NEUROBIOLOGY
The Maddening Sense of Itch

TECHNOLOGY
How to Connect a Quantum Computer

ENVIRONMENT
Replenishing Africa's Soil

SCIENTIFIC AMERICAN

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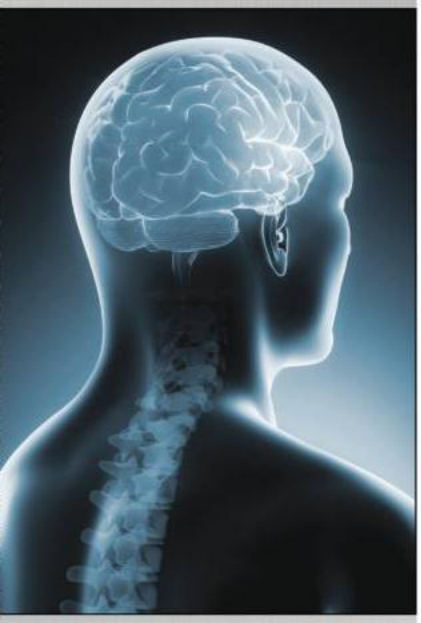
MAY 2016

Born of Chaos

How raging bouts of interplanetary destruction built our solar system

What do elite athletes, military personnel and the 50 million Americans suffering from a neurological disorder have in common?

More than you think.



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MAY 2016

VOLUME 314, NUMBER 5

SCIENTIFIC AMERICAN

ALEXANDER SEMENOV

ON THE COVER

Jupiter has played a key role in the solar system's evolution for more than 4.5 billion years. This artist's rendition shows a young, glowing Jupiter migrating through the sun's planet-forming disk of gas and dust. This migration may have destroyed a set of inner planets and cleared the way for Earth and other rocky worlds. **Image by Kenn Brown, Mondolithic Studios.**

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12

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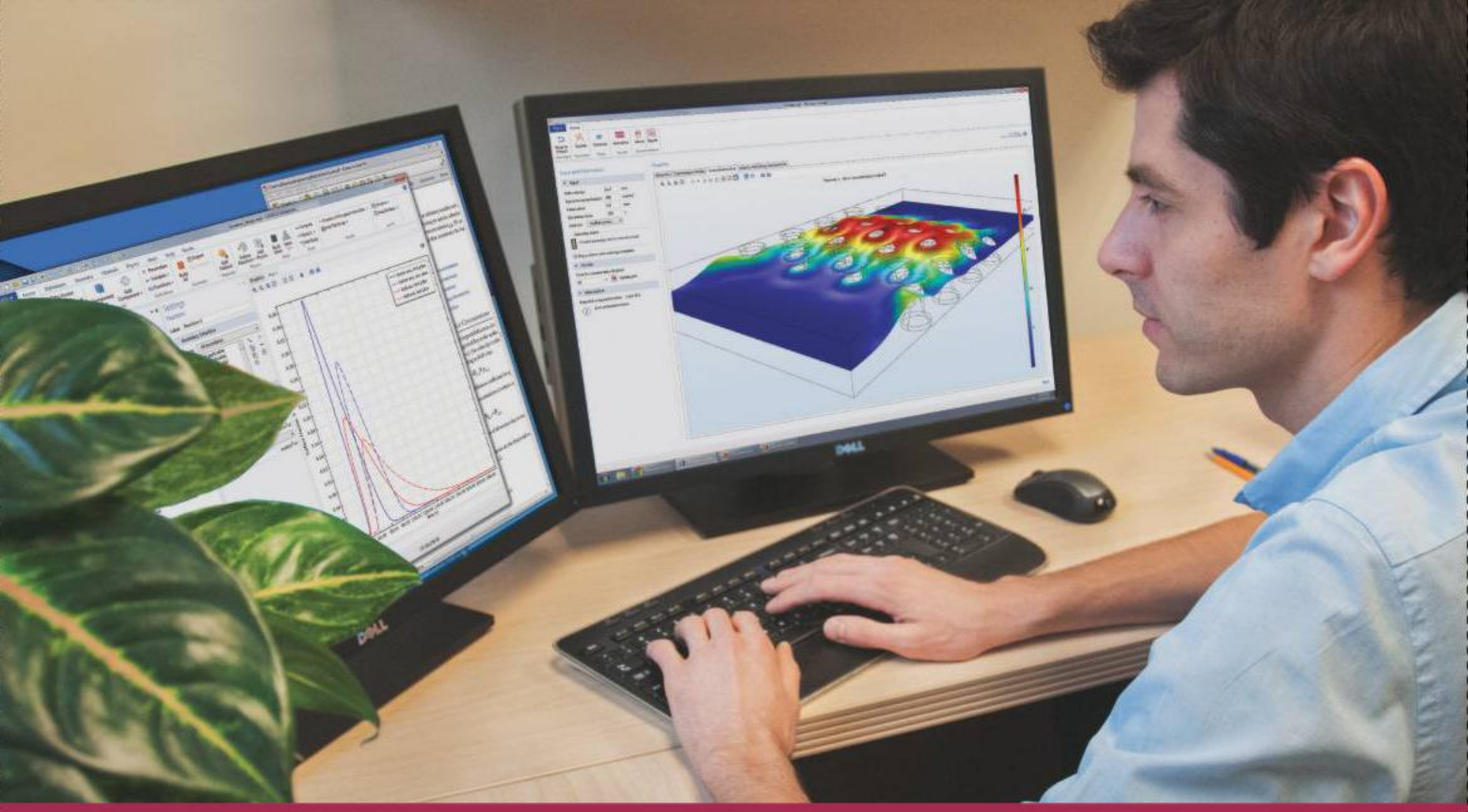

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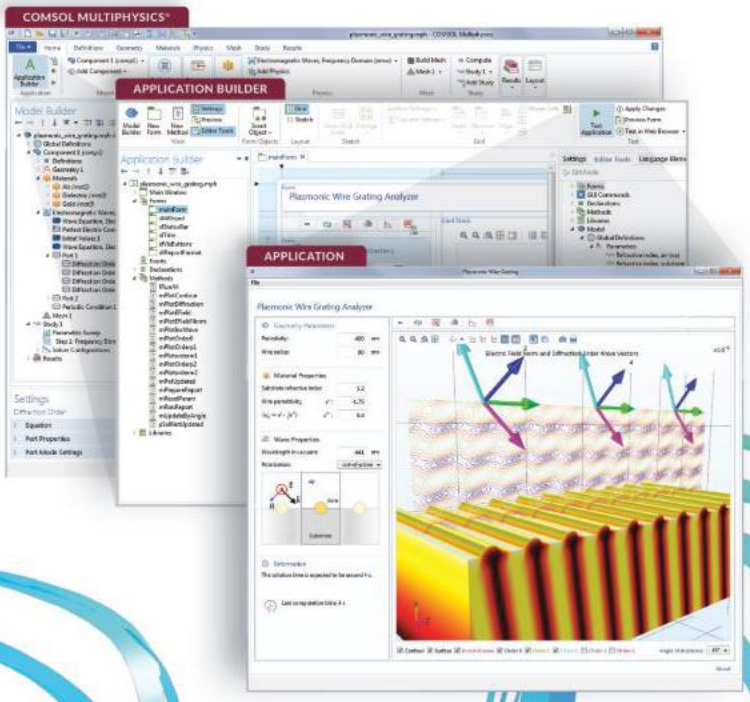

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Mariette DiChristina is editor in chief of *Scientific American*. Follow her on Twitter @mdichristina

Outer Worlds and Our Inner Itch

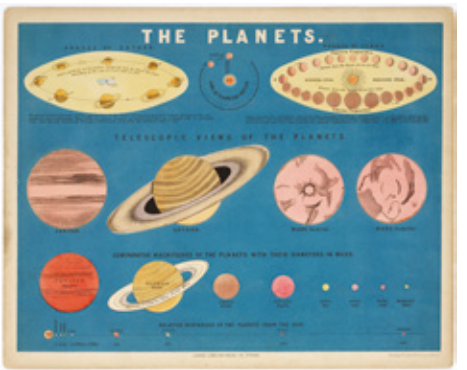
Most of us grew up with a rather placid notion of the formation of our solar system: dust agglomerating into larger clumps, with an "ice line" forming the divide between the outer behemoths like Jupiter that we see today against the smaller, rockier bodies orbiting closer to our sun. Then astronomers began to find exoplanets multiple times the size of Jupiter—and generally far too close to their stars to fit within our tidy classical theories. Time for a rewrite of the textbooks.

In this issue's cover story, "Born of Chaos," Konstantin Batygin, Gregory Laughlin and Alessandro Morbidelli trace that still evolving, new history of our stellar neighborhood: "a tale of wandering planets evicted from their birthplaces, of lost worlds driven to fiery destruction in the sun eons ago and of lonely giants hurled into the frigid depths of near-interstellar space." The adventure begins on page 28.

A different kind of materials construction is the subject of "A Cure for Africa's Soil" (*page 66*). John P. Reganold and Jerry D. Glover explain the mechanisms of soil degradation in sub-Saharan Africa. With some 220 million of the world's 800 million undernourished people living in the region, restoring soils is a top priority to improve crop yields. Just adding more fertilizer won't work and can even worsen the situation. Scientists now are looking to a solution called perenniation—in which perennial plants such as shrubs, trees or grasses are grown alongside crops. They help to supply carbon and nitrogen, and their roots hold the soil against erosion.

Researchers who have a strong desire to study something like agriculture might metaphorically say they want to "scratch an itch." But scientists have had only a piecemeal understanding of how the annoying feeling itself actually arises. In "The Maddening Sensation of Itch," Stephani Sutherland describes new insights into the causes of itch—some of the first since the molecule histamine was found to set off the sensation in the early years of the 20th century.

These investigations could lead to new treatments for itch that does not respond to antihistamines. The article, which begins on page 38, discusses the way nerve cells detect the presence of itch-inducing substances and then send off signals, relayed all the way to the brain, that tell the body it's time to scratch. Sutherland also mentions why itching is contagious—perhaps explaining why I began feeling those irritating twitches along my arm about halfway through reading the article. SA



TEXTBOOK notions of solar system formation (*shown from 1860*) as placid have proved wrong.

GETTY IMAGES

Illustration by Nick Higgins

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- What Do Scientific American Editors Read?
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- The Incredible Higgs Boson
- The Dark Side of the Universe
- Gigantic Tools to Explore the Smallest Particles
- The Tragic Destiny of Mileva Mari Einstein
- Hubble's Universe
- The Particle Zoo

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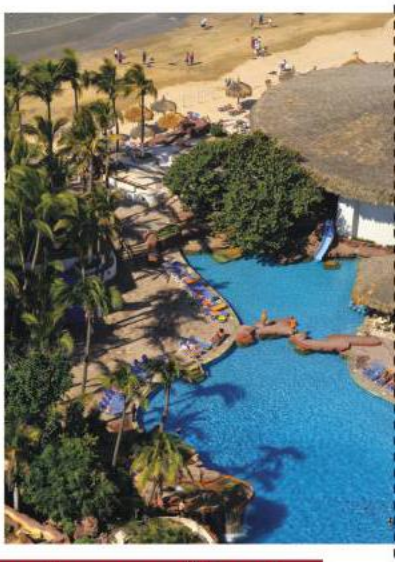
Pauline Gagnon, Ph.D.
Robin Lloyd, Ph.D.
Steve Mirsky, M.Sc.
Clara Moskowitz
Paul Rosenzweig, Esq.



