrannosaurs, demonstrate that by the Early Cretaceous tyrannosaurs had branched off into a range of new species filling different ecological roles and that some were experimenting with larger body size.

Dilong and *Yutyrannus* are also important for another reason. Paleontologists once viewed dinosaurs as scaly, plodding, overgrown reptiles. In recent years, however, researchers have found evidence that a number of dinosaur species sported downy coats rather than scales and were generally more dynamic and smarter than they had previously been thought. Which is to say, they were more like birds than reptiles. *Dilong* and *Yutyrannus* establish beyond a doubt that tyrannosaurs fit this description. The bones of these species are covered with a thick, feathery fluff—not the quill-pen feathers that make up the wings of living birds but simpler, filamentlike feathers that look like hair. Unlike birds, tyrannosaurs certainly were not flying. Instead they probably used their feathers for display or to keep warm. The presence of feathers in tyrannosaurs and many other kinds of dinosaurs makes it very likely that the great *T. rex* was feathered, too. If the tyrant king was not fearsome enough already, just imagine it as an energetic, intelligent, Big Bird from Hell.

RISE OF THE KINGS

THE NEW DISCOVERIES from Russia, China and elsewhere show that tyrannosaurs were doing quite well from the Middle Jurassic into the Early Cretaceous. They may not have been top dogs, but they had found their niche as a steady, if unspectacular, group of stealthy, fleet-footed predators. But then something changed. Sometime between 85 million and 110 million years ago, during the middle part of the Cretaceous, dinosaur ecosystems underwent a radical restructuring. The allosaurs and ceratosaurs that had long occupied the apex of the food pyramid largely disappeared, and tyrannosaurs assumed the top predator role on the northern continents. Exactly why this happened is unclear because dinosaur fossils from the Middle Cretaceous are extremely rare. A mass extinction about 94 million years ago—when temperatures increased and sea levels fluctuated—may be to blame.

However they got there, tyrannosaurs flourished once they reached the top of the food chain. During the final 20 million years of the Cretaceous, tyrannosaurs reigned supreme in North America and Asia as multiton, tiny-armed, huge-skulled superpredators. They bit so hard that they crunched through the bones of their prey. They grew so fast that they put on a few kilograms of mass every day during their teenage years. And they lived so hard that paleontologists have yet to find an individual that was more than 30 years old when it died.

Yet as successful as the colossal tyrannosaurs were in North America and Asia, they do not seem to have ever gained a foothold in Europe or the southern continents, where other groups of large predators prospered instead. Reconstruction of the earth's climate and continental configuration during the Late Cretaceous hints at why. The world at that time was very different from the setting in which smaller tyrannosaurs first evolved. The conti-

COURTESY OF JUNCHANG LÜ *Chinese Academy of Geological Sciences' Institute of Geology*

SCIENTIFIC AMERICAN ONLINE Watch a video of Brusatte talking about tyrannosaurs at ScientificAmerican.com/may2015/tyrannosaurs nents had drifted much farther apart, reaching positions similar to the ones they occupy today. Furthermore, dramatically higher sea levels bisected North America and reduced Europe to a smattering of small islands. *T. rex*'s earth was a highly fragmented planet. As a result, champions in one region might not be able to conquer another for one simple reason: they could not get there.

PERSISTENT VARIETY

IN THE REGIONS where mega tyrannosaurs such as *T. rex* did rise to power, one might expect these brawny forms to have edged out other, daintier tyrannosaurs. The latest fossil discoveries suggest otherwise. Amazing new finds have revealed an unappreciated diversity of tyrannosaurs up and down the food chain, even during those last few million years of the Cretaceous, when *T. rex* and kin ruled unchallenged.

The Pinocchio-nosed *Qianzhousaurus,* from the Chinese construction site, is a prime example. When my colleague Junchang Lü of the Chinese Academy of Geological Sciences' Institute of Geology first showed me photographs of the specimen at a conference in 2013, I was gobsmacked. Here was a tyrannosaur from the latest part of the Cretaceous that was strikingly different from the tyrant lizard king. It was noticeably smaller—just about eight to nine meters long and probably around a ton in mass. Still not any animal you would want to run into in a dark Cretaceous alley but a waif compared with *T. rex.* Even weirder, its skull was long, narrow and delicately constructed, unlike the deep, muscular, bone-crunching skull of its famous cousins.

Lü invited me to help him describe the new Chinese fossil because I had studied two other peculiar long-snouted tyrannosaurs, discovered decades earlier, that had long confused scientists. The first of these creatures was known from part of a skeleton found in Mongolia by a Russian team in the 1970s. They called it *Alioramus remotus* and suggested that it was an aberrant long-skulled tyrannosaur. But very few paleontologists were able to study the specimen during the cold war, so it remained debatable whether it was a weird new species or just a young representative of the existing tyrannosaur species *Tarbosaurus.* A few decades later, in the early 2000s, a joint Mongolian-American team led by my Ph.D. adviser, Mark Norell of the American Museum of Natural History, discovered a much more complete and better preserved specimen of *Alioramus.* On the first day of my Ph.D. studies Norell took me into the museum's prep laboratory, showed me the skeleton and told me to get to work studying it. In 2009 we announced it as a new species, *Alioramus altai*. This skeleton appeared to be distinct from *Tarbosaurus*, but because it came from a juvenile individual (as revealed by its internal bone structure), we could not rule out the possibility that its seemingly unique traits were instead the product of incomplete growth.

Sometimes debates like this one rage for decades, as paleontologists await new fossils to break a stalemate. In our case, it took only a few years, along with the dumb luck of the backhoe operator. The *Qianzhousaurus* skeleton discovered in Ganzhou had the same long snout, delicate build and small body size of *Alioramus,* but it clearly belonged to a much older and more mature individual. It was the clincher: long-snouted tyrannosaurs were distinct species that lived across Asia during the very end of the Cretaceous, probably filling a second-tier predator role on the food chain below *Tarbosaurus*.

Qianzhousaurus was not the only petite tyrannosaur to share the planet with the heavyweights. Just about two months before we published our description of *Qianzhousaurus,* my American colleagues Anthony Fiorillo and Ronald Tykoski, both at the Perot Museum of Nature and Science in Dallas, Tex., revealed an even stranger latest Cretaceous tyrannosaur from the frosty Arctic Circle of Alaska, called *Nanuqsaurus*. It is known from just a few bones that look a lot like the corresponding bones in *T. rex* but with one incredible difference: they are about half the size. The obvious explanation is that the bones belong to a baby tyrannosaur, but shockingly they have thickened sutures—the "seams" between adjacent bones that are only seen in adults. Fiorillo and Tykoski came up with an idea that may sound farfetched but one I think is very plausible: Arctic tyrannosaurs evolved small bodies because their resource-poor habitat could not support larger species. Many modern island-dwelling animals have undergone dwarfing for that same reason. So while *T. rex* ruled to the south, a Mini Me tyrannosaur patrolled the northern wilderness.

BEYOND THEIR CONTROL

THESE LATEST ADDITIONS to the tyrannosaur family tree have illuminated the evolutionary history of this charismatic group, but key questions remain. Where did tyrannosaurs originate, and did they get their start even earlier than the Middle Jurassic, perhaps during the Early Jurassic, a time when we have few fossils from around the world?

Did tyrannosaurs also live across the southern continents during the Middle Jurassic/Middle Cretaceous? Most of their fossils are from the northern continents, except for one enigmatic bone from Australia. But we know that many dinosaur groups were globally widespread during the Middle Jurassic/Middle Cretaceous, so maybe tyrannosaurs were, too. Other unknowns concern their biology. What kind of feathers did the largest tyrannosaurs like *T. rex* have, and what purposes did they serve? And how did *Qianzhousaurus* and *Alioramus* use their distinctive long snouts?

Incomplete as the tyrannosaur story is, it still reveals a deeper truth about evolution—namely that is not predictable. When tyrannosaurs originated more than 170 million years ago, no one would have guessed that these puny stalkers would come to rule entire continents. They were not preordained for success. Rather they had to navigate more than 80 million years of living in the shadows, biding their time until environmental changes gave them the opportunity to become apex predators. And then one day, when the tyrannosaurs were at the peak of their game, an asteroid fell from the sky and they disappeared. Their strength and size could not save them as wildfires raged, ecosystems collapsed and mammals began their march to the top. SA

MORE TO EXPLORE

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FROM OUR ARCHIVES

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scientificamerican.com/magazine/sa

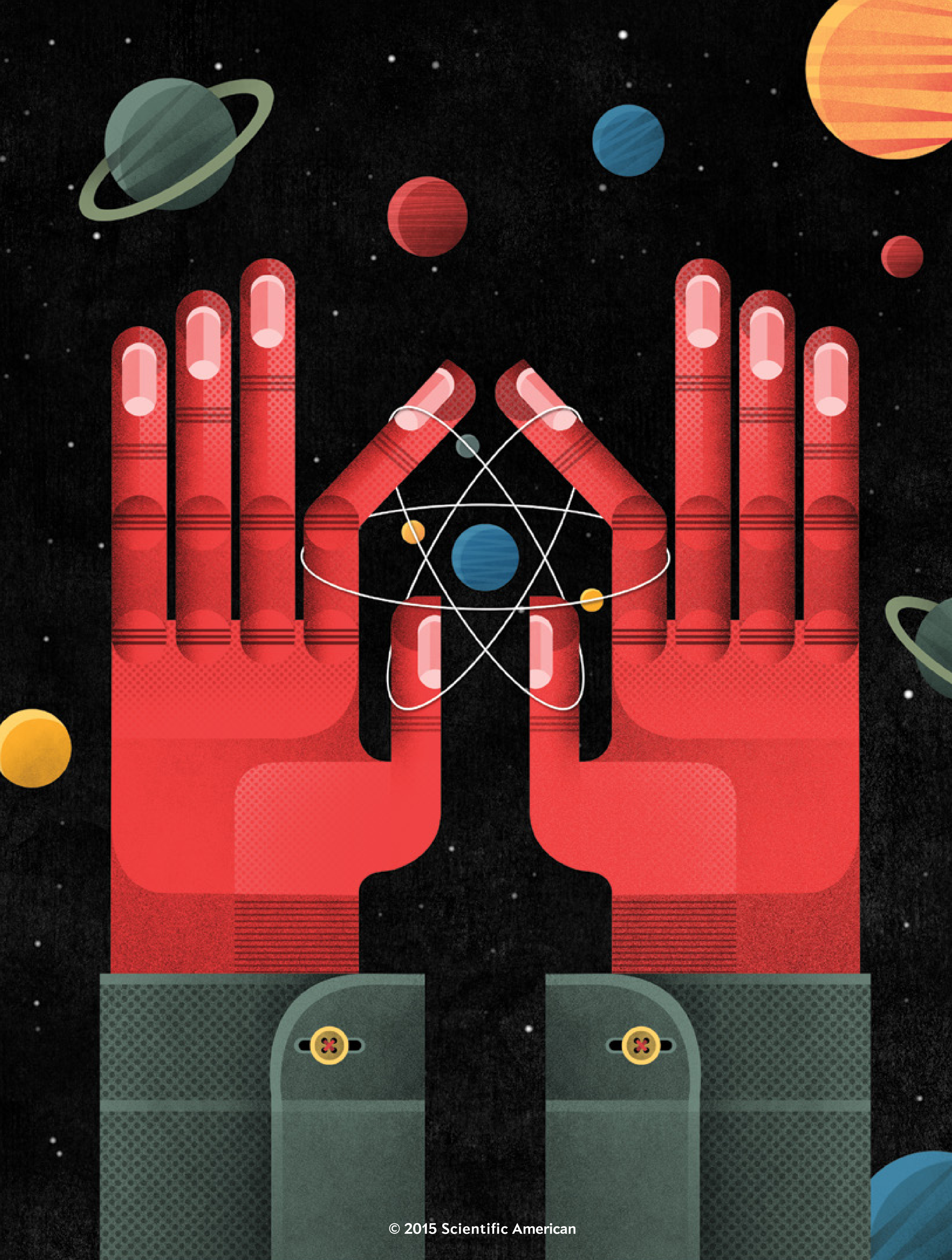
PARTICLE PHYSICS

the glue that binds us

Physicists have known for decades that particles called gluons keep protons and neutrons intact—and thereby hold the universe together. Yet the details of how gluons function remain surprisingly mysterious

By Rolf Ent, Thomas Ullrich and Raju Venugopalan

Illustration by Maria Corte



Rolf Ent has worked at the Thomas Jefferson National Accelerator Facility in Newport News, Va., since 1993. He is associate director of experimental nuclear physics there and has been a spokesperson for multiple experiments studying the quark-gluon structure of hadrons and atomic nuclei.

Thomas Ullrich joined Brookhaven National Laboratory in 2001 and also conducts research and teaches at Yale University. He has participated in several experiments, first at CERN near Geneva and later at Brookhaven, to search for and study the quark-gluon plasma. His recent efforts focus on the realization of an electron-ion collider.

Raju Venugopalan heads the Nuclear Theory Group at Brookhaven National Laboratory, where he studies the interactions of quarks and gluons at high energies.

THE ANCIENT GREEKS BELIEVED ATOMS WERE THE SMALLEST BITS OF MATTER in the universe. Then scientists in the 20th century split the atom, yielding tinier ingredients: protons, neutrons and electrons. Protons and neutrons, in turn, were shown to consist of smaller particles called quarks, bound together by "sticky" particles, the appropriately named gluons. These particles, we now know, are truly fundamental, but even this picture turns out to be incomplete.

Experimental methods for peering inside protons and neutrons reveal a full-fledged symphonic orchestra within. These particles each consist of three quarks and varying numbers of gluons, along with what are called sea quarks—pairs of quarks accompanied by their antimatter partners, antiquarks—which appear and disappear continuously. And protons and neutrons are not the only particles made of quarks found in the universe. Accelerator experiments in the past half a century have created a host of other particles containing quarks and antiquarks, which, together with protons and neutrons, are called hadrons.

Despite all this insight—and a good understanding of how individual quarks and gluons interact with one another—physicists, to our dismay, cannot fully explain how quarks and gluons generate the full range of properties and behaviors displayed by protons, neutrons and other hadrons. For example, adding up the masses of the quarks and gluons inside protons does not begin to account for the total masses of protons, raising the puzzle of where all this missing mass comes from. Further, we wonder how exactly gluons do the work of binding quarks in the first place and why this binding seems to rely on a special type of "color" charge within quarks. We also do not understand how a proton's rotation—a measurable quantity called spin—arises from the spins of the quarks and gluons inside it: a mystery because the smaller particles' spins do not easily add up to the whole.

If physicists could answer these questions, we would finally begin to comprehend how matter functions at its most fundamental level. Identifying the main enigmas surrounding quarks and gluons, which we will detail below, is itself a key step toward discerning the physics of matter at its finest levels. Ongoing and future work, including studies focused on exotic configurations of quarks and gluons, should help demystify the puzzles. With a little luck, we will soon be able to break out of the fog.

WHERE DOES PROTON MASS COME FROM?

THE MYSTERY OF MASS is one of physicists' most vexing questions and offers a good sense of why the workings of quarks and gluons are so perplexing. We have a pretty good grasp of how quarks and leptons—a category of particles that includes electrons—get their mass. The mechanism arises from the Higgs boson—the particle discovered to much fanfare at the Large Hadron Collider (LHC) at CERN near Geneva in 2012—and from its associated Higgs field, which pervades all of space. When particles pass through this field, their interactions with it imbue them with mass. The Higgs mechanism is often said to account for the origin of mass in the visible universe. This statement, however, is incorrect. The mass of quarks accounts for only 2 percent of the mass of the pro-

IN BRIEF

The matter that forms our world is fundamentally made of particles called quarks that are held together by sticky particles, the appropriately named gluons. Physicists have made huge strides in understanding the workings of quarks and gluons, but a number of puzzling mysteries remain.

It is unclear how quarks and gluons contribute to the mass of the protons and neutrons in atoms, for example, or how they give those particles spin. And quarks and gluons seem to have a strange "color" charge, yet protons and neutrons have no color.

Future experiments revealing the building blocks of matter in greater detail than ever before could help physicists better understand how quarks and gluons interact.

ton and the neutron, respectively. The other 98 percent, we think, arises largely from the actions of gluons. But how gluons help to generate proton and neutron mass is not evident, because they are themselves massless.

A clue to resolving this conundrum is provided by Albert Einstein's famous equation relating a particle's mass at rest to its energy. By inverting the equation to read $m = E/c^2$, we see that the mass (m) of the proton at rest can be said to arise from its energy (E), expressed in units of the speed of light (c). Because the energy of a proton is mostly contributed by gluons, in theory, one would only need to figure out the net energy of gluons to calculate the proton's mass.

Calculating the energy of gluons is difficult, however, in part because their total energy arises from several contributing factors. The energy of a free particle (unattached to others) is its energy of motion. Yet quarks and gluons almost never exist in isolation. They survive as free particles only on unimaginably small timescales (less than 3×10^{-24} seconds) before they are bound up into other subatomic particles and literally screened from view. Moreover, in gluons, energy comes not merely from motion; it is inseparable from the energy they expend in binding themselves and quarks together into longer-lived particles. Solving the mystery of mass therefore requires a better understanding of how gluons "glue." But here, too, gluons throw up roadblocks to deciphering their mysteries.

HOW DO GLUONS BIND?

ON ONE LEVEL, the answer to how gluons glue is simple: they wield the strong force. But this force is itself puzzling.

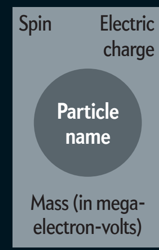
The strong force is one of the four fundamental forces of nature, along with gravitation, electromagnetism and the weak force (the last responsible for radioactive decay). Of these four, it is the most powerful by far (hence its name). In addition to binding quarks together to form hadrons, the strong force is what binds protons and neutrons into atomic nuclei, overcoming the enormous electromagnetic repulsion that exists between like-charged protons in a nucleus. Each of nature's fundamental forces appears to be tied to a particle, a so-called force carrier. Just as the photon—the fundamental unit of light—is the force carrier of electromagnetism, the gluon is the carrier of the strong force.

So far so good. But the strong force sometimes acts in surprising ways. According to quantum mechanics, the distance range of a force is inversely proportional to the mass of its force carriers. The electromagnetic force, for example, has an infinite range; a free electron on Earth will, in principle, experience a slight repulsion from an electron on the other side of the moon. Photons, which carry the force between the electrons, are therefore massless. In contrast to electromagnetism, the range of the strong force does not extend outside the nuclei of atoms. This fact would imply that gluons are very massive. Gluons, however, appear to be massless.

NATURE'S BUILDING BLOCKS

Fundamental Particles

The nuclei inside all the atoms of the universe primarily contain just two of the known fundamental particles: quarks and gluons. Gluons belong to a category called bosons (*right*), which, with the exception of the Higgs, carry nature's forces. Gluons transmit the most powerful of all the forces—the strong force, responsible for binding together quarks inside protons and neutrons. Besides bosons, the other known fundamental particles in the universe are classified as fermions (*left*), which include leptons such as the electron, and quarks. Quarks come in six types, but only the up and down flavors—the ingredients of protons and neutrons—are found in abundance in nature.