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January 2016

ASTEROID THREAT

The search for near-Earth asteroids that could threaten our planet, as described in "Fear of the Unknown," by Lee Billings [Advances], should be a worldwide undertaking, no less than the effort to tackle the human causes of global warming. And unlike that program, it should not be hampered by powerful commercial interests. But at present, it's apparently entirely dependent on NASA funding, where it competes with various projects. Are other nations making any similar efforts?

TONY BLAKE
Glenalta, Australia

BILLINGS REPLIES: Because they are everybody's problem, Earth-threatening asteroids are all too often treated as nobody's problem. There is at present very little formal international collaboration on planetary defense, and most existing programs are funded by the U.S. Indeed, NASA is the largest and most prominent organization working on the problem. It is, however, not the only one. At present, the National Science Foundation, U.S. Air Force, Federal Emergency Management Agency and nonprofit B612 Foundation are also contributing to planetary defense in various ways.

Meanwhile the European Space Agency is taking a leading role in the proposed Asteroid Impact & Deflection Assessment mission, which would attempt to alter the course of the nonthreatening binary asteroid 65803 Didymos. Are we ready to face a space rock hurtling toward Earth? Not entirely. Fortunately, our present suite of surveys suggests that time is on our side—no known asteroids pose a serious near-term threat to our planet.

"Micropayments to remove ads are on par with paying a mob boss to avoid hurting you."

GREG SMITH *VIA E-MAIL*

AD-FREE FOR A FEE

In "Click 'n' Pay" [TechnoFiles], David Pogue suggests that micropayments could make ubiquitous online ads unnecessary.

Unfortunately, ads are with us forever. Micropayments sound nice for advertisers, but I predict they will be as effective as my paid print subscription to *Scientific American*. Despite a fairly sizable fee, I still face several ads.

In terms of desirability, micropayments to remove ads are on par with paying a mob boss to avoid hurting you. Ad blockers restore the balance in favor of the consumer. We need stronger and better ones.

GREG SMITH
via e-mail

CARBON CAPTURE

"The Carbon Capture Fallacy," by David Biello, reports that all credible plans to reduce global warming depend on carbon capture but that high costs make the widespread use of capture projects unlikely.

The best way to capture carbon biologically is by enhancing photosynthesis and carbon sequestration in organic matter. A feasible and cost-effective approach to carbon sequestration is restoring the massive carbon sink in degraded grassland soils. The potential of grasslands to sequester carbon as organic matter in the soil has probably been underestimated. Most of the world's grasslands have been degraded through cultivation and soil erosion or by poor livestock management and overgrazing. Properly planned grazing on degraded grasslands worldwide has the potential to make new soil and remove huge amounts of carbon from the atmosphere.

DARYLL MEYER
Eastend, Saskatchewan

NAVIGATION NOTE

As a retired U.S. naval officer who spent much of his life navigating the world's skies and oceans, I very much enjoyed "Where Am I? Where Am I Going?" by May-Britt Moser and Edvard I. Moser. But I must dispute the authors' comparison of the biological processes they describe with the Global Positioning System (GPS).

They state that path integration is "a GPS-like mechanism in which neurons calculate position based on constant monitoring of the animal's direction and speed of movement relative to a starting point—a task carried out without reference to external cues such as physical landmarks."

This process very accurately describes inertial navigation that is augmented by other cues—something we called dead reckoning in the navy. Inertial navigation, even when augmented by cues from other sensors, is conducted internally (for example, within an airplane, boat or animal). In it, acceleration is combined with elapsed time to calculate direction and speed, with an estimated position as the output.

In GPS navigation, actual position is the input that is continually updated from an external source (satellites); speed and direction are outputs. The nervous systems of animals don't function remotely like GPS, but they do function like an inertial navigation system.

WALLACE DAVIS
Snohomish, Wash.

MYSTERY REMAINS

Isn't Michael Shermer missing the point about what is so unusual about the *Homo naledi* discovery in "Murder in the Cave" [Skeptic]? Regardless of whether the location of the remains was the result of burial, homicide or sacrifice, a creature with the brain size of a chimp engaged in humanlike behavior.

HENRY METZGER
via e-mail

SHERMER REPLIES: Indeed, the H. naledi *finds constitute one of the most unusual ever made. The number, location and espe-*

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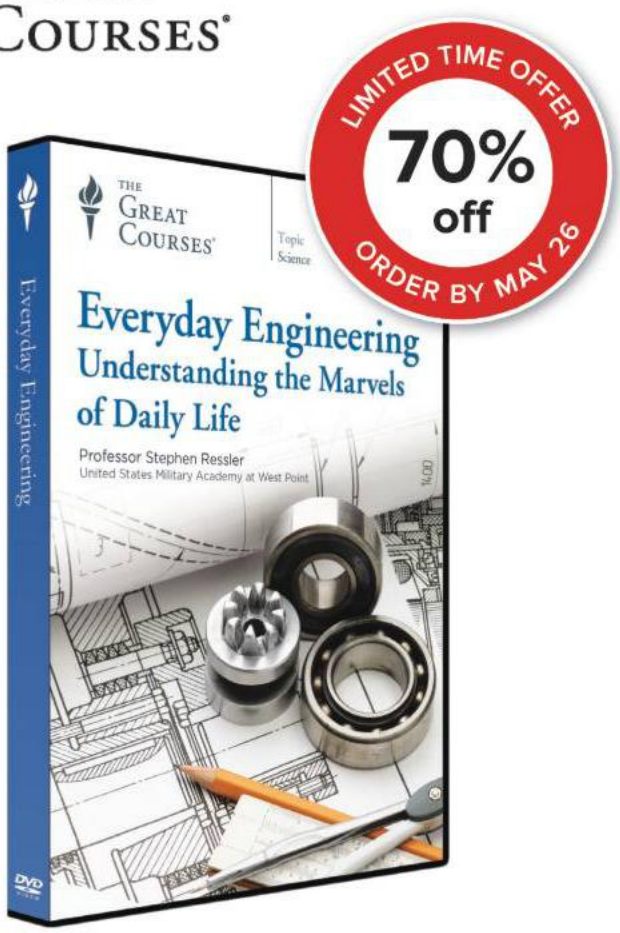

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cially the peculiar fact that the fossils appear to have been purposefully deposited leave open so many interpretations. Determining their age, along with agreement on their classification, will answer some questions, but given the contentious history of paleoanthropology, the ultimate fate of how they got in that cave may never find scientific consensus.

CLEAN AS A CATTAIL

I read with interest "Death in the Water," Katy Daigle's article about arsenic poisoning in groundwater and its devastating effects on those who must consume it. This has been a topic of concern to me for the past decade. In 2006 I presented a paper in New Delhi about a treatment process I had developed that uses common cattails. The process is simple and inexpensive: less than $5 for a system to treat a family of six's drinking water for five years. It uses no electricity, has no plumbing and relies on no moving parts. And it can remove arsenic from an average concentration of 300 micrograms per liter (μg/L) to below India's standard of 50 μg/L.

Jeremiah D. Jackson
Senior principal engineer
J2Environmental

ERRATA

"Murder in the Cave," by Michael Shermer [Skeptic], incorrectly states that it is impossible to conclude where the recently reported *Homo naledi* fits into the hominin lineage because the species' age is not yet determined. Although that age is not yet known in the case of the *H. naledi* fossils, only morphological features are needed to determine which taxon a fossil belongs to.

"Elegant Equations," by Clara Moskowitz, refers to an equation presented by David Mumford of Brown University as describing a space with dimensions numbering $3g - g$. It should have said that they number $3g - 3$. Further, the article included an image of equations representing Ampère's law that was created by Simon Donaldson of Stony Brook University and published in the Concinnitas print series. That print had an error in the second equation at the lower right corner. The equation should have read:

$$Jy = \delta Bx/\delta z - \delta Bz/\delta x$$

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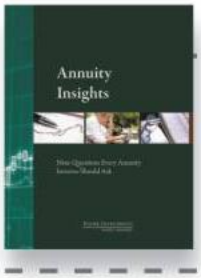

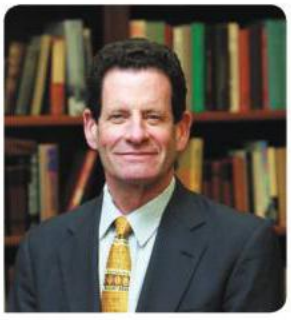

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This Drug Ad Is Not Right for You

Peddling pharmaceuticals on TV is a lousy form of health education, and it can also drive up medical costs

By the Editors

Television ads for erectile dysfunction, stroke or toenail fungus treatments have been called both a boon and a curse. Drugmakers assert that promoting their products makes patients aware of conditions they can then flag for their doctor.

Yet every developed country except the U.S. and New Zealand prohibits such direct-to-consumer prescription drug ads. It is hard to see educational value in commercials on American TV that show radiant models relaxing before a tryst, accompanied by voice-overs that warn of possible side effects, including difficulty breathing and an unsafe drop in blood pressure.

An ad that conflates an aura of glowing health and the prospect of an amorous liaison with a list of dire cardiovascular symptoms is a paradigm of confused messaging because it does not provide the viewer with a clear guide to weighing both benefits and costs entailed in using a prescription medicine. Absent further interpretation, the underlying message reduces to: Sex or death—which will it be? Of course, the ads always end with an admonition to "ask your doctor…."

Now, finally, the doctors are giving an answer. In November 2015 the American Medical Association asked for a ban on these ads, saying that they are partially responsible for the skyrocketing costs of drugs. The World Health Organization and other groups have previously endorsed such restrictions.

In 2014 pharmaceutical companies spent $4.5 billion on consumer ads, mostly for television, a 30 percent rise from two years before. The pitches can drum up sales on higher-priced medications that can drive up drug costs when less expensive alternatives are sometimes available.

Many of the newest ads are for premium drugs for life-threatening diseases or rare conditions that can cost tens of thousands of dollars and require large, out-of-pocket patient co-payments. After seeing an ad, patients may press physicians for a prescription without understanding the complex criteria needed to determine eligibility for treatment.

Despite industry rhetoric about educating the consumer, the ads do what ads do—promote the advertiser's product while failing to note these complexities or alternative options. Last October a Kaiser Family Foundation survey found that 28 percent of people who viewed a drug ad subsequently asked a physician about the medicine and that 12 percent walked out with a prescription.

A ban would be a welcome step toward trimming the nation's lofty drug bills—and it would rid the airwaves of purported health messages that baffle more than they inform. It is unclear, though, whether any prohibition passed by Congress would pass muster in the courts. Pharma would undoubtedly mount a legal challenge, claiming that the law violates First Amendment protections for commercial speech.

Steps, however, can be taken short of outright prohibition. Presidential candidate Hillary Clinton, who has highlighted inflated drug prices as a campaign issue, wants to eliminate the industry's ad-based tax deduction. There are other options as well. Because drug companies contend that the ads are an educational tool, the Food and Drug Administration might hold them to their word. They could be required to focus consumer ads on the benefits of a particular class of drugs rather than a specific product. The patient could then follow up with a physician who might recommend, say, the best diabetes medicine.

Another constructive move would be for Congress to pass the Responsibility in Drug Advertising Act, introduced in February by Representative Rosa DeLauro of Connecticut. The bill would require a three-year moratorium on ads for new prescription drugs approved by the FDA.

The proposed legislation also could be flexible in its implementation. The bill recognizes that a new approval by the FDA can have substantial public health benefits, and so it provides for the waiving of the restriction case by case. And it would permit extending the ban beyond the three years if concern over a side-effect profile persisted. A break from the up to 30 hours of prescription drug ads that the average TV viewer is exposed to every year—be it temporary or permanent—would be a refreshing relief. SA

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Illustration by Thomas Pullin

Alexander Rodin is a planetary scientist and docent at the Moscow Institute of Physics and Technology.