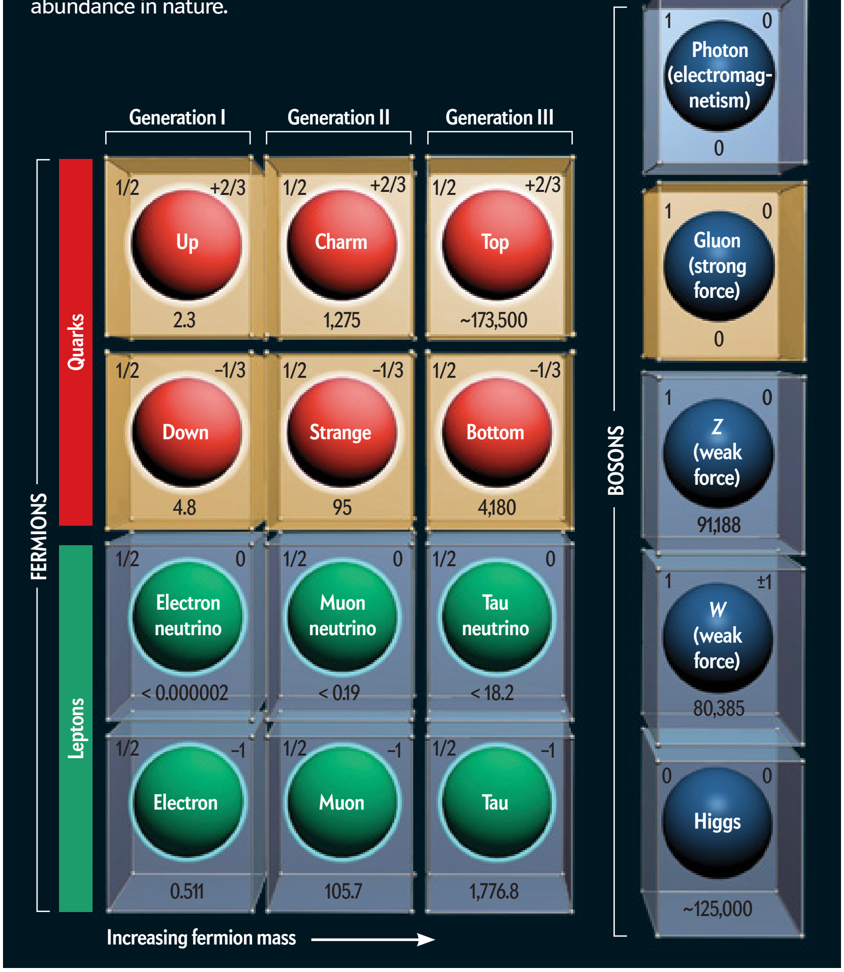


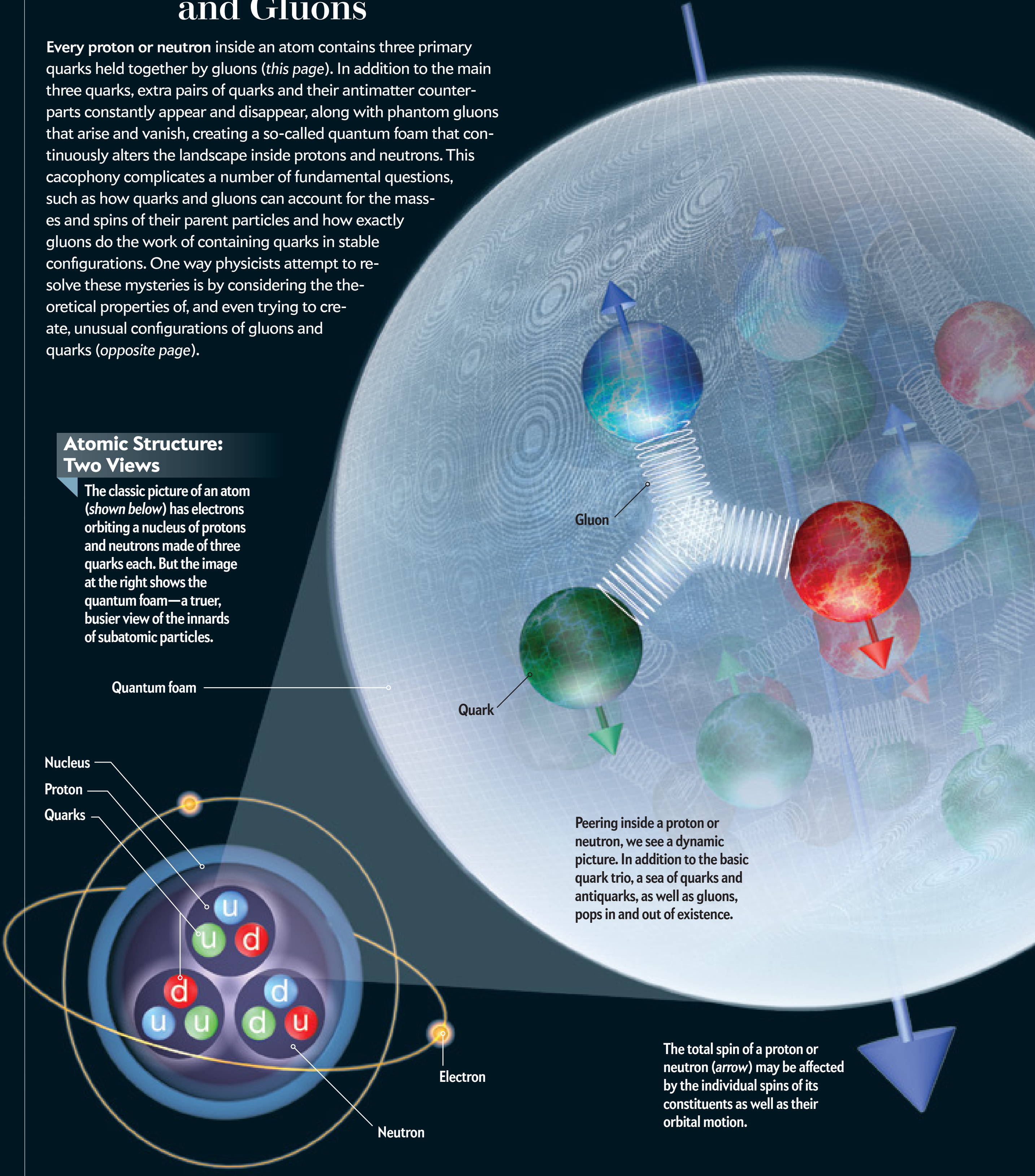
Illustration by Moonrunner Design

The Quandaries of Quarks and Gluons

Every proton or neutron inside an atom contains three primary quarks held together by gluons (*this page*). In addition to the main three quarks, extra pairs of quarks and their antimatter counterparts constantly appear and disappear, along with phantom gluons that arise and vanish, creating a so-called quantum foam that continuously alters the landscape inside protons and neutrons. This cacophony complicates a number of fundamental questions, such as how quarks and gluons can account for the masses and spins of their parent particles and how exactly gluons do the work of containing quarks in stable configurations. One way physicists attempt to resolve these mysteries is by considering the theoretical properties of, and even trying to create, unusual configurations of gluons and quarks (*opposite page*).

Atomic Structure: Two Views

The classic picture of an atom (*shown below*) has electrons orbiting a nucleus of protons and neutrons made of three quarks each. But the image at the right shows the quantum foam—a truer, busier view of the innards of subatomic particles.



Peering inside a proton or neutron, we see a dynamic picture. In addition to the basic quark trio, a sea of quarks and antiquarks, as well as gluons, pops in and out of existence.

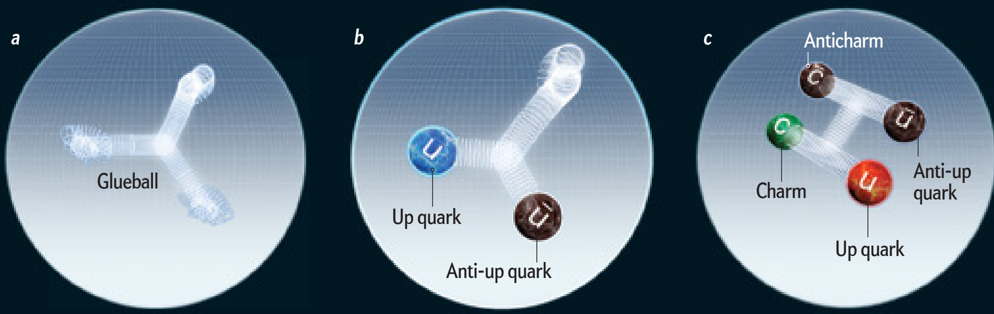
The total spin of a proton or neutron (*arrow*) may be affected by the individual spins of its constituents as well as their orbital motion.

Exotic States of Matter

Physicists have theorized and, in a few cases, created unusual combinations of quarks and gluons beyond the familiar protons and neutrons. These exotic states offer new possibilities for studying the interactions that can occur between quarks and gluons—potentially helping to resolve some basic mysteries of matter.

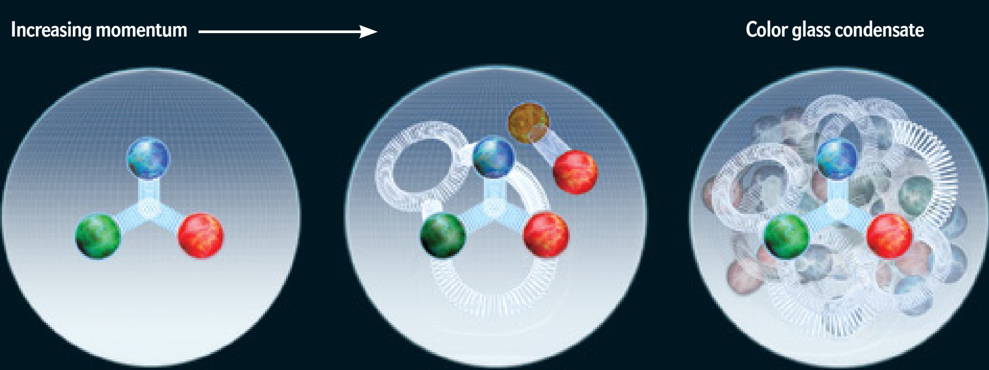
Glueballs and Their Kin

Theoretical simulations suggest that quarks and gluons can combine to create other particles beyond protons and neutrons. For example, "glueball" particles (*a*) made exclusively of gluons may exist, as well as "hybrid" particles made of quark-antiquark-gluon bound states (*b*), or "tetra quark" states where two antiquarks are bound to two quarks (*c*). There is now increasing evidence that tetra quarks have been found, although glueballs and hybrids remain to be discovered.



Saturated State

When protons and neutrons are accelerated to extreme speeds, the gluons inside them multiply. At high speeds the proton's energy increases and gluons split into daughter pairs, each with slightly less energy than the original. The new gluons, in turn, create more daughter gluons with even less energy. Eventually the proton reaches a "maximum occupancy" limit where no more gluons can fit inside—a theorized state called a color glass condensate. Strong hints of such a state have appeared in particle accelerators, but no firm proof exists so far.



Mimic of the Infant Universe

When the cosmos was young, it was too hot for atoms or even stable protons and neutrons to form. Quarks and gluons buzzed around freely in a roiling swarm. Accelerators on Earth recently succeeded in replicating this state, called a quark-gluon plasma (*artist's conception, below left*), by smashing atomic nuclei together at near light speed. By studying the plasma as it cools, physicists can learn not just about the behavior of quarks and gluons but also about the early evolution of our universe.

Illustration by Moonrunner Design

The strong force is also peculiar in that it seems to pull on quarks more strongly the farther away they get. In contrast, the electromagnetic force between two magnets is strongest when they are close and weaker when they are apart. Physicists first observed quarks in the 1960s, in experiments at the Stanford Linear Accelerator Center (now the SLAC National Accelerator Laboratory) that collided energetic electrons off proton targets. Sometimes the electrons passed right through, but other times they hit something solid and bounced back. Their rebound speed and direction revealed the presence and arrangement of the quarks inside protons. These so-called deeply inelastic scattering (DIS) experiments showed that quarks attract one another weakly at short distances; at larger separations, though, no free quarks are seen, which implies that they must pull on one another strongly.

To visualize how the strong force works, imagine two quarks tied together by strings. When they are close to each other, the tension in the string goes slack, and the quarks appear to experience no force. When they move farther apart, the tension in the string holds them together. This force between quarks corresponds to a weight of 16 metric tons at separations that are roughly the size of a proton. But what happens if an outside force pushes against the strong force's pull? The string snaps. Just how string breaking occurs is another mystery we cannot fully explain, and it is central to the story of how gluons glue inside atomic nuclei but not beyond them.

WHY DO SOME PARTICLES HAVE COLORS?

IN THE 1970S PHYSICISTS DEVISED a theory called quantum chromodynamics (QCD) that mathematically describes the strong force. Just as the electromagnetic force revolves around particles' electrical charge, the strong force, according to QCD, revolves around a property known as color charge. The concept of color does help clarify why the strong force behaves so differently from the electromagnetic force, but it also raises a bevy of new conundrums—such as why some particles have color and others lack it and are thus "color-blind."

According to QCD, both quarks and gluons carry color charge. All colored particles interact by exchanging gluons, implying that not only do quarks pass gluons back and forth but that gluons, too, exchange gluons with one another. This implication of quantum chromodynamics is a big leap from electromagnetism—photons do not interact with one another, as transparently demonstrated by crisscrossing light beams in a dusty room. Physicists think, however, that the self-interactions of gluons are central to the reason why the strong force gets weaker at close range. A gluon can temporarily become either a quark-antiquark pair or a gluon pair before turning back into a single gluon. The quark-antiquark fluctuation makes the interaction strength between color charges stronger, whereas the gluon-pair fluctuation makes it weaker. Because such gluon oscillations are more prevalent than the quark exchanges in QCD, they win. (Physicists David J. Gross, Frank Wilczek and H. David Politzer won the 2004 Nobel Prize in Physics for this discovery.)

In the decades since the advent of QCD, experiments worldwide have confirmed the theory's claim as one of the pillars of the Standard Model of physics. Yet many details of QCD remain elusive. Curiously, for instance, although the three quarks in a proton individually carry one of three, say, red, green and blue color charges, the proton does not have a net color charge. Likewise, the quark and the antiquark in a hadron known as a pi-meson (often called pion) carry color charges, but the pion is colorless. Color neutrality of hadrons is analogous to the electrical charge neutrality of atoms. But whereas the zero net charge of atoms is a clear consequence of the canceling out of the proton's positive charge and the electron's negative charge, how colored quarks and colored gluons combine to make colorless hadrons is not clear in QCD.

QCD should also explain how protons and neutrons overcome the powerful electromagnetic repulsion between protons to stick together inside atoms. But despite some progress, deriving nuclear physics from QCD is challenging. This impediment persists because the equations of QCD are fiendishly difficult to solve at the large distances where the interaction strength between quarks and gluons becomes very strong. And we lack a mathematical proof of how the QCD equations ensure that colored quarks and gluons are confined within colorless hadrons. *Confinement* is literally a $1-million problem—it is one of six outstanding puzzles identified by the Clay Mathematics Institute, whose solution will result in the award of $1 million to anyone who provides the answer.

The number of gluons and quarks inside the familiar proton can vary considerably.

WHY DO GLUONS NOT MULTIPLY FOREVER?

A STRIKING CONSEQUENCE of QCD is that the number of gluons and quarks inside the familiar proton can vary considerably. In addition to the basic three quarks, changing numbers of gluons flit around like fireflies, flickering in and out of existence, and pairs of quarks and antiquarks form and dissolve; the result is a "quantum foam" of appearing and disappearing particles. Physicists think that when protons and neutrons reach extreme speeds, the gluons inside the protons split into pairs of new gluons, each with slightly less energy than the parent. The daughter gluons, in turn, produce more daughter gluons, with even less energy. This splitting of gluons resembles an out-of-control popcorn machine. Theory suggests it could go on forever—yet we know it does not.

If gluons continued to procreate, the lid would blow off the popcorn machine—in other words, the proton would become unstable and collapse. Because matter is obviously stable (we exist), it is clear that something must rein in the runaway cascade—but what? One idea is that nature manages to put up a maximum occupancy sign when gluons become so numerous that they begin to overlap within the proton. Strong self-interactions cause them to repel one another, and the less energetic gluons recombine to form more energetic gluons. When the growth in gluon number tapers, the gluons reach a steady state of splitting and recombination called gluon saturation, bringing the popcorn machine under control.

This conjectured saturated gluon state, often called a color glass condensate, would be a distilled essence of some of the

SCIENTIFIC AMERICAN ONLINE See the evolution of the zoo of known subatomic particles at ScientificAmerican.com/may2015/gluons

strongest forces in the universe. So far we have only hints of its existence, and its properties are not fully understood. By probing this state using more powerful DIS experiments than are currently available, physicists will be able to examine gluons closely in their densest, most extreme form. Is the force field limiting the amount of gluons that can build up inside the color glass condensate the same as the confining field that holds protons together in the first place? If so, observing the same field in different contexts could give us new insights into how gluons create it.

WHERE DOES PROTON SPIN COME FROM?

YET ANOTHER MYSTERY about quarks and gluons is how their spin contributes to the overall spin of their parent particles. All hadrons have spin, which is analogous to the rotational energy of a top spinning about its axis. Hadrons with differing spins precess and curl in different directions in the fields of powerful magnets.

Experiments probing a proton's spin show that quarks generate approximately 30 percent of the total. Wherein lies the rest of these hadrons' spin? The many-body picture of the proton as a seething sea of quarks and gluons immediately suggests that the rest of the spin might be contributed by gluons. But experiments smashing polarized protons (with their spins aligned with or opposite to their motion) into other polarized protons indicate that gluon spin constitutes only about 20 percent of a proton's spin—meaning 50 percent of the spin is still missing.

A celestial analogy illustrates a possible solution. The angular momentum of the solar system consists of the sum of the spin of planets about their axes as well as their orbital motion around the sun. Quarks, antiquarks and gluons confined within protons also undergo orbital motion. To understand how significant this orbital motion is, we must map out both the velocities and positions of quarks and gluons inside a proton. One of us (Ent) is involved in performing DIS experiments with very high intensity electron beams to do so. In level of detail, we are moving from snapshots toward 3-D movies of matter at subfemtometer (below one quadrillionth of a meter) distances.

EXOTIC STATES OF MATTER

TO UNDERSTAND THE TRUE NATURE of quark and gluon interactions, we must study them not just in the familiar configurations of protons, neutrons and other well-known particles but in all their possible forms. QCD allows for the existence of exotic hadron states beyond the familiar proton and neutron. Simulations suggest that additional colorless hadrons may exist, such as "glueballs" (which contain gluons exclusively), "molecules" composed of two quark-antiquark pairs or entities that are hybrids classified as quark-antiquark-gluon-bound states. Experimental evidence for these exotic hadrons is limited, with a few tetraquark molecule candidates identified so far. This situation may be about to change significantly, however, thanks to a number of experimental searches going on worldwide. Notably, a dedicated facility called GlueX is starting operations at the Thomas Jefferson National Accelerator Facility in Newport News, Va.

Physicists have recently discovered another extreme state of matter known as a quark-gluon plasma. It forms when atomic nuclei collide at close to light speed. Theorists suspect that when the speeding neutrons and protons of the two nuclei smash into one another, their color glass condensates shatter, breaking the confinement of quarks and gluons and releasing the condensates' energy to create a feverish swarm of quarks and gluons. This plasma is the hottest matter ever created on Earth, with a temperature of more than four trillion degrees Celsius. Strikingly, this material flows with almost no resistance—at least 20 times less than that of water.

The quark-gluon plasma bears a strong similarity to the early universe. Scientists at laboratories that have created such plasmas—Brookhaven National Laboratory's Relativistic Heavy Ion Collider and CERN's LHC—are now observing the world's smallest, most perfect fluids. By watching such plasmas as they cool, two of us (Ullrich and Venugopalan) and others are gaining insights into how the universe evolved. And by engineering the destruction of protons and neutrons into plasma in this way, researchers can study confinement in reverse in hopes of uncovering the secrets to how quarks and gluons stick together.

THE WAY FORWARD

IDEALLY, PHYSICISTS WOULD LIKE to fully map out the locations, motions and spins of gluons and quarks within protons and neutrons. Such maps would help us calculate the contributions that quarks and gluons make to their parent particles' total mass and spin. These maps will provide unprecedented insight into the quark and gluon activities that bind protons and neutrons together. Constructing these images requires a quark-gluon femtoscope—a DIS tool akin to a microscope that would peer inward at the universe at scales as small as 1,000th the radius of a proton. In the U.S., Jefferson Lab and Brookhaven are seeking funding and approval for a femtoscope that would collide electrons with polarized protons and lead nuclei. In contrast to previous experiments that smashed fast-moving electrons at stationary nuclear targets, both types of particles will accelerate to near light speed in this machine before crashing head-on.

The electron-ion collider (EIC) project would achieve unparalleled levels of intensity, meaning the particles in the colliding beams would be packed together so tightly and in such high numbers that crashes would occur with higher frequency than ever before. The increase in crashes, up to 1,000-fold more than a previous DIS collider, would allow investigators to generate many individual snapshots of the innards of protons and neutrons.

Over the past four decades since the formulation of quantum chromodynamics, physicists have made some strides in explaining why the strong force behaves as it does and in understanding where the gaps in our knowledge of quark and gluon dynamics lie. Yet we have not filled in the missing pieces to create a simple and coherent story of how gluons glue. The technologies being developed today give us hope that by the time another 40 years roll around, we will have finally cracked the essential mystery of how matter, at its most fundamental level, is made. SA

MORE TO EXPLORE

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Ultraviolet Behavior of Non-Abelian Gauge Theories. David J. Gross and Frank Wilczek in *Physical Review Letters,* Vol. 30, No. 26, pages 1343–1346; June 25, 1973.

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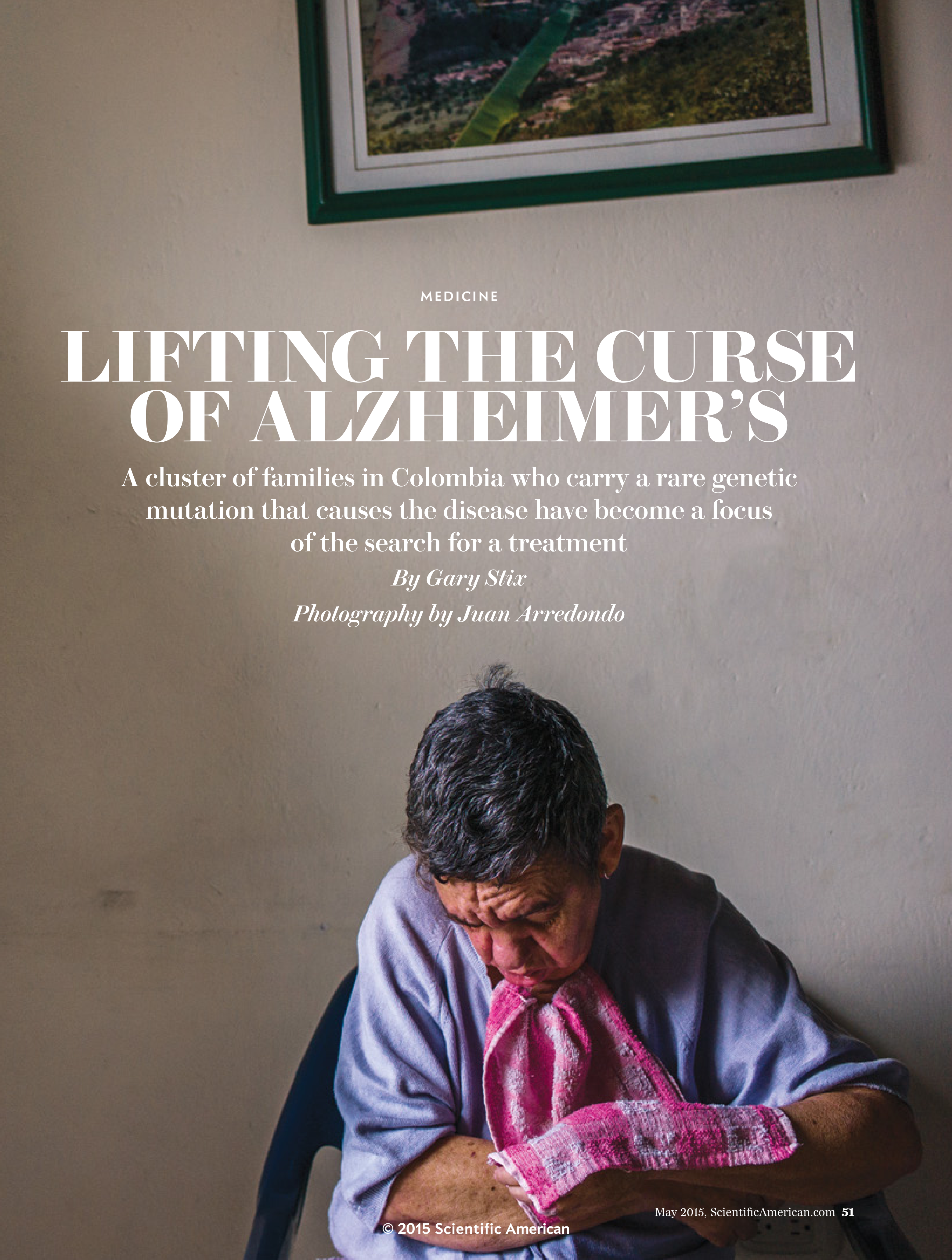
scientificamerican.com/magazine/sa

DAUGHTER AND MOTHER: Carolina, 17, left school to help care for her mother, Yolanda, 53, who has been stricken for years with a hereditary form of Alzheimer's disease.



MEDICINE

LIFTING THE CURSE OF ALZHEIMER'S

A cluster of families in Colombia who carry a rare genetic mutation that causes the disease have become a focus of the search for a treatment

By Gary Stix

Photography by Juan Arredondo

Gary Stix is a senior editor at *Scientific American.*

When Alejandra was a 16-year-old teenager back in 2007, she had the aspirations of any girl her age. She attended an *escuela secundaria* in Medellín, one of Colombia's largest cities. Schoolwork was interspersed with as many hours as she could squeeze in hanging out with friends at favorite haunts throughout the city.

Then her mother, Yolanda, started to lose her memory. The quiet but conscientious woman would say hello to a visitor and, moments later, would repeat the same greeting again—then again. By her mid-40s, Yolanda had developed early-onset Alzheimer's disease. For Alejandra, it meant that her adolescence had come to an end. Like it or not, she had to take on the chief responsibility of full-time care for her increasingly helpless mother.

Alejandra, now 24, has since moved to the nearby municipality of Copacabana, where she shares a concrete block apartment on an upper floor with her aunt and two uncles, nine-year-old daughter, Luna, and 17-year-old sister, Carolina, who dropped out of high school to help. Her mother can no longer talk nor walk; she spends much of her time bent over in a chair. One of the uncles, age 51, also has dementia.

Every day the girls cook for the two Alzheimer's patients. They feed their mother and Uncle Albeiro through tubes. They wash them by hand and carry them to bed. They repeat the same routine day after day, with no break for birthdays or holidays. "I had hopes," Alejandra says. "I had plans. I wanted to study. I wanted to be a nurse. So many plans that I haven't been able to follow through with.… I already feel like I'm becoming old."

Alejandra had a presentiment of her fate long before her mother was formally diagnosed. As a child, she remembers watching her mother tend to her grandmother, who also had Alzheimer's. Many people in this corner of the world share Alejandra's experience. She and her family are among more than 5,000 members in 26 extended families throughout the Colombian province of Antioquia who are at high risk of a rare genetic form of Alzheimer's. Paisa, the label for the mutation that causes the illness, is a regional nickname for the people of Antioquia. Located on chromosome 14, the mutation has been traced back to the time of the conquistadors, in the 16th century. When a copy of the altered gene is inherited from either the mother or father, the child is assured of getting the disease at an early age.

Familial Alzheimer's, as this form of the disease is called, accounts for only about 1 percent of the more than 35 million

IN BRIEF

A Colombian neurologist has found 26 extended families with a rare genetic form of Alzheimer's, many from rural areas outside the city of Medellín.

The size of this group—1,000-plus carriers of a mutation that virtually guarantees individuals will become ill—makes it ideal for an innovative clinical trial.

Participants in the study taking place in Medellín receive an experimental drug, in some cases 15 years before the expected onset of dementia.

A success in a trial to prevent the disease—instead of treating it after a diagnosis—could alter dramatically the way Alzheimer's drugs are developed.

DAILY GRIND: **Alejandra, 24, spends all of her days caring for her mother, Yolanda, leaving too little time for her nine-year-old daughter, Luna, who poses with her grandmother in her First Communion dress (*right*).**

Alzheimer's cases worldwide. (It has gained a high public profile recently because of Julianne Moore's Oscar-winning role in *Still Alice* as a woman suffering from early-onset Alzheimer's.) Among the extended families near Medellín, however, it is disturbingly common. The Paisa mutation is present in more than 20 percent of the 5,000-plus members of the 26 families. A carrier will most likely get the disease before age 50.

The high predictability of Alzheimer's among the people of Antioquia has now begun to attract the attention of specialists from around the world. For years repeated attempts to develop a treatment for Alzheimer's have fallen short. Frustrated by seeing drug after drug fail, scientists have come to the conclusion that it may be too late to stem progression of the disease once symptoms have appeared. Instead they have begun to focus on prevention. Rather than treating people who already show signs of dementia, it may be necessary to administer candidate drugs to individuals who are still healthy and then continually check to see whether they stay that way or develop Alzheimer's.

Running such trials in the general population would be time-consuming and expensive because of the difficulty of forecasting when, or if, the disease will develop—uncertainties not shared by the Colombian families. The families who carry the fateful mutation have been recruited for a clinical trial to test a drug to see if it can fend off Alzheimer's. Having lived with the harsh reality of the disease for centuries, they have emerged as a vital link in the search for preventive treatments.

THE VISION

THE SHIFT TO AN EMPHASIS on prevention in the fight against Alzheimer's builds on the most important advance in research on the disease in recent years. The ongoing clinical trial is deploying magnetic resonance imaging and positron-emission tomography—brain scans that combine with spinal taps to seek out telltale signs of Alzheimer's. Using these technologies, researchers can watch changes occurring in the brain of a person destined to develop dementia sometimes decades before a formal diagnosis of the disease is made.

These new tools can help determine what will happen if a drug, perhaps even one that failed in previous testing, is tried in patients years before they become forgetful. If the brain changes associated with Alzheimer's do not show up on scans—and the patient does not exhibit any cognitive changes—the drug may be helping to stave off the disease. The predictability of Alzheimer's in middle-aged Antioquians with the Paisa mutation has fueled the growing interest in recruiting them for clinical trials to test prevention strategies.

A pivotal figure in this quest is Francisco Lopera, a 63-year-old neurologist who had begun studying the families of Antioquia long before anyone thought they would become important to Alzheimer's research. Lopera spent his teenage years in Yarumal, a town from which many of the families with the Paisa mutation hail. He remembers neighbors from his boyhood who suffered from dementia in middle age. After completing postdoctoral work

DRUG OR PLACEBO? **Orfa, 36, prepares to receive one or the other. Periodically, she takes leave of her job in the coffee fields to come to the University of Antioquia to be part of the Alzheimer's Prevention Initiative.**

in Belgium in the late 1980s, he became convinced he could accomplish more as a researcher in Colombia than if he were to stay to pursue a career at a European research institution. By then, he had found the first family with what he suspected was a genetic form of the disease. In 1987 he returned to Colombia, where he took a position as a neurologist at the University of Antioquia and resumed his study of families with early-onset Alzheimer's.

Lopera, today head of the neuroscience group at the university, has built extensive genealogies of the 26 affected families over the decades. His research has presented obstacles that he would not have encountered if he had stayed in Europe. Maintaining routine contact with the various families sometimes required a military convoy to pass through regions where fighting between the Colombian army and guerilla groups persisted. For a time, about 15 years ago, it even became too dangerous to make the trip at all.

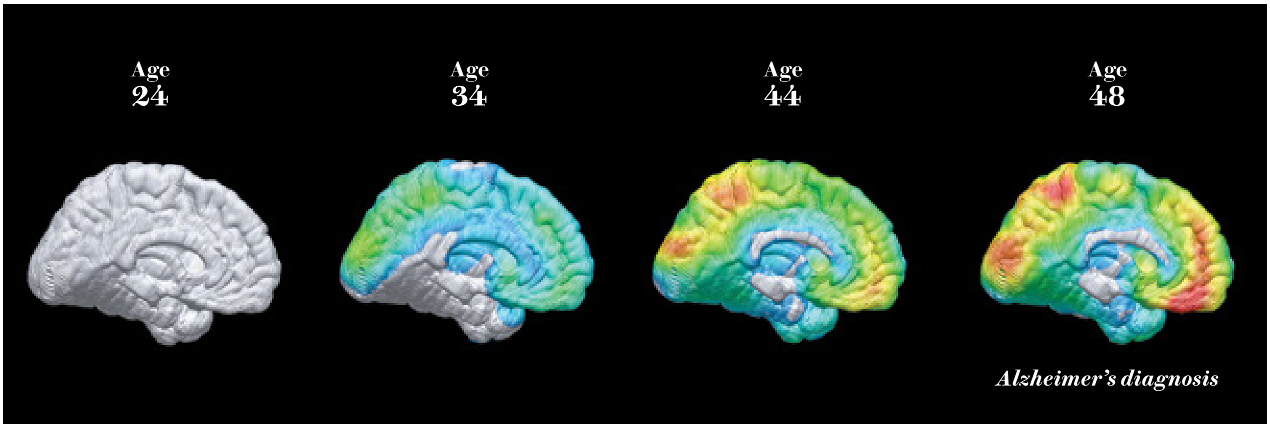
The initial curiosity about families with what appeared to be a genetic form of Alzheimer's evolved into a full-fledged research endeavor. Lopera, together with Kenneth S. Kosik, then at Harvard Medical School, Alison Goate of Washington University in St. Louis and other U.S. investigators, pinpointed the exact location of the Paisa mutation on a gene on chromosome 14 in 1995.

The new focus on prevention results from the overwhelming failure rate of potential treatments tested on Alzheimer's patients. Of the 413 clinical trials from 2002 to 2012, more than 99 percent failed. The few that have received regulatory approval can sometimes provide temporary relief from symptoms, but ultimately they cannot stop the loss of memory or other cognitive abilities.

This lack of success has forced drug companies and academic researchers to contemplate clinical trials while patients are still healthy. By the time the earliest symptoms of Alzheimer's appear, current thinking holds, neurons may have already started to die and communication links from one brain cell to another no longer function. When memory problems start to appear, no drug may be able to rescue a patient from the disease.

The 26 extended Colombian families are ideal for studying preventive treatments because the more than 1,000 Paisa mutation carriers among them provide a large enough pool of potential study participants to obtain meaningful results in a clinical trial. And because familial Alzheimer's is so predictable in this group, researchers can work backward by 10 to 15 years to calculate when to start giving a drug to stop the disease.

The existence of these extended families gained enough visibility that it drew interest from the Banner Alzheimer's Institute in Phoenix, which then brought the group to the attention of major drug companies in 2010 to convince them to contemplate prevention trials. Banner partnered with Genentech and the University of Antioquia on a trial of crenezumab, a monoclonal antibody that is intended to bind and help to remove toxic beta-amyloid protein fragments in the brain. The effort has received more than $100 million from Genentech, the Banner Alzheimer's Foundation and the U.S. National Institutes of Health.



Watchful Waiting

Clinical trials to prevent Alzheimer's have become possible because of the arrival of technologies—brain scans, spinal taps and highly sensitive psychological tests—to determine if the disease is progressing before a person becomes forgetful. A specialized form of positron-emission tomography shows a typical buildup of harmful beta-amyloid in the brains of carriers of the Paisa mutation (*colored regions above*) at various ages through the time of an Alzheimer's diagnosis. Beta-amyloid deposits are absent from brains of members of these families at the same ages if they do not carry the mutation (*not shown*). Another technology in the Colombian clinical trial, magnetic resonance imaging, reveals whether brain shrinkage has occurred as much as 10 years before a diagnosis is made (*below*).

COURTESY OF ERIC M. REIMAN *Banner Alzheimer's Institute (brain scans)*

THE TRIAL

CALLED THE ALZHEIMER'S PREVENTION INITIATIVE, the trial is unusual in several respects. It is being conducted outside the safe confines of a major medical center in Boston or San Francisco. And neither Lopera nor the University of Antioquia had prior experience with clinical trials of any kind—let alone putting in place the still evolving testing protocols for determining whether a drug is effective in stopping a disease, in some cases 15 years before symptoms appear. "Normally nobody believes that you can do this kind of ambitious project in Latin America," Lopera says. Banner "believed in us, and that was very fortunate because we've shown that we can work with them in a serious way. And this project got started successfully because of that confidence."

In late 2013 the research team began administering the drug to study participants, most of whom are in their 30s and 40s. More participants are still being recruited, but the eventual goal is to administer the drug subcutaneously to 100 carriers of the Paisa mutation. (There are also two placebo groups, made up of 100 carriers and 100 noncarriers.) Each subject will undergo a testing period of five years. Brain scans and spinal taps will determine whether the drug has halted the accretion of beta-amyloid. Psychological tests will look for cognitive decline.

If crenezumab was found to alter the course of the disease, it would constitute a breakthrough in Alzheimer's medicine. Trials would then begin to determine if the drug worked in healthy elderly people who do not have the Paisa mutation but whose brain scans show that pathological changes have very recently begun to occur.

The long-standing relationships that Lopera and his colleagues have cultivated with the 26 affected families over the course of decades have been key to recruiting and retaining patients for the trial. Lopera, with his long, gray hair parted down the middle, brings an avuncular presence to his dealings with family members. Last November, when he learned that a few journalists visiting Medellín planned to publish the surnames of patients they had met, he was adamantly opposed even though they had received permission. Lopera explained how doing so might tarnish a family name, even for those who do not carry the mutation. It might then become difficult for family members to get insurance or find a marriage partner.

The Colombian families, their memories of sick relatives stretching back multiple generations, have embraced the trial wholeheartedly. Shehnaaz Suliman, project head for the study at Genentech, expects that trial participants, many of whom must travel long distances to the hospital, are more likely to show up to receive routine drug injections than the average group of enrollees in a study being carried out in the U.S. or Europe.

Her conviction may have been reinforced by Antioquia residents such as Hugo, a 40-year-old who was working last November tending horses for wealthy owners in the town of El Retiro. Hugo makes the 20-mile trip every two weeks to Medellín to receive his treatment: either crenezumab or a placebo. Neither he nor the medical personnel who administer the injection know which it is.

Even if he turns out to be in the placebo group, Hugo says he understands why these clinical trials are important. His father and grandfather died of Alzheimer's, and four of his uncles, two of whom are now deceased, have had it. Hugo remembers how his father, once stricken, would obsessively polish family members' shoes all day and would become frantically anxious if he lost sight of his wife for just a second. "It's hard," Hugo says. "It's a legacy that comes from very long ago, and you have to face up to it."

The trials have provided a shred of hope for Hugo and his relatives. "We're doing fine because, with Dr. Lopera, we're hoping that there will be a positive result with these treatments and that there may be a cure for our children." As he speaks, Hugo sits on a bench in a picnic area near the stables. Dogs bark loudly. He locks one arm with one his nieces, who had taken the arm of her sister at her side.

Despite the burden of the family's medical history, Hugo and several family members who gather one gray November day seem to be a model of psychological resilience. They needle one another about forgetting small details and how that might mark an early sign of the disease. I ask Hugo's sister, Gudiela, age 47, who is also in the trial, if she worries about getting dementia. "Truthfully, no," she says without missing a beat. "The person who's got to worry is the person who is going to take care of me"—a response that is met with prolonged guffaws.

The first indication of whether the Colombian trial is helping people who carry the Paisa mutation will not come until 2018—the trial ends in 2021. There is no guarantee for crenezumab. It failed in a U.S. clinical trial in patients with mild to moderate Alzheimer's in mid-2014. Further analysis of the results showed that it might have provided some benefit in the early stages of the disease. For just this reason, researchers are moving ahead

SCIENTIFIC AMERICAN ONLINE See more photographs related to the Colombian Alzheimer's clinical trial at ScientificAmerican.com/may2015/alz

WILLING PARTICIPANTS: Hugo, 40 (*left*), and Gudiela, 47 (*above*), welcome the prevention trial. Even if the trial does not benefit them, it may help their family's next generation, members of whom surround Gudiela.

with the Colombian trial to determine what will happen if the drug is administered long before the first symptoms appear.

Even if crenezumab fails in Colombia, all may not be lost. The trial is the best test to date of the 30-year-old beta-amyloid hypothesis, the idea that toxic protein fragments are the cause of the pathology of Alzheimer's. If the trial does not show any benefit for Hugo, Gudiela and other members of the 26 families—and if other prevention trials just starting in the U.S. are also a bust, the scientific research establishment will have to start turning its attention to possible alternatives to the beta-amyloid hypothesis. They may need to test drugs that attempt to counter the buildup of toxic proteins other than beta-amyloid, and they may also look for chemical agents that protect neurons or deal with the biochemical processes underlying brain inflammation.

Even then, the infrastructure built in Medellín to conduct clinical trials on crenezumab may still serve its original purpose by examining new approaches to prevent the disease. The ability to predict when the disease will occur in a given patient among the Paisa mutation group may continue to be an invaluable asset to drug researchers for future trials. Medellín is now emerging as a major international center for investigating Alzheimer's—and a possible venue for a significant breakthrough—a status that may persist for years to come.

The city may have the needed staying power because the social structure of these families—and the reality of dementia in parents, grandparents, uncles and aunts—will likely keep attracting participants for clinical trials. Family members, moreover, exhibit a natural inclination in caring for the sick, a contrast to the depersonalized medicine too often practiced in the U.S. and Europe. Hugo remembers taking short walks with his father down the block, holding his hand to make sure he did not stray and then be unable to find his way home.

The close-knit family structure ensures that a rural laborer, often accompanied by relatives, will show up reliably at the hospital every two weeks to receive a drug or a brain scan. The curse of the conquistadors could turn out to be a blessing in disguise in discovering a pivotal medical advance that can benefit millions worldwide destined to receive a dreaded diagnosis. SA

MORE TO EXPLORE

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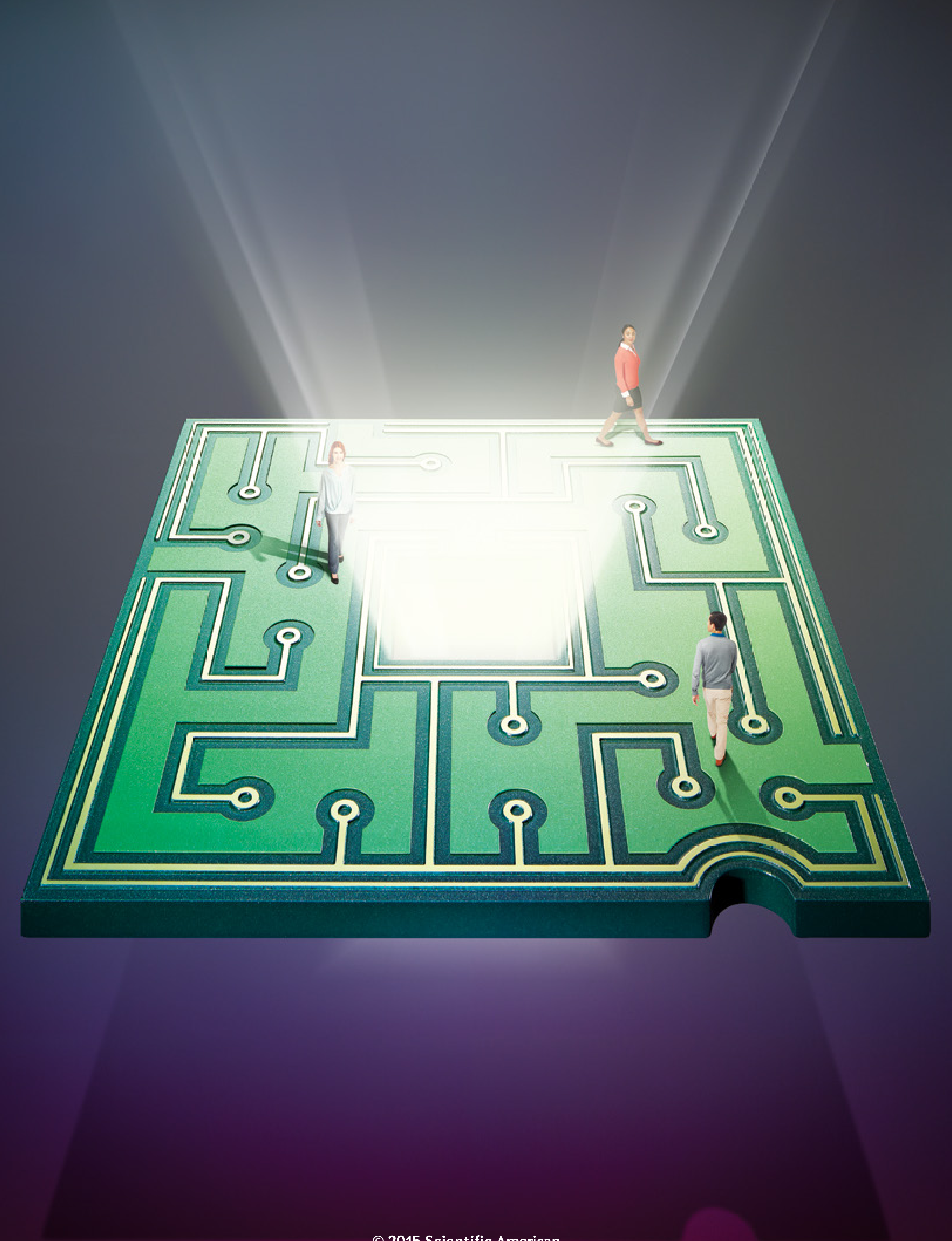

THE SEARCH FOR A NEW MACHINE

With the end of Moore's law in sight, chip manufacturers are spending billions to develop novel computing technologies

By John Pavlus

In a tiny, windowless conference room at the R&D headquarters of Intel, the world's dominant microprocessor and semiconductor manufacturer, Mark Bohr, the company's director of process architecture and integration, is coolly explaining how Moore's law, as it is commonly understood, is dead—and has been for some time. This might seem surprising, given that Bohr is literally in the Moore's law business: his job is to figure out how to make Intel's current 14-nanometer-wide transistors twice as small within the decade. But behind his round-rimmed glasses, Bohr does not even blink: "You have to understand that the era of traditional transistor scaling, where you take the same basic structure and materials and make it smaller—that ended about 10 years ago."