Show Venus Some Love

Space agencies have paid too little attention to the most Earth-like planet in our solar system

By Alexander Rodin

Both Mars and Venus have been objects of scientific and popular speculation since at least the beginning of the 20th century, and since the 1960s spacefaring nations have been sending robotic probes to explore both worlds. Mars has gotten far more attention, however. Since 2002 no fewer than two Mars probes have been actively gathering data during any given year. Last year there were seven.

This is understandable. Mars is far more hospitable than Venus, where surface temperatures reach nearly 480 degrees Celsius, surface pressure is 92 times that of Earth and the planet is permanently shrouded by thick clouds of sulfuric acid. We have direct evidence that water once flowed and pooled on Mars. It cannot be ruled out that life once existed there and may conceivably exist still.

Venus is far more Earth-like than Mars in its size (it is only 5 percent smaller than Earth), composition and surface gravity, but its harsh environment leaves little hope that the planet could ever host life. Yet it is still worth studying Venus to learn why it is the way it is—and how Earth could avoid a similar fate.

Venus could also help us understand newly discovered extrasolar planets. A surprising number of these planets lie very close to their stars, with revolution periods as short as a few days. So far most of these are massive "hot Jupiters" or "hot Neptunes," but improving instruments should one day allow astronomers to find "hot Venuses." If that happens, our sister planet would serve as an invaluable reference point for interpreting observations of distant worlds.

Venus is also an intriguing world in its own right. Although it is Earth-like in size and composition, there is no evidence of the kind of plate tectonics that continuously recycles our planet's crust. Nevertheless, Venus's surface is rich in volcanoes, lava flows and other geologic evidence of past tectonic activity. If tectonic activity is still going on, which might well be the case, studying it could give us important information about the planet's inner structure and dynamics.

The dynamics of the Venusian atmosphere are equally fascinating. The planet rotates on its axis once every 224 days—in a direction opposite to Venus's motion around the sun, unlike every other planet. But its clouds take just four days to circulate, in a phenomenon known as superrotation, and this superrotation involves virtually the entire atmosphere, up to an altitude of 80 to 90 kilometers. The only exception is the poles, where spectacular, continuously changing vortices develop. Venus's atmospheric motion thus resembles a great, planetary-scale hurricane with two "eyes" residing on both poles. Scientists hope that studying Venus's atmospheric dynamics could help them understand how to predict terrestrial hurricanes and even control them.

For the general public, the search for extraterrestrial life is probably the most important reason to do planetary exploration. Does Venus's hellish climate mean that any type of biology is strictly impossible there? Surprisingly, some experts say no. They argue that the abundant aerosol particles in Venus's atmosphere could in principle host some form of life. All the necessary components are there: a moderate thermal regime at 50 to 70 kilometers above the surface, liquid water and rich chemistry. Only future studies will show if this hypothesis, which seems fantastic, is true or not.

Yet despite all this scientific promise and Venus's proximity to Earth, the planet has been relatively poorly studied. Indeed, when the Venus Express mission was launched in 2005, it had been 20 years since the previous Venus probe. Only a tiny handful of probes have been launched since then. For all these reasons, planetary scientists around the world believe that we need a new campaign to investigate Venus, complete with orbiters, landing probes and flying platforms. We hope that funding agencies will agree. SA

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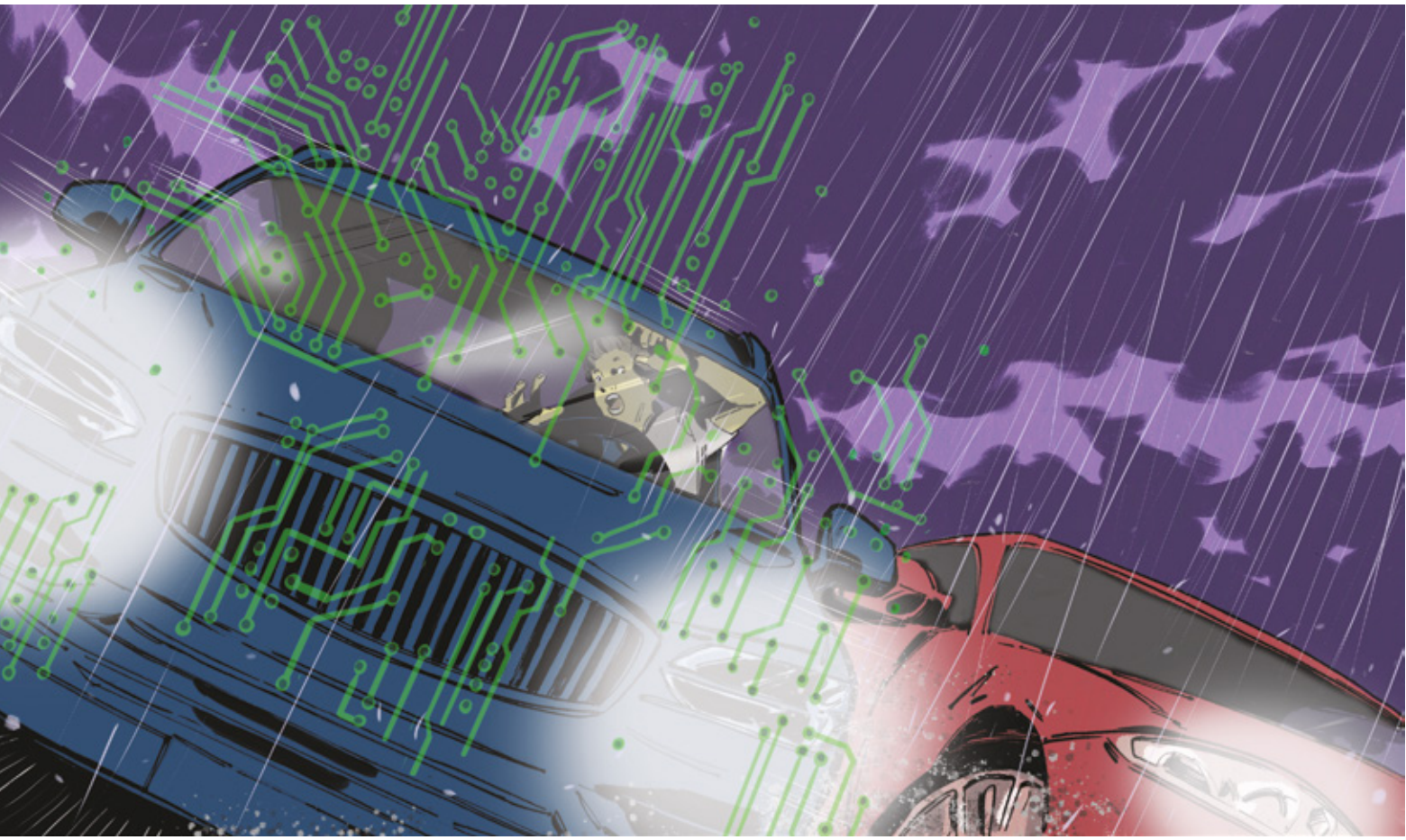
Illustration by Gloria Pizzilli



TECHNOLOGY

Who's Responsible When a Car Controls the Wheel?

As self-driving cars come closer to reality, carmakers commit to their tech by accepting blame

Valentine's Day was a bummer in Mountain View, Calif. For the first time, one of Google's self-driving cars, a modified Lexus SUV, caused a crash. Detecting a pile of sandbags surrounding a storm drain in its path, the car moved into the center lane to avoid the hazard. Three seconds later it collided with the side of a bus. According to the accident report, the Lexus's test driver saw the bus but assumed the bus driver would slow down to allow the SUV to continue.

It was not the project's first crash, but it was the first caused in part by nonhuman error (most incidents involve the driverless cars getting rear-ended by human drivers not paying attention at traffic lights). The episode shines a light on an ever looming gray area in our robotic future: Who is responsible—and pays for damages—when an autonomous vehicle crashes?

The sense of urgency to find clear answers to this and other self-driving vehicle questions is growing. Automakers and policy experts have worried that a lack of consistent national regulation would make rolling out these cars across all 50 states nearly impossible. To spur progress, the Obama administration asked the Department of Transportation to propose complete national testing and safety standards by this summer. But as far as the question of accountability and liability goes, we might already be homing in on an answer, one that points to a shift in how the root cause of damage is assessed: When a computerized driver replaces a human one, experts say the companies behind the software and hardware sit in the legal liability chain—not the car owner or the person's insurance company. Eventually, and inevitably, the carmakers will have to take the blame.

Self-driving pioneers, in fact, are starting to make the switch. Last October, Volvo declared that it would pay for any injuries or property damage caused by its fully autonomous IntelliSafe Autopilot system, which is

Illustration by Thomas Pitilli

INSIDE

scheduled to debut in the company's cars by 2020. The thinking behind the decision, explains Erik Coelingh, Volvo's senior technical leader for safety and driver-support technologies, is that Autopilot will include so many redundant and backup systems—duplicate cameras, radars, batteries, brakes, computers, steering actuators—that a human driver will never need to intervene and thus cannot be at fault. "Whatever system fails, the car should still have the ability to bring itself to a safe stop," he says.

The proliferation of vehicles already on the road with partial automation shows how quickly the scenario that Coelingh describes is coming about. A growing number of cars include crash-imminent braking systems, which rely on optics to detect potential front-end impacts and proactively apply brakes. Audi, BMW and others have developed cars that can parallel park themselves. And later this year Volvo will roll out the U.S.'s first semiautonomous highway driving feature, called Pilot Assist, on the 2017 S90 sedan. The system uses a windshield-mounted computer equipped with a camera and radar to automatically accelerate, decelerate, avoid obstacles and stay in a lane at speeds of up to 80 miles per hour.

Features such as Pilot Assist exist in what tech policy expert and University of South Carolina assistant professor Bryant Walker Smith calls the "mushy middle of automation," where carmakers still require human drivers to pay attention. "It's not always clear where the line between the human and the machine falls," he says.

For the time being, some automakers are aiming to keep human drivers clearly on the responsible side of that line. General Motors' forthcoming Super Cruise, which will launch on a Cadillac in 2017 and is similar to Pilot Assist, comes with caveats that the human driver must remain alert and ready to take over steering if visibility dips or weather changes. With Pilot Assist, Volvo puts similar onus on the driver; touch sensors on the steering wheel ensure the person remains engaged.

By the time fully autonomous driving becomes a reality, however, carmakers such as Volvo, Mercedes and Google are confident that they will have these technologies—and many more—so buttoned up that they will be able to take the driver out of the operation and liability picture almost entirely. What is more, a 2014 Brookings Institution study found that current product liability law already covers the shift, so the U.S. might not need to rewrite any laws for automation to continue moving forward.

It is a relatively safe bet for driverless carmakers to say they will foot the bill for everything from fender benders to violent crashes because semiautonomy is showing that computer drivers are likely safer than human ones. Data from the Insurance Institute for Highway Safety, for instance, have found that crash-avoidance braking can reduce total rear-end collisions by 40 percent. And Volvo's Coelingh notes that a study of the European version of Pilot Assist revealed that the computer maintains safer follow distances and has fewer harsh braking incidents than human drivers do.

In the long run, "from the manufacturer's perspective," Smith says, "what they may be looking at is a bigger slice of what we all hope will be a much smaller [liability] pie."