In 1965 Gordon Moore, then director of R&D at Fairchild Semiconductor, published the bluntly entitled document "Cramming More Components onto Integrated Circuits." Moore predicted that the number of transistors that could be built into a chip at optimal cost would double every year. A decade later he revised his prediction into what became known as Moore's law: every two years the number of transistors on a computer chip will double.

Integrated circuits make computers work. But Moore's law makes computers evolve. Because transistors are the "atoms" of electronic computation—the tiny switches that encode every 1 and 0 of a computer's memory and logic as a difference in voltage—if you double the number of them that can fit into the same amount of physical space, you can double the amount of computing you can do for the same cost. Intel's first general-purpose microprocessor, the 8080, helped to launch the PC revolution when it was released in 1974. The two-inch-long,

Photoillustration by Dan Saelinger

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candy bar–shaped wafer contained 4,500 transistors. As of this writing, Intel's high-performance server central processing units (CPUs)—the highest-density chips commercially available—contain 4.5 billion transistors each. Inside Intel's Hillsboro, Ore., fabrication facilities, or "fabs," the company's latest manufacturing process can etch features as small as 14 nanometers into a wafer of silicon. That is thinner than a bacterium's flagellum. Such exponential growth in transistor density turned the room-sized, vacuum tube–powered calculating engines of the mid-20th century into the miniaturized silicon marvels of the early 21st.

But even Moore's law buckles under the laws of physics—and within a decade it will no longer be possible to maintain this unprecedented pace of miniaturization. That is why chip manufacturers such as Intel, IBM and Hewlett-Packard (HP) are dumping billions of R&D dollars into figuring out a post–Moore's law world. It will require blowing up basic assumptions about what our technology requires to function. Does a computer chip need to be a two-dimensional array of wires etched into silicon? IBM thinks not: it is seriously investigating carbon nanotubes and graphene as a computational substrate. What about electrons—are those necessary? IBM and HP are also placing bets on photonics, which uses pulses of light instead of voltage.

HP is going even further; it wants to extend the fundamental theory of electronics itself. The company has built a prototype computer, code-named "the Machine," that leverages the power of a long-sought missing link of electronics: the memristor. This component—mathematically predicted decades ago but only recently developed—allows the storage and random-access memory (RAM) functions of computers to be combined. The common metaphor of the CPU as a computer's "brain" would become more accurate with memristors instead of transistors because the former actually work more like neurons: they transmit and encode information as well as store it. Combining volatile memory and nonvolatile storage in this way could dramatically increase efficiency and diminish the so-called von Neumann bottleneck, which has constrained computing for half a century.

None of these technologies are ready to replace, or even augment, the chips in our laptops or phones in the next few years. But by the end of the decade at least one of them must be able to deliver computational performance gains that have a chance of taking over where traditional silicon circuit engineering inevitably trails off. The question is: Which one—and when?

BEYOND SILICON

THE IDEA BEHIND Moore's law is simple—halving the size of a transistor means you can get double the computing performance for the same cost. But there has always been more to it than that. Gordon Moore's 1965 paper may have predicted *what* would happen to transistor density every other year, but he never described *how* performance doubling would emerge from that increased density. It took another nine years for a scientist at IBM named Robert Dennard to publish an explanation now known as Dennard scaling. It describes how the power density of MOSFETs (which stands for "metal-oxide-semiconductor field-effect transistors," the dominant technology in 1974) stays constant as their physical size scales down. In other words, as transistors shrink, the amount of electric voltage and current required to switch them on and off shrinks, too.

For 30 years Dennard scaling was the secret driver of Moore's law, guaranteeing the steady PC performance gains that helped people start businesses, design products, cure diseases, guide spacecraft and democratize the Internet. And then it stopped working. Once fabs began etching features into silicon smaller than 65 nanometers (about half the length of an HIV virus), chip designers found that their transistors began to "leak" electrons because of quantum-mechanical effects. The devices were simply becoming too tiny to reliably switch between "on" and "off"—and any digital computer that cannot tell the difference between 1 and 0 has a serious problem. Not only that, researchers at IBM and Intel were discovering a so-called frequency wall that put a limit on how fast silicon-based CPUs could execute logical operations—about four billion times per second—without melting down from excess heat.

Technically, Moore's law could carry on (and did): Intel continued to cram tinier transistors into its wafers every two years. Yet it did not neatly translate into cheaper, faster computers.

Since 2000, chip engineers faced with these obstacles have been developing clever work-arounds. They have dodged the frequency wall by introducing multicore CPUs (a 10-gigahertz processor will burn itself up, but four, eight or 16 3-GHz processors working together will not). They have shored up leaky transistors with "tri-gates" that control the flow of current from three sides instead of one. And they have built systems that let CPUs outsource particularly strenuous tasks to special-purpose sidekicks (an iPhone 6's screen, for instance, is driven by its own four-core graphics processor). But these stopgaps will not change the fact that silicon scaling has less than a decade left to live.

That is why some chipmakers are looking for ways to ditch silicon. Last year IBM announced that it was allocating $3 billion to aggressively research various forms of postsilicon computing. The primary material under investigation is graphene: sheets of car-

IN BRIEF

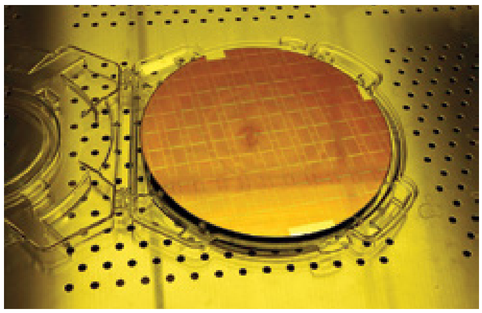
Progress in computing depends on Moore's law, the idea that every two years the number of transistors on a computer chip will double. But transistors can become only so small before engineers run up against the laws of physics, and that time is drawing near.

As a result, chip manufacturers are spending billions to develop fundamentally new computing architectures and processor designs, some based on new materials. Ideas long studied in laboratories are now being pursued with commercial fervor.

It is too early to tell which technologies will emerge as winners. The most likely outcome is that specialized technologies will come to perform specific tasks once assigned to a single central processor: Moore's law, singular, will be replaced by Moore's laws, plural.

bon just one atom thick. Like silicon, graphene has electronically useful properties that remain stable under a wide range of temperatures. Even better, electrons zoom through it at relativistic speeds. And most crucially, it scales—at least in the laboratory. Graphene transistors have been built that can operate hundreds or even thousands of times faster than the top-performing silicon devices, at reasonable power density, even below the five-nanometer threshold in which silicon goes quantum.

Yet unlike silicon, graphene lacks a “bandgap”: the energy difference between orbitals in which electrons are bound to the atom and those in which the electrons are free to move around and participate in conduction. Metals, for example, have no bandgap: they are pure conductors. Without a bandgap, it is very difficult to stem the flow of current that turns a transistor from on to off—which means that a graphene device cannot reliably encode digital logic. “We have been the leaders in this area, but the results we have seen with graphene have not been encouraging,” admits Supratik Guha, director of physical sciences at the IBM Thomas J. Watson Research Center. “Graphene has to be very cheap *and* provide some unique advantage for it to dislodge existing materials. It has very interesting properties, but it doesn’t have a killer application that we’ve been able to identify.”



Dharmendra Modha, founder of IBM’s cognitive computing group, wants to build computer chips that are at least as “smart” as a housefly.

COURTESY OF IBM (*TrueNorth microchip wafer*)

Carbon nanotubes may hold more promise. When sheets of graphene are rolled into hollow cylinders, they can acquire a small bandgap that gives them semiconducting properties akin to what silicon has, reopening the possibility of using them for digital transistors. “We’re cautiously optimistic,” Guha says. “Carbon nanotubes as individual devices, when they’re scaled down to 10 nanometers or so, outperform anything else available. If we look at our simulations of computing systems using carbon nanotubes, we expect that there may be a fivefold improvement [over silicon] in performance or energy efficiency.”

But carbon nanotubes are delicate structures. If a nanotube’s diameter or chirality—the angle at which its carbon atoms are “rolled”—varies by even a tiny amount, its bandgap may vanish, rendering it useless as a digital circuit element. Engineers must also be able to place nanotubes by the billions into neat rows just a few nanometers apart, using the same technology that silicon fabs rely on now. “For carbon nanotubes to become a worthy successor to silicon, we need to figure all this out within the next two or three years,” Guha says.

BREAKING DOWN THE MEMORY WALL

“WHAT’S THE MOST expensive real estate on the planet?” Andrew Wheeler asks. “This, right here.” He points to a box drawn in black marker on a whiteboard, representing the die of a microchip. Tall, wiry and square-jawed in straight-leg jeans and a checked cotton shirt, Wheeler looks more like an ex-cowboy than the deputy director of HP Labs, Hewlett-Packard’s research arm. He is explaining what most of the transistors occupying that premium real estate are actually used for. It is not for computation, he says. It is called “cache memory” or static RAM (SRAM), and all it does is store frequently accessed instructions. It is the silicon equivalent of the dock on your Mac—the place where you keep things you want to avoid digging for. Wheeler wants it to disappear. But he is getting ahead of himself. In the near term, he will settle for getting rid of your computer’s hard drive and main memory.

According to HP, these three items—collectively known as the memory hierarchy, with SRAM at the top and hard drives at the bottom—are responsible for most of the problems faced by engineers grappling with Moore’s law. Without high-speed, high-capacity memory to store bits and ship them as quickly as possible, faster CPUs do little good.

To break down this “memory wall,” Wheeler’s team in Palo Alto, Calif., has been designing a new kind of computer—the Machine—that avoids the memory hierarchy altogether by collapsing it into one unified tier. Each tier in the memory hierarchy is good at some things and bad at others. SRAM is extremely fast (so it can keep up with the CPU) but power-hungry and low-capacity. Main memory, or dynamic RAM (DRAM), is pretty fast, dense and durable—which is good, because this is the workbench that your computer uses to run active applications. Of course, cutting the power makes everything in DRAM disappear, which is why “nonvolatile” storage media such as flash and hard disks are necessary for saving data in long-term storage. They offer high capacity and low power consumption, but they are glacially slow (and flash memory wears out relatively quickly). Because each memory medium has overlapping trade-offs, modern computers link them together so that CPUs can shuttle data up and down the tiers as efficiently as possible. “It’s an absolute marvel of engineering,” Wheeler says. “But it’s also a huge waste.”

A universal memory that could combine the speed of SRAM, the durability of DRAM, and the capacity and power efficiency of flash storage has been a holy grail for engineers, designers and programmers for decades, Wheeler says. The Machine exploits an electronic component, the memristor, to cover the latter two items on the universal-memory wish list. Mathematically predicted in 1971, the memristor—which is a blend of the words “*mem*ory *resistor*” because the device’s ability to conduct electricity depends on the amount of current that previously flowed through it—was long believed to be impossible to build. In 2008 HP announced that it had constructed a working memristor; the research program was internally fast-tracked and became the precursor of the Machine.

Pulsing a memristor memory cell with voltage can change its conductive state, creating the clear on/off distinction necessary for storing digital data. As with flash memory, that state persists when the current is removed. And like DRAM, the cells can be read and written at high speed while densely packed together.

To achieve SRAM-like performance, though, memristor cells would need to be placed adjacent to the CPU on the same die of silicon—a physically impractical arrangement with current technology. Instead HP plans to employ photonics—shipping bits as pulses of laser light instead of electric current—to connect its high-performance memristor memory to the standard SRAM caches on logic processors. It is not quite the holy grail of universal memory—the Machine collapses the memory hierarchy from three tiers to two—but it is close.

By combining RAM with nonvolatile storage, a memristor-based architecture like the Machine could enable massive increases in computer performance without relying on Moore's law–style miniaturization. The version of IBM's Watson supercomputer that beat human contestants on *Jeopardy* in 2011 needed 16 terabytes of DRAM—housed in 10 power-guzzling Linux server racks—to perform its feats in real time. The same amount of nonvolatile flash memory could fit into a shoe box while consuming the same amount of power as an average laptop. A memory architecture that combined both functions at once would allow enormous data sets to be held in active memory for real-time processing rather than diced into smaller, sequential chunks—and at much lower energy costs.

As more and more connected devices join the "Internet of Things," the problem of streaming countless petabytes of information to and from data centers for storage and processing will make Moore's law moot, Wheeler says. Yet if universal memory enables supercomputerlike capabilities in smaller, less energy-hungry packages, these data streams could be stored and preprocessed locally by the connected devices themselves. Silicon CPU elements might never get smaller than seven nanometers or faster than four gigahertz—but with the memory wall torn down, it may no longer matter.

BEYOND VON NEUMANN

EVEN IF HP SUCCEEDS in its gambit to build universal memory, computers will still remain what they have always been since ENIAC, the first general-purpose computer, was built in 1946: extremely fast numerical calculators. Their essential design, formalized by mathematician John von Neumann in 1945, consists of a processing unit to execute instructions, a memory bank to store those instructions and the data they are to operate on, and a connection, or "bus," linking them. This von Neumann architecture is optimized for executing symbolic instructions in a linear sequence—also known as doing arithmetic. The first "computers" were human beings paid to sit in a room and work out calculations by hand, so it is no coincidence that electronic computers were designed to automate that tedious and error-prone process.

But today we increasingly need computers to do jobs that do not map well to linear mathematical instructions: tasks such as recognizing objects of interest in hours of video footage or guiding autonomous robots through unstable or dangerous territory. These tasks have more in common with the sensing, pattern-matching abilities of biological brains than mechanical calculators. Organisms must extract actionable information from a dynamic environment in real time; if a housefly were forced to pass discrete instructions back and forth, one by one, between separate memory and processor modules in its brain, it would never complete the computation in time to avoid getting swatted.

Dharmendra Modha, founder of IBM's cognitive computing group, wants to build computer chips that are at least as "smart" as that housefly—and as energy-efficient. The key, he explains, has been to scrap the calculatorlike von Neumann architecture. Instead his team has aimed to mimic cortical columns in the mammalian brain, which process, transmit and store information in the same structure, with no bus bottlenecking the connection. IBM's recently unveiled TrueNorth chip contains more than five billion transistors arranged into 4,096 neurosynaptic cores that model one million neurons and 256 million synaptic connections.

What that arrangement buys is real-time pattern-matching performance on the energy budget of a laser pointer. Modha points to a video monitor in the corner of the demo room at the IBM Almaden research campus in San Jose, Calif. The scene on it looks like surveillance footage from a camera that needs a hard reboot: cars, pedestrians, and a bicycle or two are frozen in place on a traffic roundabout; one of the pedestrians is highlighted by a red box superimposed on the image. After a minute, the cars, people and bikes lurch into a different frozen position, as if the footage suddenly skipped ahead.

It turns out that we do not want stand-alone, oraclelike "thinking machines" as much as late 20th-century science-fiction writers thought we would.

"You see, it's not a still image," Modha explains. "That's a video stream from Stanford's campus being analyzed by a laptop simulating a TrueNorth chip. It's just running about 1,000 times slower than real time." The actual TrueNorth chip that usually runs the video stream was being used for an internal training session in an auditorium next door, so I was not witnessing the chip's real performance. If I were, Modha says, the video feed would be playing at real-time speed, and the little red boxes would smoothly track the pedestrians as they entered and exited the frame.

Just like their von Neumann architecture counterparts, neurosynaptic devices such as TrueNorth have their own inherent weaknesses. "You wouldn't want to run iOS with this chip," Modha says. "I mean, you could, but it would be horribly inefficient—just like the laptop is inefficient at processing that video stream." IBM's goal is to harness the efficiencies of both architectures—one for precise and logical calculation, the other for responsive, associative pattern matching—into what it describes as a holistic computing system.

In this vision, the classic formulation of Moore's law still matters. Modha's team has already tiled 16 TrueNorth chips into a board, and by the end of this year the group plans to

SCIENTIFIC AMERICAN ONLINE See a slide show of new chip technologies at ScientificAmerican.com/may2015/moores-law

stack eight boards together into a 100-watt, toaster oven–sized device whose computational power "would require an entire data center to simulate."

In other words, silicon and transistor counts still matter—but what matters more is how they are arranged. "That was our insight: by rearranging the bricks, you get a very different functionality in the building," Modha says. "A lot of people believed, including us at first, that you really needed to change the technology to get the gains. In fact, it became clear that while new technology may bring gains, a new architecture gave orders-of-magnitude gains in performance that were easy pickings in comparison."

MOORE'S LAWS

BACK AT BUILDING RA3 in Hillsboro, Michael C. Mayberry, Intel's director of components research, is dispelling another myth about Moore's law: it was never really about transistors. "Cost per function is the game," he says. Whether it is measured in transistors per square centimeter of silicon, instructions of code executed per second, or performance per watt of power, all that matters is doing ever more work with ever fewer resources. It is no surprise that on its own Web site, Intel describes Moore's law not as a technological trend or force of nature but as a business model.

"When someone asks me, 'What keeps you up at night about Moore's law?' I say, 'I sleep fine,'" Mayberry says. "When Dennard scaling ended, that doesn't mean we stopped. We just changed. If you look forward 15 years, we can see several changes coming, but it doesn't mean we're going to stop." What Intel, IBM and HP all agree on is that the future of computational performance—that is, how the industry will collectively deliver increased function at decreased cost—will cease to look like a line or a curve and will instead look more like the multibranching tree of biological evolution itself.

That is because our vision of computers themselves is evolving. It turns out that we do not want stand-alone, oraclelike "thinking machines" as much as late 20th-century science-fiction writers thought we would. What is really dying is not Moore's law but the era of efficient general-purpose computation that Moore's law described and enabled. "Cramming everything into the box that you can," as Mayberry puts it.

Instead the relentless pursuit of lower cost per function will be driven by so-called heterogeneous computing, as Moore's law splits into Moore's laws. Companies such as IBM, Intel, HP and others will integrate not just circuits but entire systems that can handle the multiplying demands of distinct computational workloads. Bernard S. Meyerson of IBM says that people buy functions, not computer chips; indeed, they are less and less interested in buying computers at all. We just want our tools to compute, or "think," in ways that make them helpful in the contexts in which we use them. So instead of HAL, the superintelligent computer from *2001: A Space Odyssey,* we have Google Now on a smartphone telling us when to leave for the airport to catch a flight.

Futurists such as Nick Bostrom (author of *Superintelligence: Paths, Dangers, Strategies*) presume that Moore's law will cause generalized artificial intelligence to take off and coalesce into a kind of all-knowing, omnipotent digital being. But heterogeneous computing suggests that computation is more likely to diffuse outward into formerly "dumb" objects, systems and niches—imbuing things such as cars, network routers, medical diagnostic equipment and retail supply chains with the semiautonomous flexibility and context-specific competence of domestic animals. In other words, in a post–Moore's law world, computers will not become gods—but they will act like very smart dogs.

And just as a Great Dane is not built to do the job of a terrier, a graphics processor is not built to do the work of a CPU. HP's Wheeler offers the example of multiple special-purpose processing cores "bolted onto" a petabyte-scale pool of universal memory—a hybrid of processing power and massive memory that works in much the same way that dedicated graphics accelerators and memory caches are marshaled around centralized CPU resources now. Meanwhile IBM's Modha envisions golf ball–size devices, consisting of cognitive chips fastened to cheap cameras, that could be dropped into natural disaster sites to detect highly specific patterns such as the presence of injured children. Computer scientist Leon Chua of the University of California, Berkeley, who first theorized the existence of memristors in 1971, says that HP's efforts to collapse the memory hierarchy and IBM's research on reimagining the CPU are complementary responses to what he calls "the Great Data Bottleneck." "It's incredible that the computers we've been using for everything for the past 40 years are all still based on the same idea" of the calculatorlike von Neumann architecture, he says. The two-front transition to heterogeneous computing is "inevitable," he asserts, and "will create an entirely new economy"—not least because post–Moore's law, post–von Neumann computing will require entirely new methods of programming and designing systems. So much of modern computer science, engineering and chip design is concerned with masking the inherent limitations that the memory hierarchy and von Neumann architecture impose on computation, Chua says, that once those limitations are removed, "every computer programmer will have to go back to school."

What Chua, Modha and Wheeler never mention in these near-future visions are transistors—or the predictable performance gains that the world has come to expect from them. According to IBM's Meyerson, what Moore's law has accurately described for half a century—a tidy relation between increased transistor density and decreased cost per function—may turn out to be a temporary coincidence. "If you look at the past 40 years of semiconductors, you can see a very constant heartbeat," Meyerson says. "It's not that progress won't continue. But this technology has now developed an arrhythmia." SA

MORE TO EXPLORE

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des

ROUGH SEAS: North of Russia, near the Arctic islands of Franz Josef Land, open waters—which had more ice cover in the past—toss up choppy waves.

OCEANOGRAPHY

waves of truction

Scientists chase towering seas that smash Arctic ice, with far-flung effects on climate and ecology

By Mark Harris

IN BRIEF

Arctic sea ice has been melting faster than predicted by global warming models, puzzling scientists.

Giant waves, never seen before, may be the reason. A little ice melt gives waves room to grow large and powerful.

The large waves can smash still more ice as they crash around, creating more open water and more waves.

Newly opened Arctic seas may affect faraway weather patterns, erode coasts and challenge national security.

Mark Harris is a science and technology writer living in Seattle.

THE SUMMER OF 2014 WAS A STRANGE ONE IN THE CHUKCHI SEA. THE ARCTIC WATERS, historically icebound much of the year, were oddly free of ice. There was so little ice that 35,000 walruses had beached themselves on a northwest Alaska shoreline after failing to find floes to feed from. One morning in September, oceanographer Jim Thomson was on a research trip onboard the vessel *Norseman II,* hundreds of miles from land, when he noticed something else that was strange: some of his shipmates were seasick.

Nausea might sound pretty ordinary for a trip to the high seas but not out here, where the Chukchi meets the Beaufort Sea. This remote area usually has no room for waves to build. Now there was open water, and the waves were huge—15-foot rollers that tossed the ship around and exploded over its decks. The sea was so rough that the captain could not safely sail against the waves and had to run in front of them. While Thomson, a seasoned sailor, watched his fellow researchers stumbling around the ship, looking as if they were about to lose their lunch, he was reveling in the stormy weather. He had come to hunt waves, and here they were.

"These were bigger than had ever been measured or talked about or conceived of in the Arctic," Thomson recalls. A few months earlier he had deployed a small fleet of aquatic drones to monitor the seas; that day he was trying to pick one up. "In fact, the largest wave heights we recorded for the whole year were about six hours before we recovered the robot," he adds.

These waves may be the answer to an important and troubling mystery: Why is Arctic ice vanishing so fast? Climate models, driven by measurements of global warming, had projected a slower rate of shrinkage. Either the models were wrong, or something else was going on. That something, Thomson and other scientists now believe, had to do with waves. Climate-triggered melting gave waves extra room to grow, which let the rollers take over, pounding away at the ice pack and splintering it into nonexistence. When Thomson put out similar robotic buoys in 2012, one of them was tossed by a towering wave that lifted the buoy 25 feet up.

Gigantic, new waves in this region can have far-flung and world-changing effects. Arctic waters circle the pole, going from the Beaufort and Chukchi seas above Canada and Alaska, to the East Siberian, Kara and Barents seas north of Russia, to the Norwegian and the Greenland seas atop the Atlantic. In this vast area, ice cover might affect not just walrus habitat but the courses of ocean currents and even the atmospheric jet stream, influencing climate thousands of miles away. And with ice no longer protecting the land's edges in the region, fragile permafrost—which makes up a big portion of coastline—may also be in danger.

These consequences are what brought Thomson and 100 other researchers, along with the most sophisticated remote-sensing network ever deployed in cold waters, back to the Arctic in 2014. Their mission was a multimillion-dollar experiment to uncover what the appearance of giant waves might mean for the future of the world's most mysterious ocean.

NORTHERN EXPOSURE

RESEARCHERS HAVE KNOWN for years that they were missing something critical about the Arctic. No matter how scientists crunched the numbers, the annual partial breakup of the ice cap was happening faster and farther than any model predicted, even allowing for extreme versions of global warming. In 2007 Julienne C. Stroeve, a climatologist at the National Snow and Ice Data Center in Boulder, Colo., took note of this in a paper, writing that none or very few of the Arctic simulations used by the Intergovernmental Panel on Climate Change were predicting the ice retreats seen in the real world. Even after tuning the models, Stroeve says, the shrinking ice still outpaces predictions: "The recent decline is still outside the average of all the models. They aren't really picking up on what's happened."

Accurate Arctic climate models are critical. Scientists at Pacific Northwest National Laboratory think that less sea ice in the Arctic means heat energy that is usually trapped underneath this ice can escape into the atmosphere. This rising heat can disrupt the jet stream, the swiftly moving high-altitude air current that makes it quicker to fly from west to east in the U.S. than the other direction. Some scientists believe that the jet stream acts as a barrier that prevents frigid Arctic air from moving south and that changes to it can cause extreme "polar vortex" weather events such as those that have frozen East Coast cities in the U.S. during the past two winters.

Scientists at the Woods Hole Oceanographic Institution have measured an increasing volume of freshwater in the Beaufort Sea as the ice thins and retreats. There is now 25 percent more freshwater than there was 40 years ago. If this cap of freshwater were to escape into the North Atlantic, it could alter ocean currents significantly. The cap did something similar in the 1970s, for reasons that are still unknown, spilling Arctic ice south and

PRECEDING PAGES: ANDY MANN *National Geographic*

SEA WITHOUT WAVES: When dense sea ice covers the Arctic's Beaufort Sea, the water stays flat and calm. It is, however, difficult for ships, even this U.S. Coast Guard vessel, to move about.

disrupting currents that help to balance temperatures in the region. Some scientists believe that similar perturbations have driven extremely rapid climate changes in the past, such as an event around 12,000 years ago that warmed Greenland's ice sheet by around eight degrees Celsius over just a few decades.

Vanishing ice is also accelerating current coastal erosion in the Arctic. Permafrost coasts, where permanently frozen subsoil meets open water, make up around one third of all the coastline on the earth. "The only thing that holds these coasts together is the ice, and they may erode very fast when they are not protected by sea ice," says Hugues Lantuit, a geomorphologist at the Alfred Wegener Institute in Germany, a center for polar research. Some coasts along the Beaufort Sea are already retreating at up to 100 feet a year.

This erosion can wipe out human settlements, devastate ecosystems, cause land to sink, and contribute to ocean acidification and global warming. As permafrost melts, it releases carbon from plants, animals and microorganisms that had been frozen within. This organic matter will eventually decay and become a source of carbon dioxide and methane, greenhouse gases that can also acidify the ocean and make it less hospitable to sea life.

Big businesses would like a better idea of what is happening to the ice as well. Oil and gas companies spy new opportunities for drilling in previously frozen waters. And if the amount of seasonal melt can be accurately predicted, shipping firms could use the fabled Northwest Passage to cut journey times from the Pacific to the Atlantic by a week. The missing ice has also attracted the attention of the U.S. Navy, not least for the security implications of having a brand-new ocean open up on the country's northern border.

All in all, there are many pressing reasons to figure out why the ice has been going away.

Thomson suspects that big waves and their ice-destroying power could explain why predictions have not matched up with reality. "Until now, waves have not been included in a systems model that takes the ocean, the atmosphere, the weather and the sea ice, then couples them all together to make a better forecast," Thomson says. "The mechanical process is simply missing." Lantuit, the coast expert, says that although wave impacts are not well understood, they could explain his changing maps. "There isn't yet a good model of wave impacts on permafrost coasts," he notes. "But as a rule of thumb, if you get bigger waves, you can expect more erosion."

HUNTING THE BIG ONES

ALTHOUGH WAVES have been absent from the various models, scientists have long known what crashing seas can do to even the toughest ice. Elizabeth Hunke models oceans and sea ice for Los Alamos National Laboratory. On a trip in 1998 to the other side of the planet, Antarctica, she came across a rare patch of open water

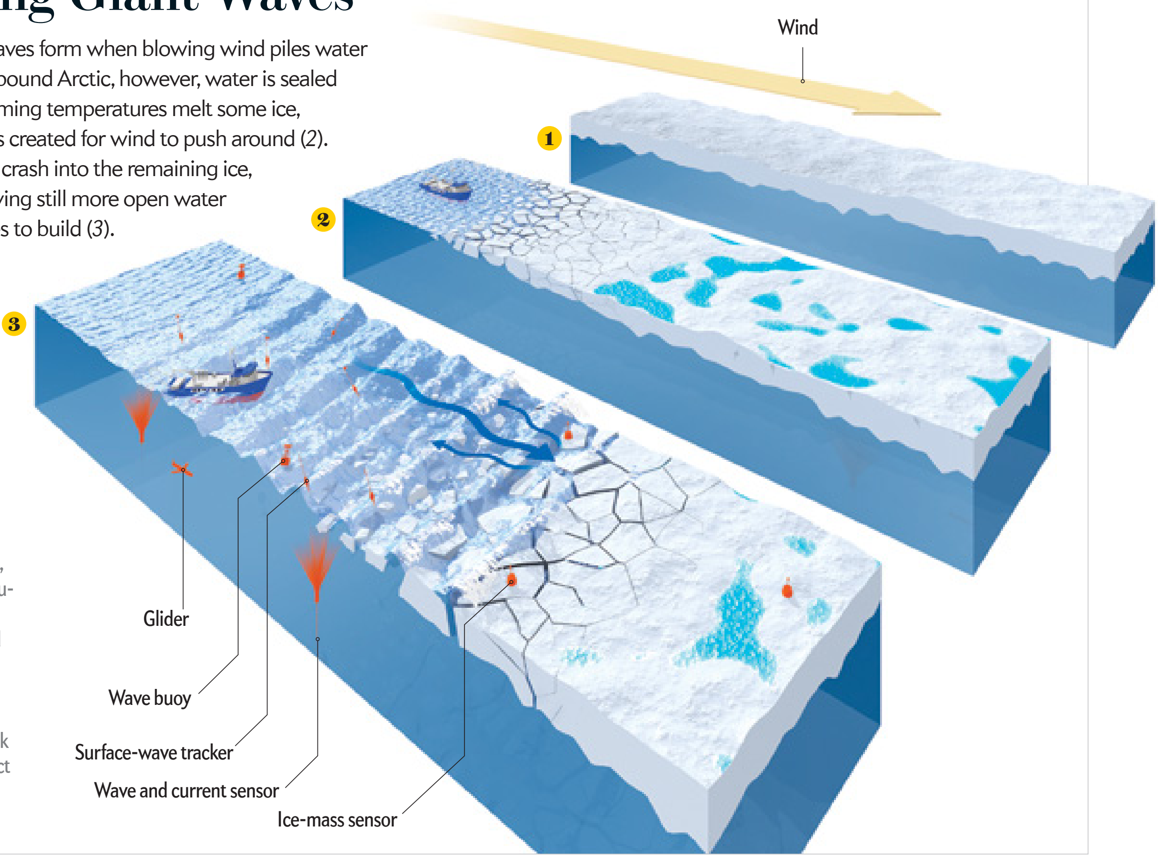
EXPLORING THE MELT ZONE: In 2014, in an area of the Arctic northeast of Alaska, scientists deployed a network of sensors to help them figure out why sea ice has been vanishing faster than expected. Large, ice-smashing waves might be a big part of the answer.

Map by XNR Productions

DANIEL J. COX *Getty Images (ice)*; SOURCE: NASA VISIBLE EARTH *(globe data)*

Making Giant Waves

Wind and water: Waves form when blowing wind piles water ahead of it. In an icebound Arctic, however, water is sealed away (*1*). When warming temperatures melt some ice, a bit of open water is created for wind to push around (*2*). The resulting waves crash into the remaining ice, shattering it and leaving still more open water for even larger waves to build (*3*).



To trace ice-wave connections in 2014, scientists used instruments shown here, including buoys and trackers to measure wave dimensions, underwater gliders to follow the ice pack and sensors to detect ice thickness.

near the Filchner-Ronne Ice Shelf in the Weddell Sea. "I watched waves batter sea ice that had been fastened to the shore for years, decades or perhaps even centuries," Hunke says. "Although the ice was really thick and hard to break off, that's just what the waves were doing."

But with no one envisioning giant waves in the Arctic, scientists had not thought to seek them out or factor them into their calculations. The startling measurements made by Thomson's lone buoy in 2012 changed all that.

It caught the eye not only of oceanographers but of the U.S. Office of Naval Research, which had already decided it was worth $12 million to find out where Arctic ice was going and launched a project called the Marginal Ice Zone (MIZ) program. Last summer wave hunting became an official part of the research.

The project brought together more than 100 international scientists in the most ambitious experiment ever to observe the seasonal breakup of the Arctic ice sheet. In years past this event would have started icebreakers churning across the ocean surface, submarines roaming the depths and satellites soaring overhead. In 2014, however, it meant small ships, short expeditions and lots of robot drones. Autonomous robots can now go places that humans can only dream of, gathering data 24 hours a day, without rest or relief.

In the spring of 2014, just over a year ago , scientists flew onto the thick, frozen ice of the Beaufort Sea and installed dozens of instruments along a 240-mile line running north from around 73 degrees north latitude toward the pole. These devices gauged the thickness of the ice, the temperature and composition of the water below it, and the weather above. The instruments were buoyed by flotation, so as the ice gradually broke up during the summer, dunking them into the chilly ocean one by one, they continued to gather water and weather data.

In late July, Thomson and five other scientists began deploying more sophisticated members of the automated team from a small converted fishing boat, the research vessel *Ukpik,* in the Beaufort Sea. At this time of year, the sun never sets, casting an endless wan light over a choppy sea and glinting floes. The scientists were possibly the farthest north mariners in the world at the time and more than 100 miles away from the nearest settlement. Despite the occasional distant spout of a bowhead whale, this region of the Beaufort is a desolate place.

What the researchers lacked in human company, they made up for in robotic companionship. They were preparing several different types of drones for work. Some were Thomson's standard wave-sensing buoys, similar to the one he moored nearby in 2012. The others were far more complex: Seagliders, six-feet-long torpedo-shaped underwater drones that propel themselves through the water, steering with a pair of adjustable wings. Each Seaglider has an external swim bladder that can be inflated to make it lighter than water or deflated to allow the robot to sink. A Seaglider can cover up to 12 miles a day, moving up and down in long, graceful arcs.

Illustration by Bryan Christie

A powerful battery keeps each robot running for 10 months and helps to steer the drone by being tilted left or right as it glides through the water. When a Seaglider reaches the top of its swooping flight, it pokes its nose briefly above the waves like an inquisitive seal. Then it can get a GPS location fix, beam data up to waiting satellites and receive new instructions. Four Seagliders were deployed and spent two months ranging back and forth between open water and the ice sheet, measuring the turbulence, temperature, salinity and organic materials in the water.

When the Seagliders were under the ice for extended periods, they were cut off from their satellite watchdogs. To keep them connected, the scientists employed a third type of drone, surface travelers called Wave Gliders . The Rube Goldberg–looking Wave Gliders, which are powered by solar panels and the motion of waves, run right up to the edge of the ice and send acoustic signals to the submariners. Lee Freitag, an engineer at Woods Hole, developed a system to broadcast low-frequency sound signals to the Seagliders, relying on reflective layers underwater to bounce the sounds over long distances. (These are the same kind of layers, created by changes in water density, that allow whale songs to traverse entire oceans. The scientists chose different layers and frequencies from those used by resident cetaceans to avoid interfering with the animals.) The signals relayed latitude and longitude information to the Seagliders, along with instructions from the researchers.

This large-scale robotic approach has several advantages over traversing the high latitudes onboard an icebreaker. First, the robots let scientists cover a wider area. Icebreakers are limited to a single path, often cruising in one direction while the action is happening hundreds of miles away. The Wave Gliders and Seagliders, following directions from their handlers, can swerve to track every twist and turn of the ice as it succumbs to the sea.

There is another plus: the robots needed only a small mother ship, the *Ukpik*. "The *Ukpik* is small enough that we can maneuver in," Thomson says. "One of the biggest problems with a traditional icebreaker is that it's just too big. It's a bull in a china shop, destroying the very waves I'm trying to measure."

One day on the *Ukpik,* while leaning against the ship's rail after helping the crew drop a pair of Wave Gliders into the water, Thomson talked about how waves evolve. "To make waves, you need wind," he said. "Given wind, you need two things: time and distance. If you have more space, you'll make bigger waves, and you'll get the same with a longer-length storm. Really big waves come from having both."

In the springtime, even during the warmest years, most of the Arctic is still locked in ice. By the end of summer it has a surface area of free water more than twice the size of the Mediterranean. The more open water, or "fetch," you have, the larger waves will grow. The wind pushes water ahead of it, and longer fetches give more water time to pile higher.

When the water is free of ice, it also absorbs more heat from the sun—ice would reflect it away—and warming water heats the air, which can create more wind. If conditions are right, this combination can break up nation-sized areas of ice in a matter of days. That, of course, creates still more open water, in a feedback loop that makes it easier and easier for big waves to form.

What remains unclear is exactly how much each element in this loop contributes to the ice breakup and whether waves can slow the ice from re-forming as autumn closes in. For that, scientists need to understand more about the way that waves and sea ice interact.

BREAKING UP THE PACK

AFTER LEAVING THE DRONES in July, the *Ukpik* encountered a wide pack of sea ice, ranging from small chunks to looming hummocks that summon memories of the berg that sank the *Titanic* in 1912. It was perfect wave-hunting ground for Thomson. He leaped up to prepare a buoy. The ship stopped outside the ice pack for him to throw one overboard, then picked its way gingerly into the pack to deploy another.

The difference between the open sea and the ice pack was obvious as the ship moved in. In open water, the sea was rough and choppy. The moment the *Ukpik* reached the first small pieces of ice in the water, the chop faded to a low, smooth swell. And by the time the ship puttered a few hundred yards farther in, bumping and skirting some bigger chunks, there was nothing more than the faintest tremble in the glassy water between them. "The ice filters the waves such that only the longest waves make it the farthest in," Thomson says enthusiastically, carving a perfect tubelike breaker in the air with his hands. One of the things he wanted to learn was how much of this filtering came from an effect called scattering and how much came from another process known as damping.

Scattering would mean that the ice is simply moving the wave energy around without absorbing it, like a prism scattering light. Damping would mean that the wave is passing energy to the ice, moving it and breaking it up. A damping effect would cause the most damage to the pack. For all the drama surrounding house-sized waves out to sea, the centimeter-scale measurements being made here could do the most to improve Arctic systems models in the years ahead.

But what Thomson has already found makes the "more waves to less ice to even more waves" cycle plausible, according to W. Erick Rogers, an oceanographer at the U.S. Naval Research Laboratory. "This feedback loop seems to be an important mechanism for understanding sea-ice extent in the earth's future, warmer climate," he says.

As the *Ukpik* cleared the drifting ice and headed back to port, the ship was approached by a small flat-bottomed boat piloted by an Inuit fisher and his grandson from a nearby settlement, who gave the research vessel's crew some freshly caught fish for supper, three plump Arctic char. Arctic sea ice is beginning to get attention in the rest of the world, but it is these communities—and wildlife such as polar bears, seals and whales and microbes buried in the permafrost—that are already feeling the impact of the shrinking ice and the ever growing waves. SA

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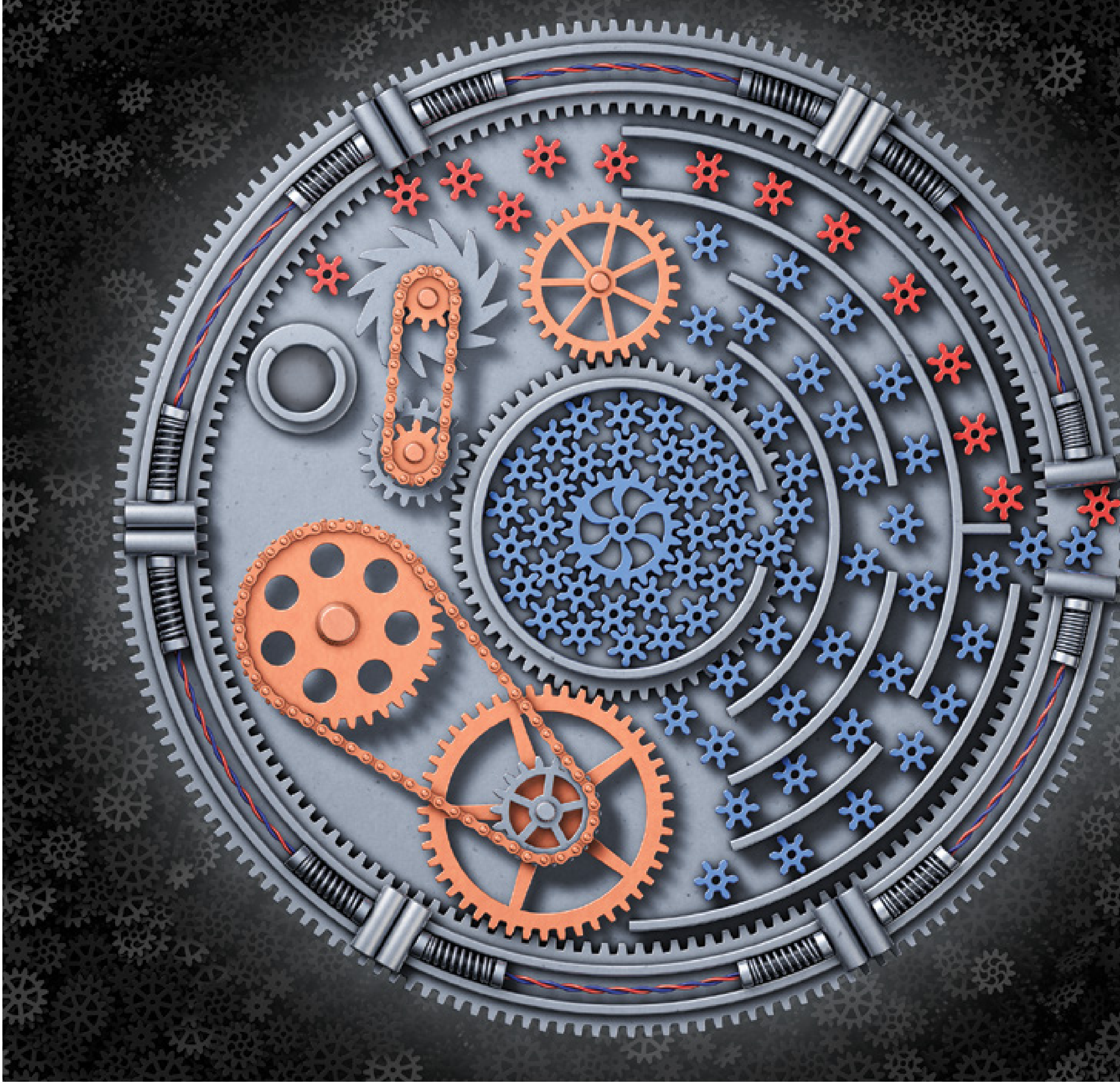
BIOLOGY

CELLULAR

Neighboring cells exchange molecular information through channels that can lead to disorders ranging from hearing loss to heart disease

By Dale W. Laird, Paul D. Lampe and Ross G. Johnson



SMALL TALK

directly connect them. Disruption of this signaling system

Illustration by Peter Kraemer

Dale W. Laird is a professor of cell biology and Canada Research Chair in Gap Junctions and Disease at the University of Western Ontario.

Paul D. Lampe is co-head of the Translational Research Program and a member of the Public Health Sciences and Human Biology divisions at the Fred Hutchinson Cancer Research Center in Seattle.

Ross G. Johnson is a professor emeritus of genetics, cell biology and development at the University of Minnesota. He began studying gap junctions in the 1960s, shortly after these cellular communication channels were discovered, and has been exploring their assembly and regulation with Laird and Lampe for more than 20 years.