—Corinne Iozzio

TAXONOMY

Monster Comes Out of Hiding

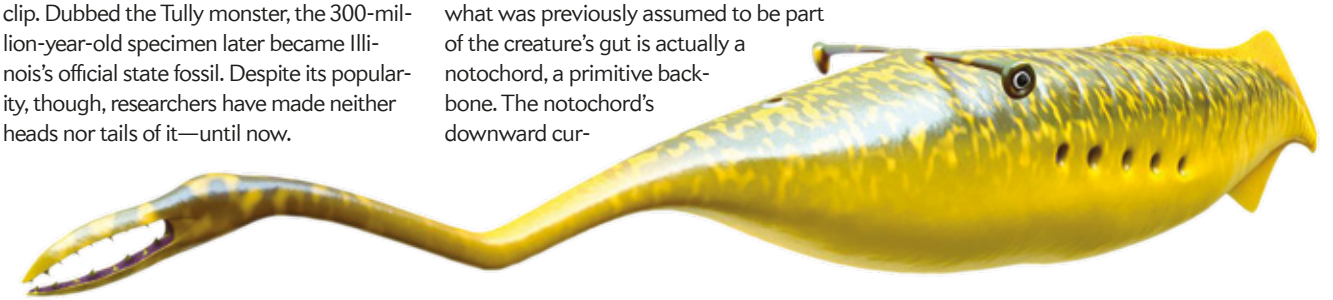
Researchers solve a long-standing phylogenetic mystery

In 1955 amateur fossil hunter Francis Tully discovered an exceedingly odd specimen in Mazon Creek, a collecting hotspot near Chicago. Imprinted on Tully's rock were the remains of a tubular creature with stalk eyeballs and a long mouth apparatus terminating in a feature that resembled an alligator clip. Dubbed the Tully monster, the 300-million-year-old specimen later became Illinois's official state fossil. Despite its popularity, though, researchers have made neither heads nor tails of it—until now.

According to findings published in *Nature,* the organism traces its evolutionary legacy to modern-day lampreys: jawless, bloodsucking fish. Researchers arrived at this conclusion after analyzing 1,200 Tully monster specimens—most about 15 to 20 centimeters long—and realizing that what was previously assumed to be part of the creature's gut is actually a notochord, a primitive backbone. The notochord's downward curvature pointed the team toward lampreys, which also share that physiological quirk.

Victoria McCoy, a paleontologist at the University of Leicester in England who led the study while at Yale University, is not ready to declare the case closed, however. "We still know very little about how the Tully monster lived," she says. "But we can now use modern lampreys and other fishes as analogues and, we hope, start to better understand the mysterious lifestyle of this ancient monster."

—Rachel Nuwer

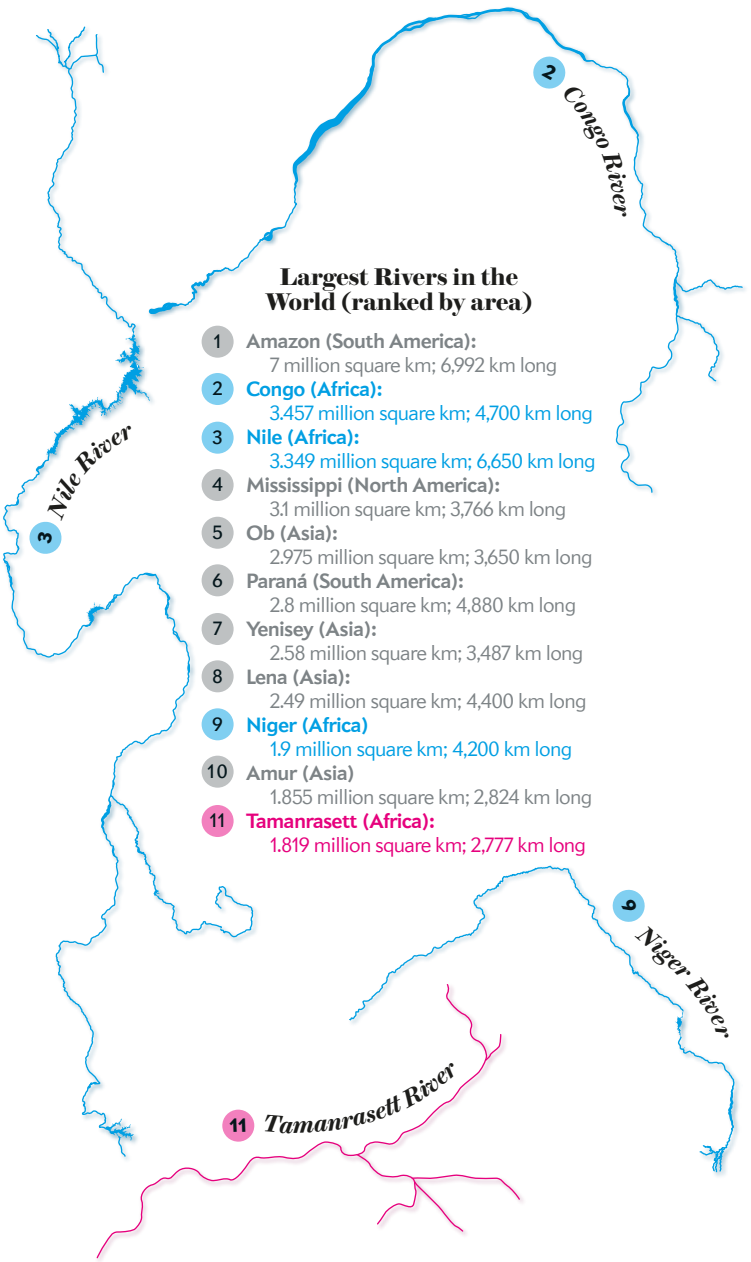


COURTESY OF SEAN McMAHON *Yale University*

GEOLOGY

Deserted Waters

No one ever says of the Sahara that a river runs through it. But somewhere between 11,700 and 5,000 years ago, one did. In full flow, it would rank 11th among the largest rivers on the earth today.* Paleoclimatologist and geochemist Charlotte Skonieczny of the French Research Institute for Exploration of the Sea and her colleagues report the evidence for the ancient channel in a recent issue of *Nature Communications*. The team discovered the so-called Tamanrasett River when examining microwave data collected by a Japanese satellite that had been mapping geologic features in the area. The hidden bedrock valley winds for more than 500 kilometers from the Atlas Mountains in northern Africa to the Atlantic Ocean. —*Shannon Hall*



*"CHARLOTTE SKONIECZNY AND HER COLLEAGUES HAD PLACED THE RIVER AS THE 12TH LARGEST, PER DIFFERENT ESTIMATES OF RIVER AREA SIZES. SOURCES: "AFRICAN HUMID PERIODS TRIGGERED THE REACTIVATION OF A LARGE RIVER SYSTEM IN WESTERN SAHARA," BY C. SKONIECZNY ET AL. IN *NATURE COMMUNICATIONS*, VOL. 6, ARTICLE NO. 8751; NOVEMBER 10, 2015 (*illustration of Tamanrasett*); "GEOMORPHOMETRIC ATTRIBUTES OF THE GLOBAL SYSTEM OF RIVERS AT 30-MINUTE SPATIAL RESOLUTION," BY C. J. VÖRÖSMARTY ET AL. IN *JOURNAL OF HYDROLOGY*, VOL. 237, NOS. 1–2; OCTOBER 25, 2000 (*area and length of Tamanrasett*); *ENCYCLOPEDIA BRITANNICA* www.britannica.com (*area and length of all other rivers*)

Illustration by Amanda Montañez

TECHNOLOGY

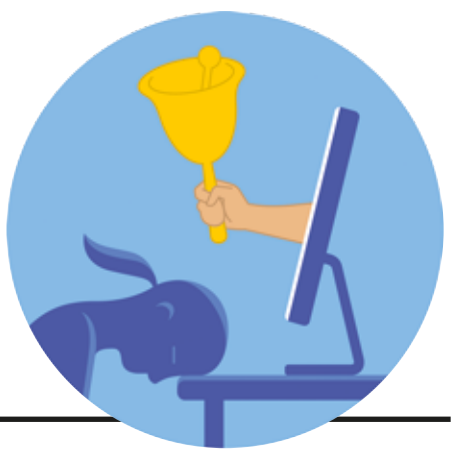
Plugged in or Powered Down?

Computers can tell if you're bored

Boredom manifests itself in more than yawns and glazed eyes. Subtle body cues called non-instrumental movements—squirming, scratching, shifting—also give away a person's mental state. Like teachers and other public speakers, machines can now also pick up on these telltale signs of restlessness. A new study reveals that when computer users tune in to on-screen material, their fidgeting lessens—and algorithms can use that information to discern attentiveness in real time.

To measure engagement, psychobiologist Harry Witchel of Brighton and Sussex Medical School in England and his colleagues outfitted 27 participants with motion-tracking markers that a computer's visual system could follow. The participants then read digital excerpts from a novel by Mark Haddon, *The Curious Incident of the Dog in the Night-Time,* and from the European Banking Authority's regulations. Based on motion in the head, torso and legs, the computer could tell when a person had mentally checked out. In fact, an analysis of the cumulative movements revealed that when people read from the novel, they fidgeted nearly 50 percent less than when reading the banking guidelines.

The system, described in *Frontiers in Psychology,* adds to a growing body of research on "affective-aware technology," says Nadia Berthouze, a computer scientist at University College London. Once the program is perfected, Witchel thinks educators could use it to create digital lessons that recognize when a student's attention is fading and respond with strategies to reengage him or her. The system could also help researchers build robots that are more emotionally sensitive companions for humans. —*Rachel Nuwer*



Illustrations by Thomas Fuchs

ENVIRONMENT

A Forest's Second Life

Given a chance to regenerate, a razed rain forest can host almost as much life as a virgin one

Conservationists who work to save rain forests typically focus on pristine stands—the dwindling number of patches where the buzz of chainsaws has yet to echo. But even clear-cut land may warrant protection. Mounting evidence shows that, under the right circumstances, heavily logged tracts can regrow to host nearly as much biodiversity as unspoiled Amazonian wilderness.

A study published in March in *Tropical Conservation Science* offers the latest look at the biological value of so-called secondary forests. An international team of ecologists and volunteers spent a year and a half identifying every bird, amphibian, reptile and medium-to-large mammal they could find on some 800 recovering hectares within Peru's Manu Biosphere Reserve, a UNESCO World Heritage site. Their final count of 570 species amounted to 87 percent of those known to exist in neighboring old-growth, or primary, forests and included many imperiled creatures, such as short-eared dogs and giant armadillos. The team even found what could be new frog species.

The Manu study area represents a "best-case scenario" for secondary forest biodiversity, says Andrew Whitworth of the University of Glasgow in Scotland, who conducted the study in partnership with the Peruvian nonprofit Crees Foundation.

Success is more likely at Manu because a longtime hunting and logging ban is in place, and animals can easily wander in from the extensive old-growth zones nearby.