LIKE PEOPLE WHO SHARE NEWS VIA TWITTER, FACEBOOK AND LINKEDIN, CELLS, too, make use of multiple modes of information exchange. Some send out hormones, which travel far and wide via the bloodstream; others emit neurotransmitters, which carry signals between one neuron and another. But virtually all cells, it turns out, network with their neighbors via extensive collections of channels that directly connect the inside of one cell with the inside of the next.

Investigators got a dramatic glimpse of this form of cell-cell communication in the mid-1960s, when they injected fluorescent dye molecules into an individual cell amid a sea of closely packed cells. Peering through a microscope, they saw the fluorescence spread rapidly from one cell to the next until sometimes hundreds of cells in the tissue were aglow. Previous studies had suggested that ions could convey electrical signals between neighboring cells. But observing the spread of dye molecules, which are small but larger than ions, confirmed beyond a doubt that cells harbor channels through which molecules pass in abundance between adjacent cells.

Biologists now know that these channels are everywhere. Collections of them occur in the tissues of all animals, including humans, where they participate in an extraordinary variety of functions. The collections, called gap junctions, help to synchronize the beating of muscle cells in the heart and the contraction of the uterus during childbirth. Gap junctions allow the eye to adjust to different levels of light. They even play a role in organ formation during embryonic development.

Over the past 20 years scientists have discovered that defects in the assembly or activity of gap junctions contribute to a range of human diseases, including hearing loss, cataracts, skin conditions, neurological disorders, heart disease and even certain cancers. A single mutation affecting a constituent protein of a gap junction in the inner ear accounts for hearing loss in up to 40 percent of individuals with inherited deafness. And new diseases linked to gap junctions are being discovered all the time—several in just the past few years, including a type of epilepsy that strikes children.

Now studies are providing exciting insights into how gap junctions are built, and they are beginning to reveal how disruption of gap junction assembly and activity precipitates disease. The findings should lead to new therapies for many disorders that result when cells can no longer share "inside" information.

BUILDING BRIDGES

INVESTIGATORS WERE NOT THINKING in terms of medical relevance back when the early dye injection experiments were first performed. In the 1960s and 1970s they were focused on uncovering further evidence of this mysterious neighbor-to-neighbor

IN BRIEF

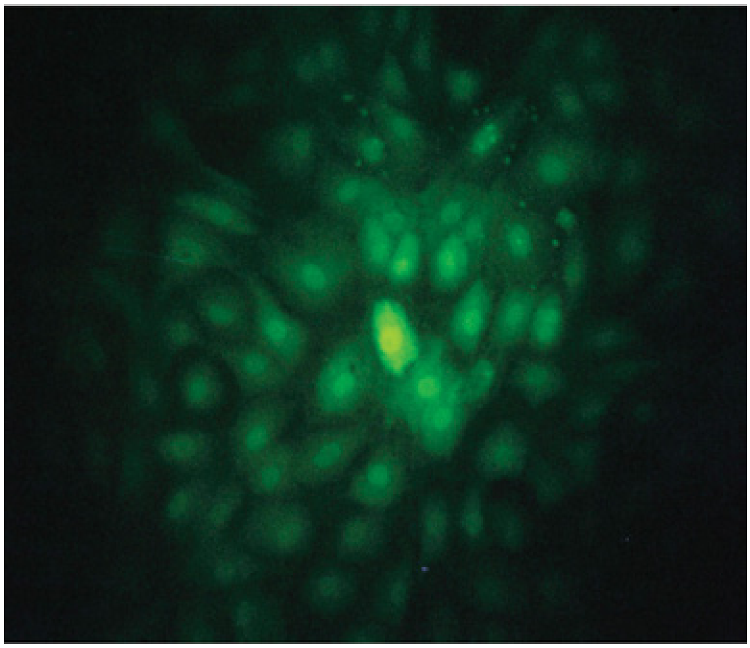
Cells exchange information with their immediate neighbors through gap junctions—structures that directly connect one cell to another. These "conversations" are involved in everything from the synchronized beating of heart cells to our ability to hear.

Although gap junctions are complex and often made of more than 100,000 individual proteins, they are taken apart and rebuilt continuously. This carefully controlled restructuring allows cells to respond rapidly to injury or stress.

Mutations in the genes that encode gap junction proteins lead to a range of human conditions, including skin disorders, heart disease, epilepsy and deafness. Learning how these defects affect the assembly and activity of gap junctions should lead to new treatments.

communication between cells and on learning more about its properties. Before gap junctions were identified and named, physiologists found that this sharing of molecular information occurs in a variety of organs and organisms, from squid embryos and electric fish to an assortment of mammalian cells. And they confirmed that the molecules do move directly between cells at points where their membranes come in close physical contact.

By the late 1960s scientists had their sights set on determining what the channels look like and how they form. Earlier microscopic studies had revealed the presence of large, flat patches where the membranes of two neighboring cells lie closely apposed. At these junctions, the cells appeared to be separated by a very thin gap, just a few nanometers wide, leading the structure to be called a gap junction. The name stuck even after investigators discovered that this narrow space is not empty but is filled with the parts of the channels that connect one cell to another.



DYE INJECTED into a cell in a culture (*center*) quickly crossed into other cells by way of gap junction channels that link neighboring cells.

COURTESY OF MICHAEL ATKINSON AND JUDSON SHERIDAN *University of Minnesota*

To explore the role that these flat membrane patches play in the "cellular connectivity" seen in the dye and electrical experiments, one of us (Johnson) began studying what happens as these junctions are assembled. Along with his colleagues at the University of Minnesota, Johnson gently teased apart cultured cells derived from a liver tumor and then mixed them back together. Within minutes, flattened patches arose on the cell membranes but only where the two cells made contact. This observation confirmed a suspicion that gap junction assembly is a joint project that requires the collaboration of adjacent cells. As these flattened patches expanded and matured, the electric current passing between the cells also increased. These junctions, it seemed, could facilitate the exchange of ions.

Peeling apart the membranes of the connected cells to take a closer look, Johnson and his team saw what appeared to be large particles that had accumulated within the flattened patches. These particles, it later turned out, were the channels that are the very building blocks of the gap junctions [*see box on next page*]. Each channel is formed from molecules called connexins, which belong to a family of proteins identified in the late 1980s.

Six connexin proteins come together to form a doughnut-shaped structure called a hemichannel. This hemichannel gets inserted into the cell's outer membrane, where it can then interact with a hemichannel in a neighboring cell. When the connexins in these matching hemichannels interact, they form a continuous pore that connects the cells in a way that puts the cytoplasm of one cell in direct communication with the cytoplasm of another. This pore is, in effect, a single gap junction channel, hundreds or thousands of which aggregate to form each gap junction.

Building these enormous communications conglomerates is a massive undertaking for cells. A single gap junction can contain 10,000 channels. Because each gap junction channel involves two hemichannels, that would make a total of 120,000 connexins per junction. The heart alone contains billions of cells, each one of which interacts with several of its neighbors via gap junctions. The assembly of these colossal structures, in other words, is a marvel of molecular engineering.

Even more remarkable is that gap junctions are not permanent or even long-lived but are continuously taken apart and rebuilt. It has been shown that half the connexins in a cardiac gap junction are replaced every two hours. Over the course of a day every single gap junction in the human heart is most likely torn down and replaced with channels that are newly assembled.

Given the complexity of these extraordinary structures, it seemed likely that systems must exist to ensure that their construction runs smoothly so that cell-cell communications are not lost. To get a handle on these regulatory mechanisms, the three of us, who were all studying gap junctions, chose to combine our expertise; in particular, we wanted to explore how the assembly and removal of these extensive communication channels are controlled.

COMING TOGETHER

WE HATCHED OUR PLAN to collaborate over coffee at a conference on gap junctions at the Asilomar Conference Center in Pacific Grove, Calif. It was 1991, and one of us (Lampe) was a postdoctoral fellow in Johnson's lab at the University of Minnesota, where the focus had turned to the regulation of gap junction assembly. The final member of our trio (Laird), then a postdoc in Jean-Paul Revel's lab at the California Institute of Technology, had just developed a set of antibody molecules that bound specifically to connexin proteins. These antibodies would allow us to interact with connexins and see which bits of the molecules are critical for gap junction formation and activity.

Laird's antibodies recognized one particular type of connexin: Cx43. Humans have genes that encode 21 different connexin proteins, and each cell type produces its own characteristic set of connexins. Skin cells, ambitiously, make up to nine different connexins. Cx43, though, is the most widespread member of the family and is present in many organs, including skin, heart, brain, lungs and bone.

Cx43, like all connexins, consists of four membrane-spanning segments that anchor the protein in the cell membrane. The protein's tail, which dangles inside the cell, contains a variety of elements that we would later determine are involved in regulating its activity and assembly into channels and junctions. And two loops made by the protein as it weaves in and out of the membrane protrude into the space between the cells. Some of the antibodies that Laird had generated homed in on these extracellular segments.

Because the loops stick out from the surface of the cell, it seemed reasonable to think that they might function as Velcro-like hooks that enable connexins to latch onto one another. To examine that supposition, we again teased apart cultured cells and then mixed them back together—but this time we added in Laird's antibodies. Now gap junctions did not form at all; we saw no cell-to-cell transfer of injected dye and no flattened patches characteristic of developing gap junctions. By sticking to the loops, the antibodies had prevented the connexins in one cell from "docking" with the connexins in the neighboring cell.

Such antibody studies demonstrated that connexin attachments are critical to the construction of gap junctions. But a different technique was needed to watch connexins in real time as they made their way around a living cell.

FOLLOW THAT PROTEIN

IN 1994 THE THREE of us found ourselves together at another conference—this time the American Society for Cell Biology's meeting in San Francisco. Over late-night chats about the presentations we had heard, we became increasingly excited about green fluorescent protein (GFP)—a molecular tool whose usefulness would ultimately be recognized by a Nobel Prize. One speaker at the meeting described how she had linked this fluorescent marker to her favorite protein to track its travels in live cells. So we wondered whether our research groups could use GFP to monitor the movements of connexins.

We began by tacking GFP to the tail ends of the connexins. To our great delight, this approach worked well: the tagged connexins were inserted correctly into the cell membrane, where they assembled into functional gap junctions that exhibited nearly all the properties of those built from unmodified connexins. We now had a powerful way to observe the behavior of connexins inside cells—work that Laird continued at his new position at the University of Western Ontario.

Our very first observations were surprising. We initially took pictures of the cells containing tagged connexins every 10 minutes, thinking we could stitch these stills together to make a time-lapse movie highlighting connexin movement. But the connexins traveled so quickly that we could not tell which protein was which or where each had gone. We tried again every two minutes, but that time frame still was not good enough. To watch individual tagged molecules as they trucked around the cell, we ended up having to collect images every few seconds.

The resulting movies allowed us not only to follow connexins but also to watch hemichannels as they were transported inside cells along molecular tracks made of structures called microtubules. We and others saw that smaller gap junctions can

BASICS

The Making—and Breaking—of Gap Junctions

Cells continously and rapidly build up and remodel their gap junctions (*bottom right*). Buildup begins with the synthesis of proteins called connexins (*1*), their arrangement into structures called hemichannels (*2*) and insertion of the hemichannels into the cell membrane (*3*). If hemichannels encounter existing gap junctions, they can dock with hemichannels in a neighboring cell, forming new passageways between the cells (*4*). Meanwhile cells remove and degrade old gap junction channels (*5* and *6*).

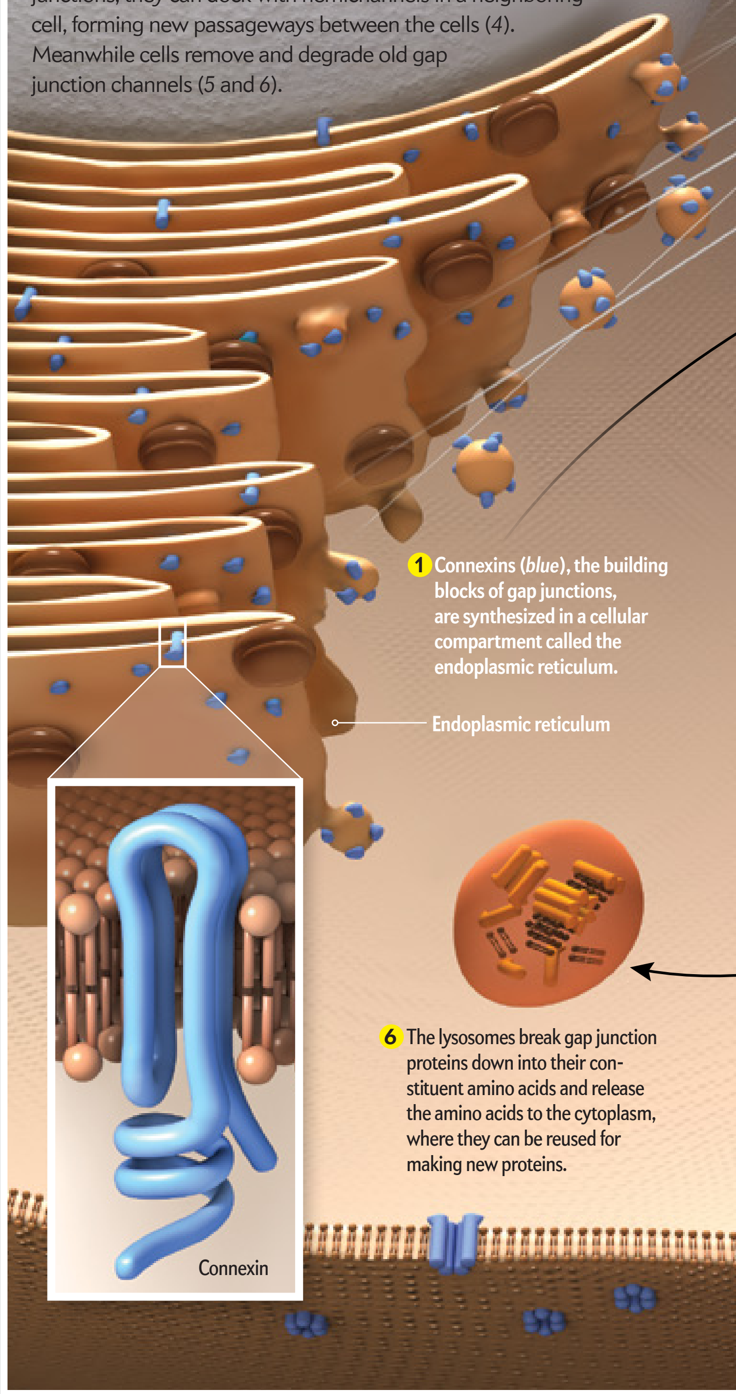
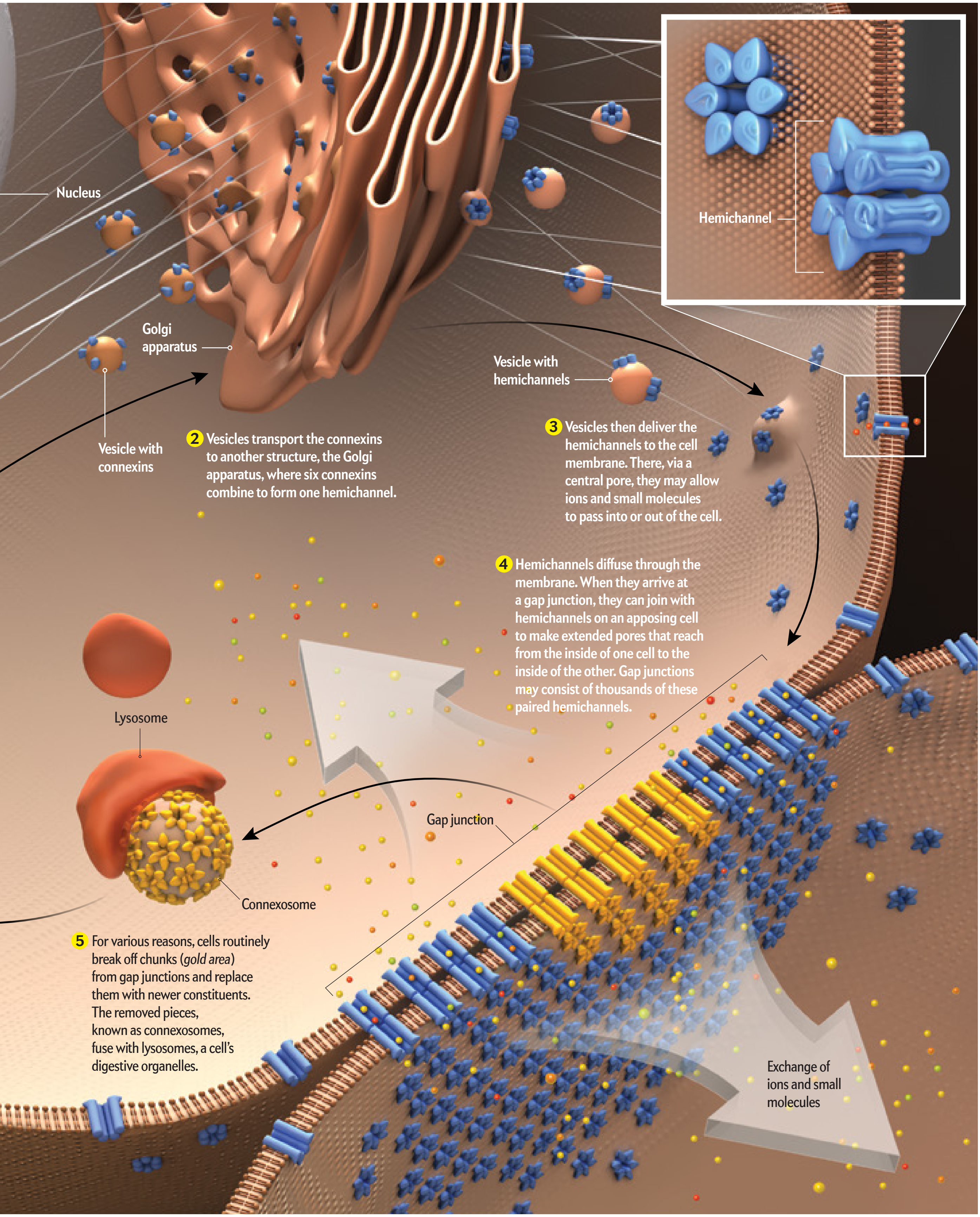


Illustration by Emily Cooper



Nucleus
Golgi apparatus
Vesicle with connexins
2 Vesicles transport the connexins to another structure, the Golgi apparatus, where six connexins combine to form one hemichannel.
Vesicle with hemichannels
Hemichannel
3 Vesicles then deliver the hemichannels to the cell membrane. There, via a central pore, they may allow ions and small molecules to pass into or out of the cell.
4 Hemichannels diffuse through the membrane. When they arrive at a gap junction, they can join with hemichannels on an apposing cell to make extended pores that reach from the inside of one cell to the inside of the other. Gap junctions may consist of thousands of these paired hemichannels.
Lysosome
Gap junction
Connexosome
5 For various reasons, cells routinely break off chunks (*gold area*) from gap junctions and replace them with newer constituents. The removed pieces, known as connexosomes, fuse with lysosomes, a cell's digestive organelles.
Exchange of ions and small molecules

combine to form larger ones—something we had gleaned hints of in our electron microscopic studies. We also demonstrated that larger gap junctions can break apart to form smaller ones, a kind of gap junctional remodeling that takes place as the cells grow, move, flex and divide.

Our colleagues devised more methods to tag connexins and found that gap junctions grow by the addition of hemichannels to their perimeter—so that the central part of a gap junction represents the "oldest" section of the plaque. These older components appear to be removed as gap junctions age, an observation that could explain how gap junctions remain established even as the connexins within them are lost; newer channels crowd inward to replace the channels that are older.

Perhaps the most striking finding from our live-cell studies was that gap junctions can also be reclaimed by the cell in large chunks, when one of the participating cells essentially takes a bite out of its neighbor, a mechanism others had proposed based on some earlier electron microscopic images. This radical maneuver ingests the junctional components contributed by both cells in one fell swoop—a process that may provide a failsafe way to rapidly shut down communication between two cells when it is no longer desirable. Such large-scale elimination of gap junctions actually takes place in the uterus after childbirth, disabling the communication networks that have formed to coordinate contractions.

Studying how mutations affect gap junctions could lead to therapies

TAKING CONTROL

KNOWING THAT GAP junctions constantly get renewed, we next set out to explore how cells might supervise this massive molecular resculpturing. Early studies pointed to proteins called kinases as the regulators. By the simple step of adding phosphate groups to a target protein, kinases can alter that protein's activity or location within the cell.

Our challenge was to figure out whether protein kinases also regulate the behavior of connexins and, if so, what exactly this phosphorylation does. Lampe took the lead in this set of studies when he set up his lab at the Fred Hutchinson Cancer Research Center in Seattle in 1994. By taking apart Cx43 and examining the protein one small piece at a time, Lampe and his colleagues discovered that, over its life span, this connexin gets phosphorylated at up to 15 different places along its tail. This information allowed us to work out some of the regulatory code that controls the formation of gap junctions containing Cx43. When specific kinases act on certain parts of the protein tail, the modification enhances the assembly of Cx43-containing junctions; other kinases acting on different parts of the tail inhibit junction formation, activity or size.

Insights into the regulatory code are now making it possible for us to examine human tissue samples for clues to how changes in phosphorylation might alter the way gap junctions are assembled and function in response to injury or during disease. We and others have begun to ascertain, for instance, how communication through gap junctions changes when cardiac cells are trying to recover from oxygen deprivation after a heart attack or when cells in the skin mobilize to heal a cut or scratch. In both cases, Lampe's team found that phosphorylation increases on one particular site in Cx43's tail. This phosphorylation briefly boosts the size of gap junctions in these tissues by preventing Cx43 from interacting with a protein (studied by other groups) that restricts the ability of new connexins to integrate into existing junctions. The resulting increase in gap junction size serves to increase communication—which is critical in the first minutes after injury—and helps to preserve function in cardiac tissue and to facilitate the migration of the skin cells needed to close an open wound.

Knowing how phosphorylation affects connexin assembly and function—and how gap junction communication changes in response to injury or disease—has opened a door to the development of therapeutics that can promote or inhibit the activity of the relevant protein kinases. Such treatment strategies must be pursued with caution, however, because an increase in gap junctions during one stage of disease may prove harmful later on. For example, although gap junctions briefly enlarge immediately after an injury, they are later rapidly degraded to promote proper healing. In people who have diabetes, wound closure is delayed by a continued overproduction of Cx43. And when the cornea is scratched, connexins can promote inflammation and scarring rather than healing. In these cases, limiting the production or function of Cx43 in the cells surrounding an injury promotes the rapid repair of wounds without scars—an approach that is being pursued by several biotechnology companies.

To fully capitalize on our knowledge of gap junction biology for designing effective therapies, though, investigators need a deeper understanding of how connexins come together in different tissues under different conditions—and how their aggregation and activity go awry in the face of disease. The study of disease-causing mutations in the genes that code for connexin proteins is beginning to offer some useful insights.

INTERRUPTING COMMUNICATIONS

INVESTIGATORS UNCOVERED the first solid genetic evidence that connexins can participate in disease in the mid-1990s. Mutations in the gene encoding Cx32 were found to cause one form of a neurological condition called Charcot-Marie-Tooth disease. In this disorder, gap junctions disappear in the myelin sheath that insulates nerves, causing the myelin to degrade and leading to nerve degeneration; that loss, in turn, precipitates muscle atrophy and weakness, particularly in the limbs.

With the discovery that mutations in connexin genes have serious physiological consequences, the gap junction field witnessed an explosion of interest from researchers and clinicians intent on determining the genetic basis of these diseases. Additional studies turned up new connexin mutations, and today 14 different disorders are known to stem from defects in gap junction connexins.

The most striking thing about this collection of conditions is how different they are from one another. In addition to the neu-

SCIENTIFIC AMERICAN ONLINE See gap junctions at work at ScientificAmerican.com/may2015/gap-junctions

rodegenerative Charcot-Marie-Tooth disease, mutations in connexins can underlie hearing loss, epilepsy, heart disease, skin ailments, cataracts and a variety of disorders that arise during embryonic development. As might be expected, mutations in different connexins contribute to different diseases. But in a more surprising finding, it turns out that mutant connexins do not necessarily afflict all tissues or organs equally; if a particular mutant is produced in two organs, it might impair function in one but not the other.

Many research groups are laboring to understand this phenomenon. One explanation could be that in certain tissues, other healthy connexins can compensate for a defective variant, allowing gap junction communication to continue at an adequate level. Such a compensation mechanism may occur in some tissues but not others. Or perhaps a particular connexin plays one role in one tissue but different roles in others, depending on which other connexins are present. The various connexin family members can also intermix, yielding hybrid channels that could facilitate the passage of different molecular signals—some of which are more important in one tissue than another.

that counteract these defects without triggering serious side effects.

For some connexins, however, defects do compromise multiple tissues. Take a disorder we study, called oculodentodigital dysplasia (ODDD). People with this condition, caused by mutations in the Cx43 gene, display a range of symptoms, including small eyes, underdeveloped teeth, skeletal deformities in the face and head, and webbing between the fingers or toes. As if that were not enough, some affected individuals develop a skin condition that produces thickened, scaly callouses on the palms of the hands and the soles of the feet. Recent studies on the life cycle of connexins have offered some hints as to why some people have a more severe form of the disease than others.

More than 70 mutations in Cx43 have been found in people with ODDD, and we began by exploring what these mutations do to the protein—and how they affect the construction of gap junctions. Laird and his colleagues have found that many of the mutations in the Cx43 gene result in a connexin that reaches the cell membrane but does not form a functional gap junction; dyes do not flow through these junctions from cell to cell, indicating that the gap junction channels are either not properly assembled or not allowing the molecular signals to pass. Either way, these mutations diminish cell-cell communication.

Other ODDD mutations prevent connexins from ever reaching the cell membrane. Patients harboring these mutations generally have the more severe form of the disease, including the skin condition, along with other defects. This finding suggests that connexin hemichannels might have a job beyond their role in building gap junctions and that when this job goes undone—as happens when connexins never get to the cell membrane—more severe problems arise. Perhaps, for instance, instead of pairing up to form channels, some hemichannels remain uncoupled, allowing cells to release signals or to take up molecules from their environment. These molecules may be different from the ones that normally pass through gap junction channels. Such hemichannel activity has been demonstrated experimentally, adding a new dimension to our understanding of the role that connexins play in cell communication. Further studies of mutant hemichannels could reveal new targets—including as yet unidentified molecules that pass through uncoupled hemichannels—for the treatment of ODDD or other connexin-based disorders.

TELLING SECRETS

STUDYING HOW MUTATIONS affect the construction and behavior of gap junctions could also lead to highly targeted therapies that counteract the effects of a mutation without triggering serious, unwanted side effects. Knowing, for example, that a particular mutation alters the assembly of a gap junction—but not the transport of connexins to the cell surface—could point the way toward a drug that might restore the ability of the connexin to form a functional channel. Such targeted therapies could provide a way to reestablish cell-cell communication without having to replace the mutant connexin entirely—a process that would involve gene therapy, an approach that is still risky and experimental.

Discovery of disease-causing mutations in connexins does more than provide promising therapeutic targets. It gives investigators a novel set of tools for studying the basic biology of gap junctions. We still do not have a complete understanding of the specific molecules that pass between cells via gap junctions, for example. In the case of heart cells, we know that the ions that flow through gap junctions carry an electrical signal from cell to cell. But we have little idea of what passes between cells to support the function of, say, the hearing apparatus in the ear or the wound-healing response in skin. By seeing how the connexin channels behave in different cells and how changes in their assembly and activity can invoke disease, we will finally be able to address the most fundamental questions about this intimate form of cell communication: What exactly are cells whispering to one another, and how do these molecular secrets govern the assembly and operation of complex creatures—including ourselves? SA

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scientificamerican.com/magazine/sa

Steven D. Miller is a senior research scientist at Colorado State University's Cooperative Institute for Research in the Atmosphere. He generated many of the images for this article.

SATELLITE IMAGERY

Night Watch

A satellite sensor that can see in the dark is revealing new information for meteorologists, firefighters, search teams and researchers worldwide

By Steven D. Miller

IN BRIEF

The new Day Night Band satellite sensor can detect lights on Earth that are many times as faint as those that previous sensors could find.

The instrument can also see clouds, snow and other features that are hidden on a moonless evening, lit only by the atmosphere's glow.

Sensor data are helping researchers track objects that are nearly invisible at night, such as hurricanes, smoke from wildfires and ships lost at sea.

Adding similar sensors to geostationary satellites would provide 24-hour movies of the lights on Earth rather than snapshots taken twice a day.

BLACK MARBLE: Satellite analysts stitched together two months of images from the Suomi-NPP satellite's Day Night Band sensor to create a unique view of Earth at night.

NO ONE LIKES TO BE “IN THE DARK” about what is going on around them, especially in times of peril. Yet when night overtakes a continent or ocean, scientists and forecasters suddenly lose important satellite imagery in the visible-light range—information that can reveal swirling storms, the choking smoke of wildfires, massive chunks of sea ice that threaten ships, and much more.

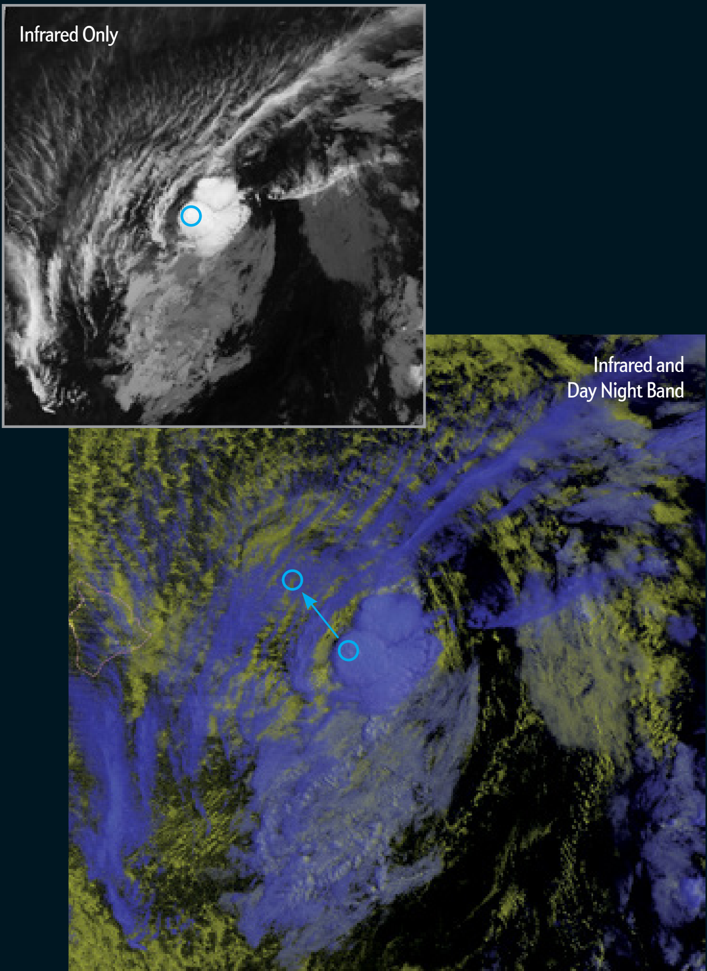
A new sensor called the Day Night Band is beginning to fill that void. Part of the Visible Infrared Imaging Radiometer Suite flying on the Suomi-NPP satellite, the instrument is so sensitive that it can measure the glow of a single streetlamp, the deck light of a lone boat in the middle of a pitch-black Atlantic Ocean or a flickering gas flare in the vast North Dakota oil fields. Even on a moonless night, the sensor can discern clouds and snowfields, illuminated by the atmosphere's own faint, nocturnal glow.

In the past three years researchers who work with the sensor have seen fascinating features of Earth's forces, including great waves of energy launched high into the atmosphere by violent thunderstorms. And they have improved forecasters' ability to warn residents about the path of hurricanes, helped firefighters monitor shifting plumes of deadly smoke and directed lost ships away from moving sea-ice flows [*see images on next two pages*].

The Day Night Band, very useful on its own, also complements infrared sensors, which have trouble identifying low clouds and snow cover that tend to blend into their surroundings at night. What is more, scientists are beginning to merge the Day Night Band data with software to specify how much moonlight is present on a given evening, helping them determine a cloud's reflectance and therefore how much moisture it holds. Forecasters can use this information to predict how clouds will affect nighttime temperatures on the ground and to assist pilots in avoiding hazardous icing conditions on aircraft. The data can also improve day-to-day weather forecasts for communities in high latitudes that endure perpetual darkness for months on end without critical nighttime information about the changing weather mix around them.

Only one Day Night Band sensor is aloft today. Suomi-NPP, operated by the National Oceanic and Atmospheric Administration, flies in an orbit 500 miles high, synchronized to the sun, so it only passes over any given location at a local time of about 1:30 P.M. and again at about 1:30 A.M. If such sensors were included on satellites that hover in geostationary orbit, scientists could record continuous movies of the world's lights instead of snapshots.

One possible platform for this night vision is a future series of Geostationary Operational Environmental Satellites (GOES) now being planned by NOAA for launch in the 2030s. If they carried a sensor like the Day Night Band, researchers could determine the changing character of lights on land and sea and monitor clouds, rain, oil slicks, fires, smoke, dust storms, volcanoes and ice all night long. They could also track boats fishing illegally in restricted waters and help to locate downed aircraft such as those in the recent Malaysia Airlines, Air Algérie and AirAsia disasters.



HURRICANE HUNTER

Knowing the exact position of a hurricane's eye is crucial because the most intense winds and highest storm surges occur right around it. More accurate tracking can save lives, influence decisions by local emergency managers about evacuations, and spare millions of dollars by optimizing the deployment of safety personnel and disaster relief resources.

On July 28, 2013, Hurricane Flossie was bearing down on the Big Island of Hawaii. Weather forecasters were charting its movement closely, but as night fell, they lost sight of the eye. High cirrus clouds obscured the storm's lower-level center of circulation from infrared sensors on satellites above (*black-and-white image*). As night wore on, the forecasters became increasingly uncomfortable about a possible "sunrise surprise"—when they think they are tracking a hurricane's nocturnal path correctly, only to realize at sunrise that its center is displaced from the deepest clouds because of changes in upper-level winds that sheer and steer such storms.

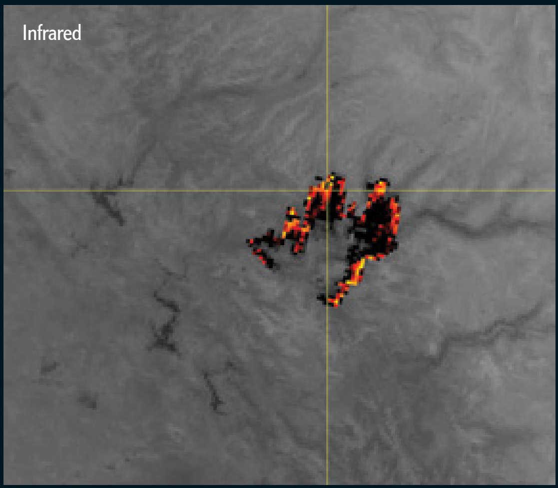
Luckily, the satellite carrying the new Day Night Band sensor flew overhead in the predawn hours. It peered right through the high, thin clouds (*blue in color image*) and showed the hurricane's near-surface circulation (*yellow*). The imagery revealed that the center of the storm was farther north than expected (*northwestern shift in blue circle*), posing less of a threat to the island. Forecasters at the National Weather Service office in Honolulu quickly released a 5:00 A.M. forecast notifying emergency personnel of the revised storm path, preventing unnecessary evacuation and saving thousands of dollars in the process.

RESCUE AT SEA

The fishing vessel *Kiska Sea* is an American member of the Bering Sea crabbing fleet, which was followed in the hit television series *Deadliest Catch.* In February 2014 strong northerly winds descended on the central Bering Sea, rapidly pushing free-floating sea ice into a region where the fleet had deployed traps called pots. On February 10 the crew on the *Kiska Sea,* the northernmost vessel at the time, contacted the National Weather Service Sea Ice Program in Anchorage, Alaska, to ask about the status of ice near its string of 150 pots, each as big as a queen-size bed.

The weather service confirmed that ice was encroaching. The *Kiska Sea* headed in to retrieve the pots, maintaining contact with ice program personnel. But on February 13 the vessel found itself surrounded by ice, some of it greater than three feet thick. To avoid being capsized or crushed, the *Kiska Sea* had to quickly get out, but the short day and moonless night made navigation treacherous. The ice program used Day Night Band data to find the ship's lights, accurately pinpointing its location (*white dot in center of image at right; other ships are visible in lower right corner*). The sensor also outlined the current ice edge, illuminated by the atmosphere's faint "nightglow" (*jagged lines moving down from top right*).

With this fine-tuned information, the weather service



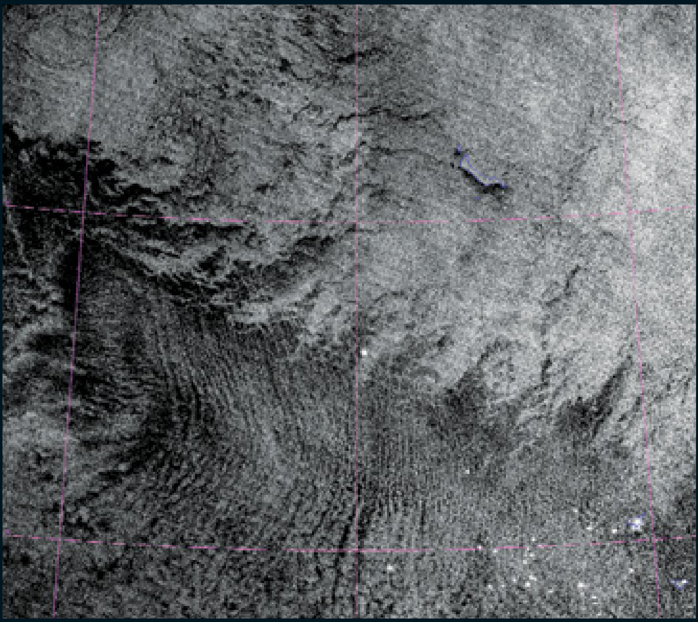
PEERING THROUGH THE SMOKE SCREEN

Wildfires are on the rise in the western U.S., in part because of multiyear droughts. Firefighters who battle these violent conflagrations during the day often lose ground overnight, when it is difficult to track dangerous smoke and smoke-obscured fire lines. Wildfires can also create strong, shifting winds that modify the speed and direction of the blaze, suddenly putting firefighters in harm's way. The temperature of smoke rapidly cools to that of the surrounding atmosphere, making these plumes of small particles nearly invisible to infrared satellite sensors at night. The sensors also often miss small flare-ups along fire lines.

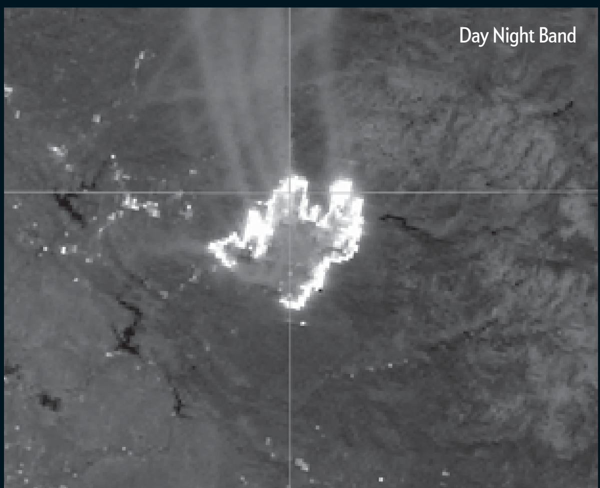
The inability to combat blazes at night is frustrating

PRECEDING PAGES: SATELLITE COMPOSITE COURTESY OF NASA EARTH OBSERVATORY; THIS PAGE AND OPPOSITE PAGE: IMAGES BY STEVEN D. MILLER

SCIENTIFIC AMERICAN ONLINE For more images from the Day Night Band, see ScientificAmerican.com/may2015/miller

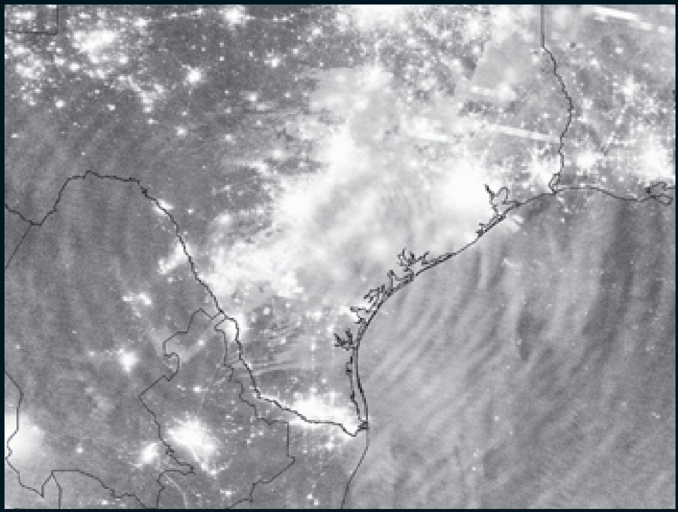


personnel helped the ship's captain chart a safe path to the west-southwest, out of the shifting ice pack. Earth's atmospheric "night-light" helped to guide the *Kiska Sea* to safety.



COURTESY OF WILLIAM STRAKA *University of Wisconsin–Madison* AND COOPERATIVE INSTITUTE FOR METEOROLOGICAL SATELLITE STUDIES *(top right)*

because cooler temperatures, higher humidity and lighter winds make the nocturnal hours ideal for gaining an advantage. Low-light sensors can help, as seen in images of the 2013 California Rim Fire (*above*). First, when moonlight is available, the sensors can often show smoke plumes clearly, providing reliable warning to firefighters (*right-hand image; smoke is missing from left-hand image, which is infrared*). Second, the sensors can more accurately pinpoint the fire lines, including any small flare-ups (*greater detail in right-hand image*). The plumes also contain valuable information about near-surface winds that are fanning flames. The right-hand image shows strong southerly winds carrying the smoke northward; firefighters would be well advised to attack the burn from its southern flanks.



OUR ATMOSPHERIC NIGHT-LIGHT

Even on a moonless night, far away from any lights, you can see a vague silhouette of your hand against the "black" sky. That is because complex chemical reactions in the upper atmosphere give off faint light. Astronauts on the International Space Station document this nightglow regularly, but its detailed structure has been elusive. Researchers working with the Day Night Band were astounded when they realized that features of nightglow seemed to be showing up in the data gathered one night near a thunderstorm. The imagery revealed characteristic ripples in the glow. Energy released within thunderstorms launches atmospheric waves that propagate upward. When these waves reach 55 to 60 miles up, near the top of the mesosphere, an hour or two later, they disturb the nightglow layer, creating glowing, concentric ripples. As on other occasions, the sensor captured this effect during a massive Texas thunderstorm in 2014 (*above*).

The waves are more than curiosities; they carry energy that drives the circulation of the upper atmosphere. The Day Night Band's ability to detect the waves and ripples is filling a gap in models of upper-atmosphere dynamics, helping researchers better predict weather and understand climate change. Surface-based observations have also linked nightglow waves to major earthquakes, including the one that generated the devastating 2011 tsunami near Tohoku, Japan. It appears that the seismic motions create upward-moving pressure waves in the atmosphere. It is possible that the Day Night Band could help scientists identify tsunamis as they cross an ocean basin by tracking the atmospheric waves riding above them.