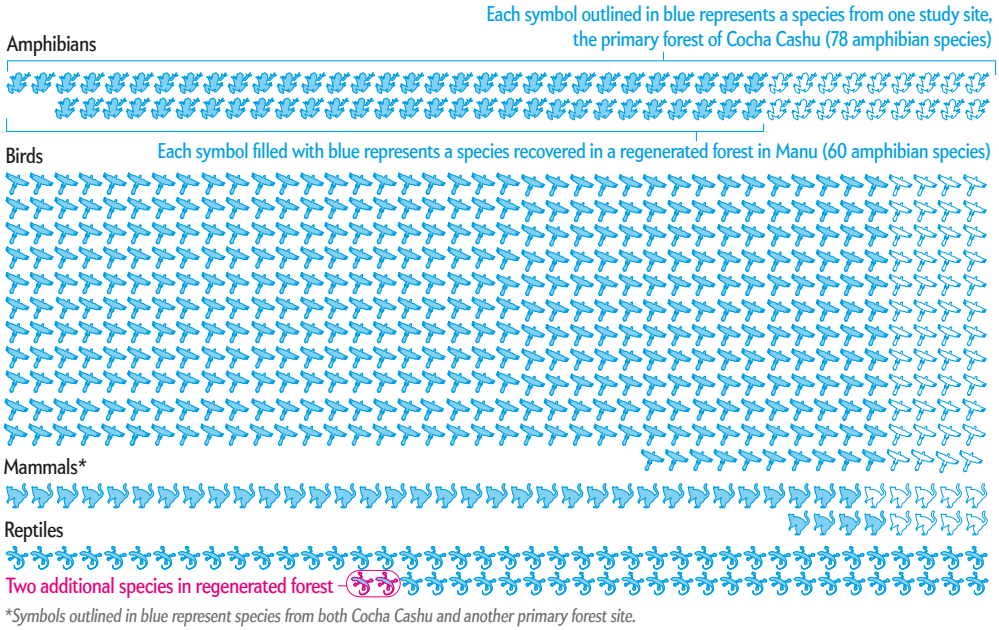
Nevertheless, even lesser-quality sites in the beginning stages of renewal provide myriad environmental benefits, including watershed preservation and wildlife corridors. Secondary-growth forests also reduce carbon dioxide pollution: in February researchers reported that regenerating tropical forests pull about 11 times more carbon from the atmosphere than old-growth swaths (which have already approached the maximum amount of carbon they can sequester).

"We're not saying at any point that this is more important than primary forest," Whitworth says. "But with good protection and time to regenerate, secondary forests could become very valuable again." Robin Chazdon, an ecology professor at the University of Connecticut, and her colleagues agree, quipping in a paper that regenerating forests are "like a good Bordeaux," in that their worth appreciates with each passing year.

For now cleared lands in the tropics usually are converted into palm oil plantations or other agricultural sites without any attempt to assess the potential for reforestation (*western Amazon, at left*). People are beginning to pay attention, however. At a 2014 United Nations climate summit in New York City, several dozen of the world's largest governments, multinational companies, nonprofits and indigenous groups pledged to restore 350 million hectares of degraded forest by 2030.

"We can't stop [at] protecting old growth," says Chazdon, who is advising Brazil on how to revitalize its decimated Atlantic Forest. "That's not going to be enough." —*Jesse Greenspan*

Biodiversity: How Does Regenerated Rain Forest Stack Up?



**Symbols outlined in blue represent species from both Cocha Cashu and another primary forest site.*

COURTESY OF ANDREW WHITWORTH *University of Glasgow (Amazon)*; SOURCE: "HOW MUCH POTENTIAL BIODIVERSITY AND CONSERVATION VALUE CAN A REGENERATING RAINFOREST PROVIDE? A 'BEST-CASE SCENARIO' APPROACH FROM THE PERUVIAN AMAZON," BY ANDREW WHITWORTH ET AL. IN *TROPICAL CONSERVATION SCIENCE*, VOL. 9, NO. 1: MARCH 2016 *(chart)*

Graphic by Amanda Montañez

HEALTH

Heartburn Meds Alter the Gut

Acid blockers reduce the diversity of bacteria in the intestines—and that could lead to trouble

Heartburn has nothing to do with the heart. Instead the burning sensation occurs when acid from the stomach enters the esophagus.

SEBASTIAN KAULITZKI *Getty Images*

In 2014 Americans filled more than 170 million prescriptions for acid blockers known as proton-pump inhibitors (PPIs) to treat gastric conditions, including indigestion, peptic ulcers and acid reflux. These medications are among the top 10 prescribed in the country as a class and are also available over the counter. Surveys suggest that they are widely overused, and in such cases, the drugs may do more harm than good. In fact, two new studies found that PPIs alter gut bacteria in ways that could increase the risk for dangerous intestinal infections, adding to a body of research highlighting the drugs' adverse effects.

To figure out why people who take PPIs are more likely to get an intestinal infection, researchers at the University of Groningen and Maastricht University Medical Center in the Netherlands, as well as the Broad Institute of Harvard University and the Massachusetts Institute of Technology, sequenced the bacterial DNA found in the fecal matter of 1,815 people. Doing so gave them a snapshot of the bacteria found in the subjects' intestines. A comparison of the profiles of subjects taking PPIs with those who were not revealed that, among other things, PPI users had less gut bacterial diversity.

The researchers, who published their results in the journal *Gut,* found that these differences existed even when PPI users did not have gastrointestinal conditions, which suggests that the differences were caused by the drugs rather than simply an artifact of disease. (PPIs are also prescribed to hospital ICU patients to prevent stress ulcers, among other uses.)

Researchers at King's College London, Cornell University and Columbia University obtained similar results from a comparably designed study as well as a small interventional study in which individuals' gut bacteria were analyzed before and after patients took PPIs for four to eight weeks.

PPIs may limit the gut's diversity by reducing its acidity and thus creating an environment that is more or less amenable to certain microbes. And that imbalance could then lead to infection, says Rinse Weersma, a gastroenterologist at the University of Groningen. The drugs may induce "a change in the microbiome that creates a niche where *Salmonella* or *C. difficile* can grow," he explains.

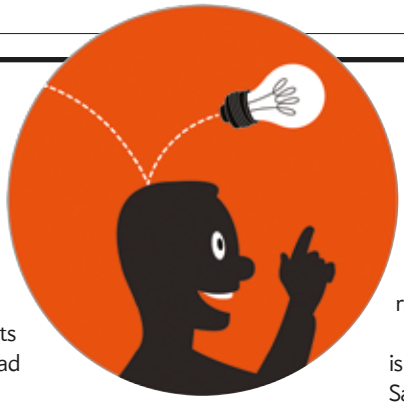
Because a person's microbiome can also influence intestinal absorption of calcium and other vitamins and minerals, these drug-induced changes could explain why people who take PPIs are more likely to fracture certain bones and have nutritional deficiencies. Although no one yet knows how concerned long-term PPI users should be, one thing is for sure: "There should be ongoing dialogue and management between physicians and patients who take these drugs," says Joel Heidelbaugh, a family physician at the University of Michigan who studies PPI overuse. "There are thousands of patients who are on these drugs indefinitely without needing to be."

—Melinda Wenner Moyer

PSYCHOLOGY

Is Eureka Right?

New research shows sudden insights are usually correct



Aha! moments are satisfying in part because they feel so right; all the pieces of a puzzle appear to fall into place with little conscious effort. But can you trust such sudden solutions? Yes, according to new research published in *Thinking & Reasoning*. The results support the conventional wisdom that this type of insight can provide correct answers to challenging problems.

In four experiments, Carola Salvi, a postdoctoral researcher at Northwestern University, John Kounios, a psychologist at Drexel University, and their colleagues presented college students with mind teasers, such as anagrams and rebus puzzles. At the completion of a timed trial, subjects were asked to report if they had arrived at their answer by thinking the problem through step by step (analytical problem solving) or if the solution had sprung to mind (insight).

In all four experiments, aha! solutions were more often correct than those achieved deliberately. For instance, in one experiment, in which 38 participants had to think of a single word that could form a compound phrase with three previously presented words (such as "apple" for the trio "crab," "pine" and "sauce"), aha! solutions were correct 94 percent of the time compared with 78 percent accuracy for analytical solutions.

This outcome may result from the way the brain generates insights. Because such processing occurs largely outside a person's awareness, it is all or nothing—a fully formed answer either comes to mind or it doesn't. This hypothesis is supported by EEG and functional MRI scans, which revealed in previous studies that just before insight takes place, the occipital cortex, which is responsible for visual processing, momentarily shuts down, or "blinks," so that ideas can "bubble into consciousness," Kounios says. As a result, insights are less likely to be incorrect. Analytical thinking, in contrast, happens consciously and is therefore more subject to rushing and lapses in reasoning.

That is not to say that insight is always the best strategy. The Salvi and Kounios experiments involved puzzles with clear right and wrong answers. So the results may not apply to real-world situations, where problems are typically highly complex and may require days—if not months or years—to solve.

In fact, difficult questions often necessitate several different strategies to arrive at a solution, says Janet Metcalfe, head of the Metacognition and Memory laboratory at Columbia University, who was not involved in the study. She adds: "There may not be a perfect solution to a problem." —*Roni Jacobson*

ANN JOHANSSON *Corbis (water main break)*; SOURCES: *WATER MAIN BREAK RATES IN THE USA AND CANADA: A COMPREHENSIVE STUDY*, BY STEVEN FOLKMAN, UTAH STATE UNIVERSITY, APRIL 2012 *(miles of pipes)*; *2013 REPORT CARD FOR AMERICA'S INFRASTRUCTURE*, AMERICAN SOCIETY OF CIVIL ENGINEERS, MARCH 2013 *(water main breaks)*; *BURIED NO LONGER: CONFRONTING AMERICA'S WATER INFRASTRUCTURE CHALLENGE*, AMERICAN WATER WORKS ASSOCIATION, 2012 *(replacement costs)*

Cracks, pits and holes in water mains, often caused by corrosive soil, can allow potentially harmful microbes to enter pipes carrying drinking water (*Los Angeles in 2009, at left*).

INFRASTRUCTURE

Mortal Mains

Flint, Mich., was in the midst of its leaded water crisis in February when its residents suffered yet another hit to their water supply. A cracked pipe that delivered potable water to the town meant that for three days they had to boil their tap water to protect against bacterial contamination. Such water main breaks nowadays are hardly unexpected—much of the nation's waterworks requires upgrades and replacement. Solutions include relining pipes or replacing them with corrosion-resistant polyvinyl chloride (PVC). Some communities also have embraced reclamation of household wastewater, along with the capture of storm water on roofs and streets. These approaches can reduce total volume and pressure spikes that overstrain pipes while lowering the energy required to pump and treat all that water. —*Robin Lloyd*

BY THE NUMBERS

1,180,000
Miles of water main pipes in the U.S.

240,000
Total number of water main breaks that occur annually in the U.S.

$17 billion
Estimated increase over the next 30 years in annual U.S. costs required to replace aging water mains

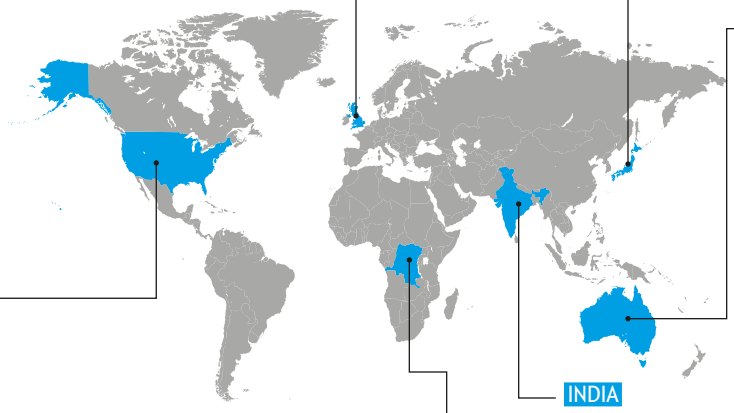
IN THE NEWS

Quick Hits

U.K.
A self-propelling underwater drone began patrolling the area around the Pitcairn Islands, the world's largest continuous marine reserve. The autonomous vehicle takes photographs of illegal fishing vessels and reports the boats' locations to a monitoring team in Oxfordshire, which can alert the proper authorities.

JAPAN
Electronics firm Kyocera has kicked off construction on the most massive floating solar farm planned to date. The 13.7-megawatt power plant will sit atop a reservoir near Tokyo and is expected to supply power to nearly 5,000 homes when completed in 2018.

U.S.
The American Academy of Pediatrics now recommends that doctors inquire about poverty-related stress during a child's regular checkups. Such stress is a strong risk factor for asthma, obesity and other health problems.



AUSTRALIA
Fairy circles, bare patches of earth arranged in a honeycomb pattern, were found on a continent other than Africa for the first time. Researchers are divided as to whether such circles are caused by termites or plants competing for water.

DEMOCRATIC REPUBLIC OF THE CONGO
The government plans to lift a ban on logging licenses in the Congo Basin rain forest, second only to the Amazon rain forest in size. Conservationists say the ban's removal could unleash a wave of environmental destruction.

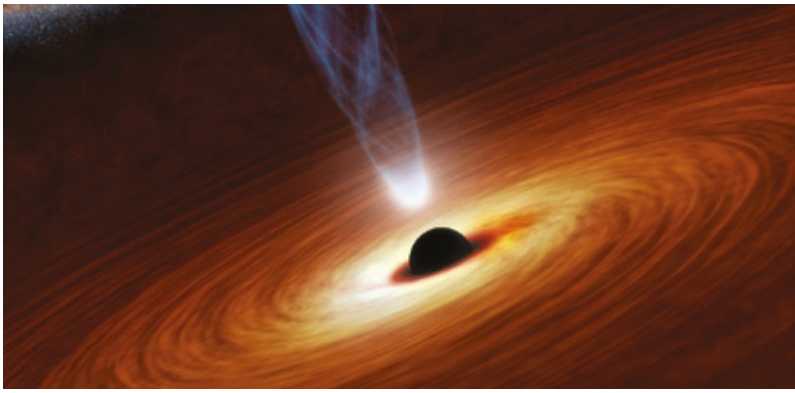
INDIA
A local company released Freedom 251, the cheapest smartphone on the market. Demand for the sub-$4 Android device was so high that the order Web site crashed briefly. It comes with two cameras, Wi-Fi connectivity and a handful of preinstalled apps.

For more details, visit www.ScientificAmerican.com/may2016/advances

ASTRONOMY

Spin Cycle

Astronomers exploit a black hole duo to measure how fast one is spinning



COURTESY OF NASA/JPL/CALTECH (*artist's conception of supermassive black hole*)

Black holes may be massive, but they are also extraordinarily compact. That combination of properties makes them challenging regions to evaluate across vast cosmic distances. To learn more about these objects' physical properties, astronomers must therefore come up with measuring tricks. An international team of astronomers recently invented a new one: in the *Astrophysical Journal Letters,* the members report how to determine a black hole's spin using the interactions of two giant holes bound in mutual orbit.

OJ 287, a binary supermassive black hole system, sits about 3.5 billion light-years from Earth. The duo's primary black hole weighs in at an estimated 18 billion solar masses; the second is a mere 150 million solar masses. Because of this dramatic inequality in size, the smaller hole follows an orbit that punches through a disk of superheated matter swirling around the larger hole. These "outburst" events always occur within a 12-year orbit and are read by astronomers as changes in the system's visible light, which is for the most part produced by the superheated material.

The predictability of this phenomenon and the associated precession, or shifting, of the smaller hole's elliptical orbit helped the astronomers to prepare for two outbursts at OJ 287 in November and December 2015. By precisely measuring the variation in light radiation from the system during those outbursts, the astronomers were able to indirectly measure the spin of the larger black hole. They found that it is spinning at 31 percent of the maximum allowed according to general relativity.

These data, along with earlier observations, clearly indicate that the orbital period is getting shorter with time. That is because the system is losing energy as it emits gravitational waves—ripples in spacetime that steal energy from the holes' orbits, causing them to contract. In other words, in OJ 287 astronomers are witnessing the gradual merging of two supermassive black holes. And as most couples know, outbursts and fast pivots are likely to occur in the run-up to any merger. —*Caleb Scharf*

GLOBAL HEALTH

Drawing for a Remedy

A new blood test for TB could save millions of lives

Tuberculosis is especially a problem in developing countries. In 2014 in Bangladesh about 640,000 people carried the disease.

As much as one third of the global population is currently infected with the bacterium that causes tuberculosis (TB), a disease typically concentrated in the lungs and characterized by weakness, fever, coughing and chest pain. About 9.6 million new infections occurred in 2014, the most recent year for which numbers are available. Roughly 1.5 million people died of TB that same year. The ability to easily, inexpensively and accurately diagnose TB is of utmost importance, but the most commonly used method fails, at least to some extent, on all three counts. A new blood-based technique might considerably rein in this epidemic.

The conventional TB test scans for bacterial DNA in coughed-up mucus, or sputum. But some children struggle to produce a sample on request. The test also can miss TB in people simultaneously infected with HIV because the telltale bacteria may exist in numbers too low to detect or outside the lungs. In addition, the test costs up to $10, a prohibitive fee in many developing countries. As a result of these constraints, a large percentage of TB cases are diagnosed late or not at all, leaving serious infections untreated and more liable to spread.

Two years ago the World Health Organization put out a call for an improved TB diagnostic. In response, Purvesh Khatri, a Stanford University medical professor, and his colleagues combed through the human genome and found three genes that distinguish active TB from other diseases. The team then developed a way to detect these genes in blood.

According to their study, published in the *Lancet Respiratory Medicine*, the test is equally sensitive among patients with and without HIV coinfection and correctly detected TB in 86 percent of pediatric cases. Additional points in favor of a blood assay include that it can be performed at a clinic and yield same-day results, unlike the case for a sputum test. That is especially advantageous in the developing world, where showing up for even a single appointment presents a tremendous burden. "You want to be able to initiate treatment immediately," says Sheela Shinoi, a Yale University professor of medicine focused on AIDS.

The technology has not been used in the diagnosis of new patients and may be difficult to scale up, but in the meantime, Khatri has filed a patent for the test. He thinks it could cost less than half as much as the current one. "If this three-gene signature could be developed into a point-of-care test," Shinoi says, "it would revolutionize TB diagnostics." —*Jessica Wapner*

PROBAL RASHID *Getty Images*

PHYSICS

How to Split Wood

When wind speed snaps trees indiscriminately

DAVID R. FRAZIER *Science Source*

After a particularly strong storm named Klaus hit southwestern France in 2009, researchers made a curious observation about the devastation: nearly all the trees whipped by winds blowing at speeds of 94 miles per hour or more had snapped, regardless of their species, height or diameter, whereas most trees hit by gusts below that threshold were left intact. Was this wind-speed threshold really the arbiter of destruction?

Physicist Christophe Clanet and his colleagues at France's École Polytechnique and ESPCI ParisTech set to find out by fracturing beechwood rods of various lengths and diameters under controlled conditions. To do so, they inserted one end of a given rod into a hole of the same diameter in a block of steel and slowly added force to the other end, causing the rod to bend. They then measured the critical curvature at which the rod cracked and ran those values through mathematical fracturing formulas to determine a corresponding wind speed. What they found matched the real-world scenario of 2009: the calculated wind speed to break the rods—no matter the size—was about 94 mph. The study was recently published in *Physical Review E*.

Why such consistency? The results come down to a combination of physics and evolution. Although mathematics alone would predict that the wind speed required for tree fracture should depend on trunk diameter and tree height, nature does not make trees that are both thin and tall. Instead short trees are thin and tall ones thick. Even more, thicker trees have larger defects, such as knots, where stress concentrates when a tree bends.

Together those characteristics—flaws, length and diameter—cancel one another out, leaving wind speed as the major determiner of a snap. So although a short tree has smaller stress points for cracks, it is thinner and could more easily split. On the other hand, a tall tree has width and stiffness going for it, but larger internal flaws undermine its sturdiness.

The finding is notable for its simplicity: one equation to understand tree mechanics. Several outside experts have concerns about this very quality, however. For example, Lee Frelich, director of the University of Minnesota Center for Forest Ecology, says that modeling trees as branchless cylinders neglects the streamlining of branches in the wind, which in turn changes the relation between force on the trunk and wind speed. In other words, the setup did not reflect the complex interactions of real-life biology, weather and physics. Regardless, Clanet and his colleagues do think the results have utility and plan to study whether wind gusts, as opposed to the steady wind speeds assumed for this project, change the breaking point. —*Tim Palucka*

A Surprising Fix for Sickle Cell

When it comes to finding a genetic cure for this devastating blood disorder, sometimes two wrongs make a right

By Karen Weintraub

Ceniya Harris, age nine, of Boston should be a very sick little girl. Both her parents unknowingly passed her a copy of the genetic mutation for sickle-cell disease, a debilitating and sometimes fatal blood disorder. With a double dose of the mutant gene, Ceniya's body produces a defective kind of hemoglobin—the molecule in red blood cells that takes oxygen from the lungs and releases it into tissues throughout the body. The flawed hemoglobin molecules can deform the normally round blood cells into a crescent, or sickle, shape, leading the cells to clump together and hinder oxygen's passage into tissues. The subsequent physiological havoc, known as a sickle-cell crisis, is incredibly painful and frequently requires emergency treatment to prevent life-threatening strokes and organ failure.

Karen Weintraub is a freelance health and science journalist who writes regularly for the *New York Times*, STAT (www.statnews.com) and *USA Today*, among others.

And yet the bouncy fourth grader, who is fond of sparkly shoes, is able to dance, participate in gymnastics and attend school without a hint of any health troubles. The secret to Ceniya's good fortune lies in a second genetic mutation she inherited—one that limits the aberrant curving of red blood cells. This unusual combination of genetic alterations means that she has yet to suffer a sickle-cell crisis, and her doctors believe that she will probably be protected from the effects of the defective hemoglobin for the rest of her life.

For decades physicians have known that a few children like Ceniya have unusual genetic mutations that counteract the effects of the sickle-cell flaw. Researchers would like to re-create their uncommon physiology in everyone with sickle-cell anemia. Though not technically a cure, the compensatory treatment would spare many of the 300,000 infants around the world who are born every year with sickle cell and who often do not live beyond childhood. It would also make life a lot easier for the more than 70,000 individuals living with the disease in the U.S., who, despite treatment that mitigates some of the most serious effects of the condition, often die in their 40s.

Investigators are now beginning to test such approaches, which depend on the precise alteration, or editing, of certain genes using new techniques in genetic engineering. (As will be addressed shortly, providing the compensatory mechanism should be easier to achieve than fixing the original sickle-cell genetic defect.)

"Gene-editing approaches have the potential to be game changing and really revolutionize the therapy," says Lloyd Klickstein of health care company Novartis, which is among the firms and universities exploring new sickle-cell treatments.

WHAT DOESN'T KILL YOU

FOR A CONDITION that causes life-threatening problems in childhood, sickle cell is surprisingly widespread. After all, if a mutation tends to kill people in childhood, you would expect few of the affected individuals to live long enough to mate and pass the trait to the next generation. The spread could be explained, however, if inheritance of just one copy of the mutation somehow protected people against a different threat to survival. In the late 1940s British scientist J.B.S. Haldane noted that inherited hemoglobin disorders are common in tropical areas where malaria is prevalent. He hypothesized that children born with a single mutated hemoglobin gene (which does not cause major problems) were somehow better able than their peers to fight off malaria and would survive to deliver the gene to their future children.

Subsequent studies supported Haldane's hypothesis, at least in part. Although individuals who carry a single sickle-cell gene actually can acquire malaria, they are less likely to die from the parasitic infection than those who do not have the mutation. How the altered hemoglobin confers this biological protection is still not entirely understood.

In contrast, researchers understand pretty well why two copies of the sickle-cell mutation can prove lethal. A molecule of hemoglobin is made up of four subunits: most commonly two identical proteins called alpha-globins and another pair of proteins known as beta-globins. Each of these subunits contains an iron-

Illustration by Christian Dellavedova

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bearing structure, which, under normal circumstances, can grab on to or release a molecule of oxygen. Thus, each hemoglobin can carry up to four oxygen molecules. Individuals who inherit a single sickle-cell mutation produce one defective and one normal beta-globin; those who inherit sickle-cell genes from both parents produce only defective beta-globins.