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Illuminating the Capabilities of the Suomi National Polar-Orbiting Partnership (NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band. Steven D. Miller et al. in *Remote Sensing,* Vol. 5, No. 12, pages 6717–6766; December 2013.

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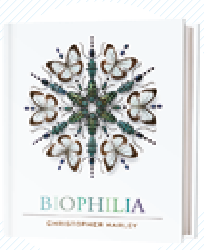
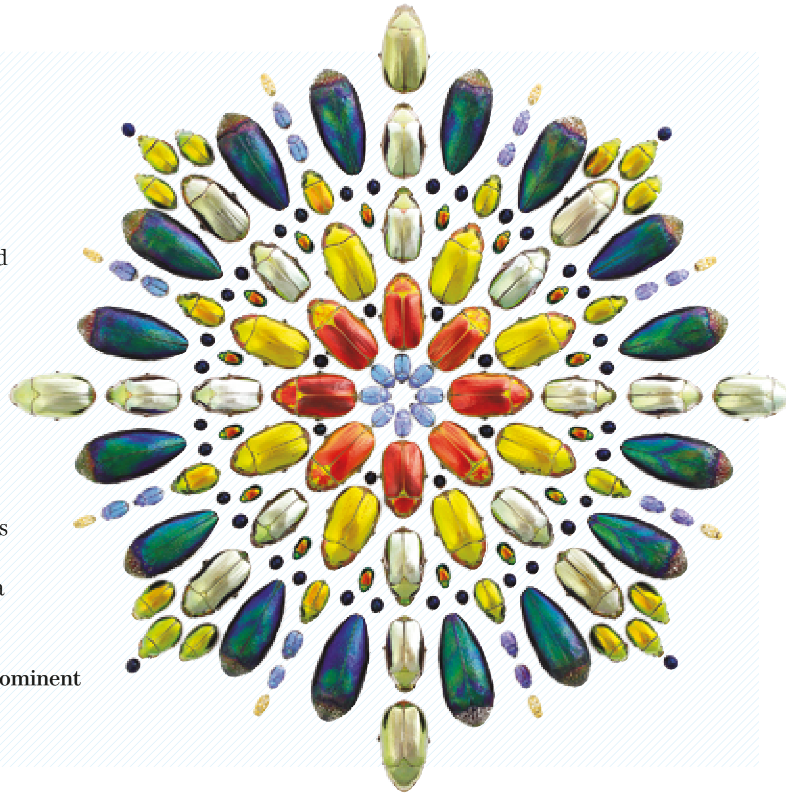
MORE TO EXPLORE
For more recommendations and an interview with author Cédric Villani, go to ScientificAmerican.com/may2015/recommended

Biophilia

by Christopher Marley. Abrams, 2015 ($50)



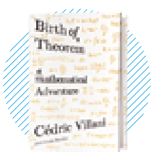
All manner of living things, including pythons, octopuses, orchids and crystals, are turned into art in the photographs of *Biophilia* (meaning "love of life") by artist and designer Marley. Geometric patterns, larger-than-life close-ups and mosaics of various creatures showcase the stunning colors, shapes and textures of the natural world. "We do not love nature because it is beautiful," Marley writes in an introductory essay to the large-format book. "We find beauty in nature because we are a part of it, and it is a part of us."



JEWEL SCARABS, or *Chrysina*, are the most prominent of these brightly colored, iridescent beetles.

Birth of a Theorem: A Mathematical Adventure

by Cédric Villani. Farrar, Straus and Giroux,* 2015 ($26)



Villani, a mathematician at the University of Lyon in France, won a Fields Medal—akin to a Nobel Prize—in 2010 for a new theorem describing a phenomenon known as Landau damping that occurs in plasmas (the most energetic state of matter). By sharing conversations with colleagues, e-mail chains with his main collaborator, and anecdotes of insights that arrived via dreams and stray thoughts in airport waiting lounges, he illustrates the day-to-day process of devising a theorem, a task that took him two grueling and exhilarating years to complete. Rather than glossing over the mathematical intricacies, Villani includes many of the details and even the equations that went into a proof of his theorem, giving readers a vivid sense of the problems he ran into and the solutions he found, even if the subtleties are beyond many nonmathematicians.

Invisible: The Dangerous Allure of the Unseen

by Philip Ball. University of Chicago Press, 2015 ($27.50)

Humans have always imagined the invisible—whether spirits that are summoned or appeased, intangible ether suffusing the universe, or x-rays, magnetic forces and microbes that can be put to work. Science writer Ball takes readers through history to show how myths and legends of the invisible, along with the science of each time period, have influenced our quest to understand what we cannot see. His narrative explores the earliest spells and recipes for supposedly creating or penetrating invisibility, and it recalls disappearance illusions on stage, screen and battlefield, as well as humankind's many theories about invisible entities both real and imagined—such as germs, ghosts and dark matter. Finer tools and measurements through the ages have made our understanding of the imperceptible particles and forces in the world much more precise and actionable—but no less astonishing. *—Sarah Lewin*

How to Clone a Mammoth: The Science of De-extinction

by Beth Shapiro. Princeton University Press, 2015 ($24.95)

It has been several millennia since the last mammoths died out, after more than 100,000 years of dominating Arctic ecosystems. But the hairy elephants could return within decades, brought back to life by recent breakthroughs in biotechnology. In this lucid road map for the nascent discipline of "de-extinction," Shapiro, an evolutionary biologist, examines not only how we can resurrect long-vanished species but also when we cannot or should not. Cloning a mammoth from frozen remains, for example, is unlikely to succeed, she writes, because it requires living cells; efforts to introduce mammoth genes into existing elephant species are more plausible. Most poignantly, Shapiro argues that without revitalizing ecosystems in which a resurrected species might flourish, in many cases de-extinction could be too cruel to countenance. *—Lee Billings*

CHRISTOPHER MARLEY

*SCIENTIFIC AMERICAN AND FARRAR, STRAUS AND GIROUX ARE AFFILIATES.

Viewing the world with a rational eye

Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com). His new book is *The Moral Arc* (Henry Holt, 2015). Follow him on Twitter @michaelshermer

Terrorism as Self-Help Justice

The moralistic motivations of ISIS

In an unintentionally hilarious video clip, primatologist Frans de Waal narrates an experiment conducted in his laboratory at Emory University involving capuchin monkeys. One monkey exchanges a rock for a cucumber slice, which he gleefully ingests. But after seeing another monkey receive a much tastier grape for a rock, he angrily hurls it back at the experimenter when he is again offered a cucumber slice. He rattles the cage wall, slaps the floor and looks seriously peeved at this blatant injustice. (See the video at http://goo.gl/uTCILt.)

A sense of justice and injustice—right and wrong—is an evolved moral emotion to signal to others that if exchanges are not fair there will be a price to pay. How high a price? In the Ultimatum Game, in which one person is given a sum of money to divide with another person—with the stipulation that if the offer is accepted both keep the money, but if the offer is rejected no one gets any money—offers less than 30 percent of the sum are typically rejected. That is, we are willing to pay 30 percent to punish an offender. This is called moralistic punishment.

In a classic 1983 article entitled "Crime as Social Control," sociologist Donald Black, now at the University of Virginia, notes that only about 10 percent of homicides are predatory in nature—murders that occur during a burglary or robbery. The other 90 percent are moralistic, a form of capital punishment in which the perpetrators are the judge, jury and executioner of a victim they perceive to have wronged them in some manner deserving of the death penalty. Black's disturbing examples include a man who "killed his wife after she 'dared' him to do so during an argument," a woman who "killed her husband during a quarrel in which the man struck her daughter," a man who "killed his brother during a heated discussion about the latter's sexual advances toward his younger sisters," a woman who "killed her 21-year-old son because he had been 'fooling around with homosexuals and drugs,'" and others "during altercations over the parking of an automobile." Recall the murder of three Muslims in Chapel Hill, N.C., this past February, which at least partly involved a parking spot dispute.

After the Middle Ages, such morally motivated self-help justice was replaced for the most part by rationally motivated criminal justice. Black notes, however, that when people do not trust the state's justice system or believe it to be biased against them—or when people live in weak states with corrupt governments or in effectively stateless societies—they take the law into their own hands. Terrorism is one such activity, the expression of which, Black argues in a 2004 article in *Sociological Theory* entitled "The Geometry of Terrorism," is a form of self-help justice whose motives depend on the particular terrorist group. These have ranged from revolutionary Marxism in the 1970s to apocalyptic Islam today as practiced by the Islamic State of Iraq and Syria (known as ISIS or ISIL), which is not a state at all but a loose confederation of jihadists.

Many American liberals and media pundits have downplayed their religious motives, but as Black told me in an e-mail, "Muslim terrorists should be taken at their word that their movement is Islamic, anti-Christian, anti-Jewish, etc. We have their word as evidence, and in my view that is the proper basis on which to classify their movement. Would we have said that the violence used by Protestants and Catholics during the Protestant Reformation had nothing to do with religion? That would be absurd."

No less absurd is the belief that jihadists are secular political agitators in religious cloak. As Graeme Wood writes in "What ISIS Really Wants," his investigative piece in the March issue of the *Atlantic,* "much of what the group does looks nonsensical except in light of a sincere, carefully considered commitment to returning civilization to a seventh-century legal environment, and ultimately to bringing about the apocalypse." Yes, ISIS has attracted the disaffected from around the world, but "the religion preached by its most ardent followers derives from coherent and even learned interpretations of Islam," Wood concludes, adding that its theology "must be understood to be combatted." SA

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Illustration by Izhar Cohen

The ongoing search for fundamental farces

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

Have a Seat

Some chairs you would want of wood, some chairs you would not want

The electric, push button–operated reclining chair (as opposed to the plain old electric chair) is clearly one of the hallmarks of an advanced civilization. Some models of recliners should probably be sold by prescription only, so soporific can be the effect of yielding one's back and nether region to its welcoming embrace. I have often mused while relaxing in my own recliner that even if sitting be the new smoking—as it has lately been labeled by virtue of the deleterious effects of long-term butt parking—then splay on.

So it was in early March that while thusly ensconced I was surprised to come across an article about another kind of lounger, the ubiquitous Adirondack chair. One might expect to find such a piece in, say, *Consumer Reports* or *Smithsonian*. But what took me aback while almost lying on my back was that this write-up appeared in the publication *JAMA Dermatology*. What was it doing there, among the latest reports concerning seborrheic dermatitis, psoriasis and malignant melanoma?

Author Megan E. MacGillivray, a student at the Queen's University School of Medicine in Ontario (and surely a future academic department chair), explained that upstate New York Adirondack Mountains region resident Thomas Lee in 1903 "built a pine chair with a long sloping seat and wide armrests." He intended to make a few for family use, but the design caught on.

Meanwhile nearby Saranac Lake had become a haven for tuberculosis patients who benefited from the clean air and sunlight. Ultraviolet light had recently been recognized as a killer of the bacterium that caused TB, which made sunlight effective as a treatment, for at least the cutaneous (and finally we arrive at the dermatology connection) form of the disease. The patients needed to sit in the sun—and the Adirondack chair became the standout choice.

This connection between seats and science got me curious enough to check the *Scientific American* archives for any page space we might have devoted to chairs. Turns out we have not been sitting down on the job.

For example, in 1906 we reported on the invention by one George Fentrick of a combination deck chair/life preserver. The chair's back was filled with cork. "The shipwrecked passenger need not worry about the proper adjustment of his life preserver," we explained, "but may cling to his chair for support," as he left his fellow swells onboard the cruise liner to confront the freezing swells of the North Atlantic. Based on my latest cruise experience, the proposed chair was a long-term bust, with life preservers and lifeboats still very much in fashion. Deck chair cushions may indeed float today, but the cork onboard cruise liners is under the command of the sommelier.

Even further back, in 1897, *Scientific American* noted the creation of "a rocking chair provided with an air-compressing device adapted to deliver a current of air for cooling the occupant of the chair, for sounding a music box or for any purpose for which compressed air may be applied." Our article said that the inventor was one Charles Michaelson and not Rube Goldberg, who was only 14 years old at the time and probably still in his early better-mousetrap phase.

"Beneath the chair seat are two bellows, having the usual valves, and discharging into a receiver above," we deadpanned. "As the chair rocks … the air is forced into the receiver, from which a tube leads into a small compressed air reservoir at the top of the chair back, and in this reservoir is a passageway with reeds and adapted to be used as a music box." We then added helpfully, "The music box is operated in the usual way."

Like the deck chair/life raft, this device seems to have been consigned to history's furniture junk heap. But bad ideas persist: a quick Google search turns up, available for purchase today, an inflatable rocking chair with a built-in MP3 speaker, thus combining the worst qualities of the unfulfilled dreams of Messrs. Michaelson and Fentrick. Unlike Mr. Lee's Adirondack chair, this seat is not outstanding. SA

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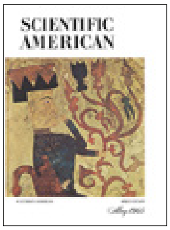
Illustration by Matt Collins



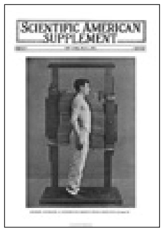
May 1965

The Scythians

"In central Siberia, a land whose prehistory has been almost completely unknown, Soviet archaeologists have in recent years uncovered the remains of an ancient people kept remarkably intact. The find consists of a number of burial mounds high in the Altai Mountains on the border between Siberia and Outer Mongolia. Here, in these chambers of eternal frost, the bodies of ancient chieftains, with their horses, clothing and varied possessions, have been preserved from decay. The Altai finds have opened up a significant ancient culture. These buried horsemen belonged to one of the great tribes of 'barbarians'—nomads who roamed the steppes of Eurasia in the time of ancient Greece and Persia and were called by ancient writers the Scythians. —Mikhail I. Artamonov"

The Truth about Lie Detectors

"A Congressional committee has issued a report casting serious doubt on the validity of polygraph 'lie detector' tests and castigating the Federal Government for their indiscriminate application. The committee's primary conclusion was: 'There is no "lie detector," neither machine nor human. People have been deceived by a myth that a metal box in the hands of an investigator can detect truth or falsehood.' The report points out that the polygraph is an instrument that records a person's respiration, blood pressure and pulse and also his 'galvanic skin response.' These are physiological responses that 'may or may not be connected with an emotional reaction—and that reaction may or may not be related to guilt or innocence.'"



May 1915

Lusitania Sunk

"The sinking, on sight, of the *Lusitania* is the latest and most atrocious instance of a relapse to that gratuitous cruelty which we all thought had been relegated to a bygone and far-distant age. One of the most remarkable psychological phenomena of the present war is the specious sophistry with which Germany has attempted to justify her multitudinous breaches of the humanitarian laws of war; and surely the most amazing instance of this is the fact that to-day Germany is justifying this slaughter of innocent non-combatants by stating that she gave them full warning that she was going to perpetrate the deed. This is a new philosophy, indeed!"

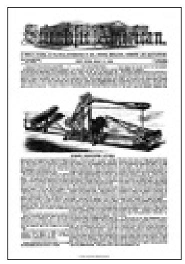
The attack killed 1,200 civilians onboard the liner, 120 of them U.S. citizens. The ship's cargo included four million rounds of rifle ammunition.

GAS WARFARE: German troops use lethal chlorine gas for the first time on the battlefield, 1915

Poison Gas for War

"In the present European war the application of knowledge seems to be reaching the utmost limit of ingenuity. It may almost be called a chemist and physicist war. Latest of all is the manufacture of poisonous gases to be used for tactical purposes [*see illustration*]. The reports seem to show that the gas so far used is chlorine. The greenish yellow color, the strong smell, the great density of the gas causing it to flow along the ground are indications of chlorine. The symptoms shown by its victims are those exhibited by persons who have been poisoned by chlorine in industrial accidents."

A slide show of images from the Great War in our archives from 1915 is at www.ScientificAmerican.com/may2015/wwi1915



May 1865

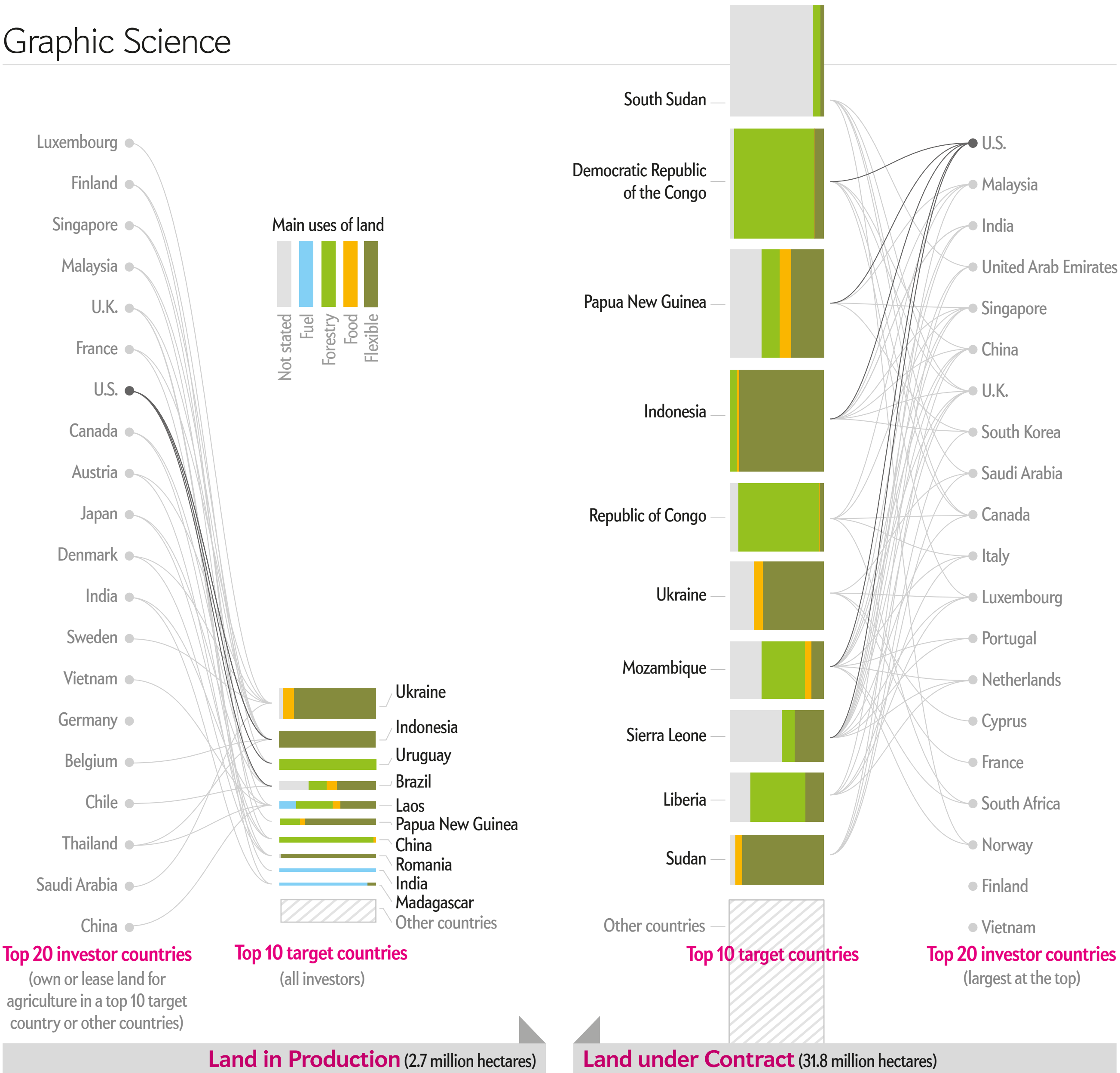
Gatling Gun

"This invention promises to revolutionize the art of war. From experiments made under the inspection of ordnance officers, a rate of three discharges per second was kept up, the penetration being superior to the Springfield rifle. It was conceded that one of Mr. R. J. Gatting's [*sic*] guns worked by two men would put a larger number of shots into an average target at four hundred yards than one hundred men. The barrels and locks rotate in concert and continuously, and each load is delivered as its barrel arrives at a certain point. Fixed ammunition [metal cartridges containing bullet and powder] is fed to the gun from cases set into a hopper."

Beef Jerky

"South American jerked beef, or beef dried in the air, is being largely exported to England, where it is consumed by the poorer classes; it being sold at three pence, English money. It is not very delicate food, being tough and stringy, but it is said to be better than going without meat altogether."

SCIENTIFIC AMERICAN, VOL. CXII, NO. 20; MAY 15, 1915



This Land Is My Land

To meet demand for food, fuel and wood, countries are snapping up property beyond their borders

Fertile land is becoming scarce worldwide, especially for crops for food, feed, biofuels, timber and fiber such as cotton. To produce those goods, wealthy countries such as the U.S. and small countries with little space are buying up or leasing large tracts of land that are suitable for agriculture in other nations. Products are shipped back home or sold locally, at times squeezing out native farmers, landowners and businesses. In the past 15 years companies and government groups in "investor" countries have grabbed 31.8 million hectares of land, the area of New Mexico (*column on right*), according to the Land Matrix Global Observatory's database of transactions that target low- and middle-income countries. Crops are being produced on only 2.7 million of those hectares thus far (*column on left*). Overall, a large transfer of land ownership from the global south to the global north seems to be under way. —*Mark Fischetti*

The U.S., Malaysia and India are grabbing the largest areas of land (*list at far right*). Countries with weak governance, such as South Sudan and Papua New Guinea, are often top targets (*right-hand column*), according to Kimberly Nicholas and Emma Li Johansson, both at Lund University in Sweden, who have analyzed the data.

Data shown cover land acquired from 2000 to 2014. They do not include deals involving multi-country partnerships, which may not distinguish each country's share; these deals boost the total land under contract to 51.1 million hectares.

SOURCE: LAND MATRIX GLOBAL OBSERVATORY; ACCESSED FEBRUARY 4, 2015 www.landmatrix.org; EMMA LI JOHANSSON *Lund University (additional data categorization and processing)*

Graphic by Nigel Hawtin

SCIENTIFIC AMERICAN ONLINE For more graphics about the acquisition of farmland, see ScientificAmerican.com/may2015/graphic-science

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