When there is not enough oxygen around, these two defective beta-globins attach to each other. The connection is so tight that it causes the rest of the hemoglobin molecule to link up with other similarly affected hemoglobin molecules. The molecules end up forming long strands that distort the red blood cells into the sickle shape responsible for sickle-cell crises. Eventually the malformed molecules poke through the red blood cells in which they are found, like nails inside a plastic bag, says Matthew Heeney of the Dana-Farber/Boston Children's Cancer and Blood Disorders Center. The defective hemoglobin can puncture the cell, reducing its life span from the typical 120 days to fewer than 20 days. The body tries to replace these lost red blood cells, but if it cannot keep up, the resulting anemia causes its tissues to become oxygen-starved. The resulting tissue damage also triggers inflammation that can damage vessels and tissues.

LESSONS FROM NATURE

THE ONLY KNOWN CURE for sickle-cell disease is bone marrow transplantation, which, in effect, provides a new circulatory system. But transplantation is expensive and requires a level of medical expertise that is unavailable in all but the wealthiest countries. Even there it is an option only for people who have an unaffected sibling with the right "tissue match." As if that were not challenging enough, the procedure itself carries about a 5 to 10 percent risk of death, presenting parents with a terrible choice between risking their child's life and relieving his or her pain.

There is another situation, however, in which everyone with sickle-cell disease gets a temporary reprieve from its life-threatening effects: during development in the womb.

A fetus has a distinct kind of hemoglobin that binds very tightly to oxygen, allowing it to compete successfully with its mother's hemoglobin for oxygen in the placenta. Sometime early in an infant's first year after birth, the production of this fetal hemoglobin usually drops off, decreasing the amount of oxygen found in red blood cells. In a child who inherits the sickle-cell flaw from each parent, cells usually start to sickle several months after birth. And the march of symptoms begins.

Intriguingly, no one ever shuts off production of fetal hemoglobin entirely. Most adults—whether they have sickle-cell disease or not—produce about 1 percent fetal hemoglobin. In Ceniya's case, the gene that codes for fetal hemoglobin never received the message that it was no longer needed. Her hemoglobin remains 20 percent fetal, high enough to continue protecting her. The abundant oxygen it supplies to her red blood cells keeps her defective hemoglobin from behaving badly.

MAKING REPAIRS

THE NEW IDEA for therapy would reawaken the fetal hemoglobin gene by disabling yet another gene—the one that essentially tells the fetal hemoglobin gene to stop working. How could giving sickle-cell patients the equivalent of a second genetic mutation be more practical than repairing the mutation that causes their condition in the first place? Because, at the moment, turning genes off is a lot easier than replacing the single mistake in the DNA molecule that causes the disease.

After decades spent studying the genetic underpinnings of sickle cell, Stuart Orkin, another researcher at Dana-Farber/Boston Children's, recently located the precise spot in the DNA of long-lived blood-making cells (stem cells) where a tiny snip would allow for indefinite manufacture of fetal hemoglobin. By inducing this mutation, Orkin and his colleagues have found a way to make two wrongs into a right. Sangamo BioSciences, in collaboration with Biogen, is gearing up to test a gene-editing technology using so-called zinc-finger scissors to make the snip that Orkin recommends. And Novartis's Klickstein says that, among other approaches, his company hopes to do the same with a different technique, known as CRISPR/Cas9.

Other firms are exploring the possibility that protective genes can be safely added after all. One such company, known as bluebird bio (based in Cambridge, Mass.), relies on a virus to deliver an antisickling gene that triggers production of healthy hemoglobin in blood-making stem cells. A year after a French 13-year-old with severe disease received the treatment, he was faring well, with no sickling events and no need for painkillers, says bluebird bio's chief medical officer David Davidson. The group has begun a 20-person study in the U.S. to explore the procedure further.

Both these paths are fraught with dangers, however. Patients need to undergo chemotherapy to wipe out most of the existing stem cells that make the wrong kind of hemoglobin so that there is room for new cells that make the right kind. Even though such treatment would be available to more people than are candidates for bone marrow transplants, it is so toxic in its own right that it can cause cancers to develop years after treatment. And virtually all patients will become infertile as a result. Again, a terrible decision for a parent to make on behalf of a child.

Global Blood Therapeutics in South San Francisco hopes to develop a drug that achieves the same benefits as gene therapy but without the side effects. The goal is to keep mutated hemoglobins from glomming on to one another—something they cannot do if they are holding on to an oxygen molecule. So the company is developing a pill, currently called gbt440, that binds oxygen to the alpha-globins longer than usual. Delaying their release of oxygen even just a bit prevents the beta-globins from getting close enough to connect—especially in the tiny capillaries where sickling occurs most often. Global Blood Therapeutics expects to begin a clinical trial later this year.

But as much as these therapies may make a difference for patients with sickle cell who live in wealthy countries, an entirely different solution is needed to help children elsewhere. "It's the undeveloped world that has the burden [of this disease]," says David G. Nathan, president emeritus of the Dana-Farber Cancer Institute and a leading sickle-cell researcher. For patients in the U.S., living with sickle cell is difficult, painful and terrifying; in the developing world, Nathan says, "it's a disaster." SA

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

In the Movies

Why virtual reality will not replace flat—or 3-D—films anytime soon

By David Pogue

As any tech headline will tell you, 2016 is the Year of Virtual Reality. Every billion-dollar corporation and its brother are rushing into the VR-headset market (Sony, Samsung, Google, Microsoft, HTC). Ever since 2014, when Facebook bought Oculus, a fledgling VR company, for *$2 billion,* journalists and investors have become part of the hype machine.

With this technology, image-filled goggles immerse you in a world. When you turn your head in any direction, your "camera angle" changes—an obvious tool for games. Why just shoot aliens in front of you when you can fire behind you, too?

But according to the tech's advocates, the next step is VR *movies.* Fox, Disney and Lionsgate have already committed huge sums to producing 360-degree movies.

According to the pundits, these immersive films will make traditional movies seem pathetic. "Even the greatest cinematic achievements are inherently oppressive to the viewer," asserts Digital Trends. "The camera tells you what to look at." Ewww. Who'd want that?

And according to Gizmodo, the VR movies at this year's Sundance Film Festival could be the "first nails in the flatties' coffin." ("Flatties" is the derogatory term for traditional movies.)

Okay then. VR movies, where you can look around, will replace flat movies, which are boring and bossy. Right?

Wrong.

In the short term, it's easy to see why. VR equipment is expensive ($600 for Oculus Rift's headset, plus $1,000 for a compatible computer). And the headset is far too heavy to wear for a two-hour movie.

Then there's the technical challenge: VR movies are ridiculously difficult to shoot. Even when you're shooting a flatty, it takes enormous effort to keep lights, crew and vehicles out of the shot. Where will you hide your equipment, lights and crew when the camera films 360 degrees around it?

But those are small potatoes next to the towering problem that no VR filmmaker has yet cracked: audience attention.

Movie directors don't just direct the actors; they also direct your attention, using camera angle, lighting, selective focus, even sound to create a desired effect. A movie is a story that everyone experiences the same way because we all witness the same events.

But in a spherical movie, how will we know where to look? How can a director be sure we'll see the unmasking of the villain off to the right if we've been inspecting the wreckage of the car behind us?

That's exactly the problem you'll encounter in some of the first VR movies. In *Backwater,* a short 360-degree VR movie sponsored by Mini (the carmaker), the hero shoves a factory worker into a pile of crates and then runs off camera. I was still looking at the worker, wondering if he was okay, when a crash off (my) screen told me that I'd just missed the next major action point.

Sometimes graphic signals direct you where to turn your head, like a firefly in *Lost,* a Pixar-like VR animation made by Oculus, or arrows in some of the *New York Times*'s experimental VR scenes. Pretty clumsy.

In most VR "movies," though, there *is* no plot. Somebody has plopped down the panoramic camera somewhere interesting—a marketplace, a ship, a sporting event—and you just look around.

That's immersive and interesting. And some of the games are exceptionally cool. But it's not *storytelling.* They're not *movies.*

History tells us two things about new technologies that are predicted to change life as we know it. First, they settle into niches, but they rarely become household objects. (See also: 3-D printers and the Segway scooter.) And second, new inventions rarely replace older ones as they're predicted to; they just add on.

So, yes, there are already very successful VR scenes, VR games, VR concerts, VR real estate "visits" and VR city tours. Someday there may be hybrid movie-games.

But VR will remain a novelty experience, something like IMAX movies or those hydraulic "4-D" rides at amusement parks, malls and science museums. Until someone figures out a way to tell the same story to every VR viewer, those oppressive, linear flatties will remain our cinema. SA

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Illustration by Chris B. Murray

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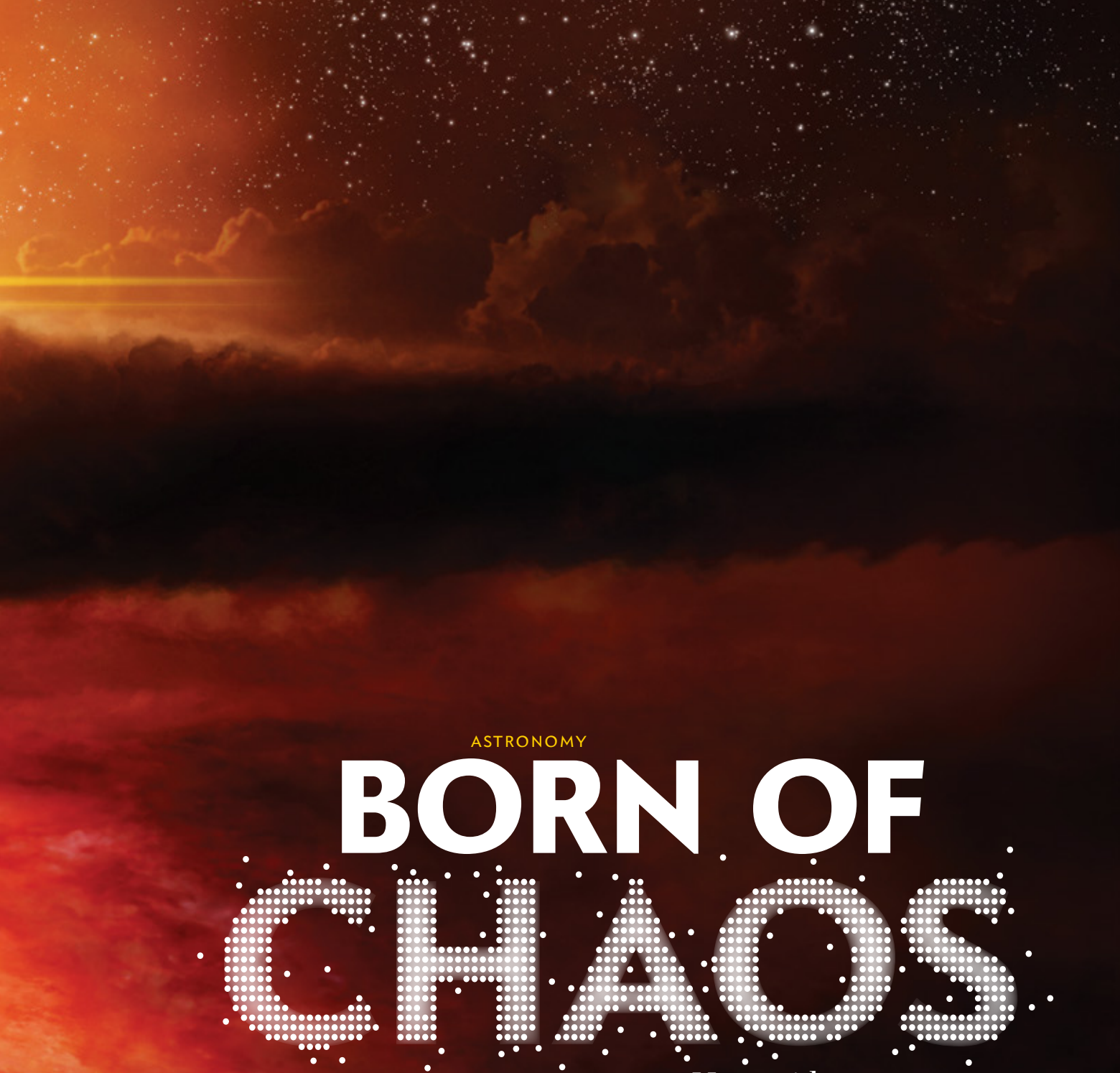

ASTRONOMY

BORN OF CHAOS

New evidence suggests the solar system's early eras were defined by wandering worlds and staggering displays of interplanetary destruction

By Konstantin Batygin, Gregory Laughlin and Alessandro Morbidelli

Konstantin Batygin is an assistant professor of planetary science at the California Institute of Technology. His primary research interests include formation and dynamical evolution of planetary systems. When not professor-ing, he enjoys making noises on the guitar.

Gregory Laughlin is a professor of astronomy and astrophysics at the University of California, Santa Cruz. His research focuses on the detection and characterization of exoplanets. He writes a popular blog on planets (interpreted broadly) at www.oklo.org

Alessandro Morbidelli is a planetary scientist based at the Côte d'Azur Observatory in Nice, France. A member of the French and Belgian academies of science, he has developed leading models for the various phases of the solar system's evolution.

The story of the birth of our solar system has been worn smooth through years of retelling. It starts billions of years ago with a black, slowly spinning cloud of gas and dust. The cloud collapses, forming our sun at its heart. In time, the eight planets, along with lesser worlds such as Pluto, emerge from leftover gas and debris swirling about our star. This system of sun and planets has been whirling through space ever since, its motions as accurate and predictable as clockwork.

In recent years astronomers have glimpsed subtle clues that belie this familiar tale. In comparison with the architectures of thousands of newfound exoplanetary systems, our solar system's most salient features—its inner rocky worlds, its outer gas giants and its lack of planets interior to Mercury—are actually quite anomalous. Turning back the clock in computer simulations, we are learning that these quirks are the products of a troubled youth. The emerging rewrite of the solar system's history includes far more drama and chaos than most anyone had expected.

The new history is a tale of wandering planets evicted from their birthplaces, of lost worlds driven to fiery destruction in the sun eons ago and of lonely giants hurled into the frigid depths of near-interstellar space. By studying these ancient events and the scars they may have left—such as the recently postulated Planet Nine that could be lurking unseen beyond Pluto—astronomers are gaining both a cohesive picture of the solar system's crucial formative epochs and a new appreciation for its cosmic context.

THE CLASSICAL SOLAR SYSTEM

PLANETS ARE A BY-PRODUCT of star formation, which occurs in the hearts of giant molecular clouds 10,000 times the mass of our sun. Dense core regions within a cloud can collapse in on themselves, forming a central glowing protostar encircled by a sprawling, opaque ring of gas and dust called a protoplanetary disk.

For decades theorists have looked to our sun's primordial protoplanetary disk to explain one of the solar system's most distinctive features: its bifurcated brood of rocky and gassy planets. Four terrestrial worlds are confined between Mercury's 88-day and Mars's 687-day orbital periods. In contrast, the known gas-rich giant planets reside on much more distant orbits, have orbital periods ranging from 12 to 165 years and contain more than 150 times the mass of the terrestrial bodies.

Both varieties of planet are thought to come from a universal formation process, in which motes of dust swirling within the gassy, turbulent disk collided and stuck together to make kilometer-scale objects called planetesimals, akin to the dust balls formed by air currents and electrostatic forces on an unswept kitchen floor. The largest planetesimals also had the greatest gravitational pull and rapidly grew even larger as they swept up lingering debris in their orbits. Within perhaps a million years of its collapse from a cloud, our solar system's protoplanetary disk—just like any other

IN BRIEF

A wealth of new evidence from computer simulations as well as observations of planets throughout the galaxy is revealing new details of our solar system's dynamic and violent history.

The solar system's configuration of small inner rocky worlds and large outer giants is anomalous in comparison with most other planetary systems, which have different architectures.

The best explanation for the solar system's oddity is that the giant planets went through an extended sequence of orbital migrations and dynamical instabilities billions of years ago.

These tumultuous events could have sent entire planets tumbling into the sun or out to interstellar space and may have been crucial for the origins and earliest evolution of life on Earth.

in the universe—teemed with moon-sized planetary embryos.

The largest embryo resided past the present-day asteroid belt, far enough from the newborn sun's light and heat for ice to exist in the protoplanetary disk. Beyond this "ice line," embryos could feast on plentiful planet-building ices to grow to enormous sizes. In a familiar example of the rich getting richer, the largest embryo was also the fastest-growing, as its greater gravitational field rapidly carved most of the available ice, gas and dust from the surrounding disk. Within only a million years or so, the greedy embryo had grown to become the planet Jupiter. This, theorists believed, was the crucial moment where our solar system's bifurcated architecture emerged. Outpaced by Jupiter, our sun's other giant planets formed into smaller bodies because they grew slower, ramping up their gas-attracting gravitational pulls only after Jupiter had diminished the amount available. The inner worlds were far smaller still because they were born inward of the ice line where the disk was relatively devoid of gas and ice.

Save for a few bothersome details, such as the exceedingly small masses of Mars and Mercury, this "Jupiter-first" narrative appeared satisfactory as an explanation for our solar system's architecture. The expectations were clear for systems orbiting other stars: giant planets would eventually be found in long-period orbits beyond the ice line, whereas rocky worlds would abound with orbital periods on the order of a few years or less. These preconceptions, however, proved to be deceptive.

Based on thousands of exoplanets, astronomers are now arriving at the uneasy conclusion that solar system look-alikes are relatively rare.

THE EXOPLANET REVOLUTION

WHEN ASTRONOMERS BEGAN discovering exoplanets more than 20 years ago, they also put the theory of the solar system's formation to the test on a galactic scale. Many of the first known exoplanets were "hot Jupiters," gas giant planets whizzing around their stars with orbital periods of just a few days. The existence of giant planets in such scorching proximity to a stellar surface, where ice is utterly absent, is entirely contradictory to the classical picture of planet formation. To reconcile this discrepancy, theorists concluded that these planets formed farther out before somehow migrating inward.

Furthermore, based on thousands of exoplanets found by surveys such as NASA's Kepler mission, astronomers are now arriving at the uneasy conclusion that solar system look-alikes are relatively rare. The average planetary system contains one or more super Earths (planets a few times bigger than Earth), with orbital periods shorter than about 100 days. Conversely, giant planets—Jupiter and Saturn analogues—are found around only about 10 percent of stars, with even lower fractions occupying sedate, nearly circular orbits.

With their expectations in tatters, theorists realized that the "few bothersome details" of the classical theory of our solar system's formation demanded better explanations. Why is the solar system's inner region so depleted in mass compared with its exoplanetary counterparts, with relatively runty rocky worlds instead of super Earths and no worlds at all inside Mercury's 88-day orbit? And why are the orbits of the sun's giant planets so calm and spread out?

As it stands, answers to these questions can be drawn from the failure of classical planet formation theory to account for the fluid mutability of protoplanetary disks. It turns out that a newborn planet, like a life raft in an ocean, can drift far from its point of origin. Once a planet grows large enough, its gravitational influence propagates through the surrounding disk, raising spiraling waves that themselves exert gravitational forces of their own, generating powerful positive and negative feedbacks among planets and disks. Correspondingly, time-irreversible exchanges of momentum and energy can occur, allowing young planets to set off on epic journeys through their natal disks.

When the process of planetary migration is accounted for, ice lines within disks no longer play a singular role in shaping the architectures of planetary systems. For instance, giant planets born beyond an ice line can become hot Jupiters by drifting inward, traveling along with gas and dust spiraling down toward a star. The trouble is that this process works almost too well and seems to be a ubiquitous property of all protoplanetary disks. So how could one account for Jupiter's and Saturn's distant orbits from the sun?

THE GRAND TACK

THE FIRST HINT of a compelling explanation arrived in 2001 from computer simulations by Frederic Masset and Mark Snellgrove, both then at Queen Mary University of London. Masset and Snellgrove modeled the simultaneous evolution of Saturn's and Jupiter's orbits within the sun's protoplanetary disk. Because of Saturn's lower mass, its inward migration rate is more rapid than Jupiter's, and as their migrations proceed, the two planets draw closer. Eventually the orbits reach a specific configuration known as a mean motion resonance, in which Jupiter makes three revolutions around the sun for every two orbital periods of Saturn.

Two planets linked by a mean motion resonance can exchange momentum and energy back and forth between each other like an interplanetary game of hot potato. Because of the coherent nature of resonant perturbations, both worlds essentially exert an amplified common gravitational influence on each other and their surroundings. In the case of Jupiter and Saturn, this seesawing allowed the planets to collectively throw their weight against the protoplanetary disk, carving a great gap within it, with Jupiter on the inner side and Saturn on the outer side. At this point, because of its larger mass, Jupiter exerted a greater gravitational pull on the inner disk than Saturn did on the outer disk. Counterintuitively, this caused both planets to reverse course and begin drifting away from the sun. This inward-then-outward swoop is often referred to as the Grand

Tack, after its similarity to the motions of a sailboat tacking to change directions against a steady wind.

In 2011, a decade after the Grand Tack's initial conception, computer simulations by Kevin J. Walsh, then at the Côte d'Azur Observatory in Nice, France, and his colleagues showed that it can neatly explain not only the dynamical history of Jupiter and Saturn but also the distribution of rocky and icy asteroids, as well as the diminutive mass of Mars. As Jupiter migrated inward, its gravitational influence captured and shepherded planetesimals in its path through the disk, scooping them up and pushing them ahead of it like a snowplow. If we suppose that Jupiter migrated as close to the sun as the present orbit of Mars before turning back around, it could have ferried icy building blocks totaling approximately 10 times the mass of Earth into the terrestrial region of the solar system, seeding it with water and other volatiles. This process would have also created a clear outer edge to the inner nebula's planet-forming material, truncating the growth of a nearby planetary embryo that went on to become the world we know as Mars.

JUPITER'S GRAND ATTACK

AS COMPELLING AS the Grand Tack scenario appeared to be in 2011, its relation to the other great remaining mystery of our solar system, namely, the utter lack of planets inward of Mercury, remained elusive. In comparison with other systems packed with close-in super Earths, ours seems almost hollowed out. Why? It seems strange that our solar system did not participate in the dominant mode of planet formation we see elsewhere in the cosmos. In 2015 two of us (Batygin and Laughlin) considered what the consequences of the Grand Tack would be on a hypothetical retinue of close-in super Earths around the sun. Our startling conclusion is that they would not have survived the Grand Tack. Remarkably, Jupiter's inward-outward migration can account for many properties of the planets that we do have, as well as for the ones we do not.

As Jupiter plunged into the inner solar system, its snowplow-like influence on the planetesimals in its way should have stirred their neat, circular orbits into a disordered swarm of spiraling, intersecting trajectories. Some of the planetesimals would collide with great force, shattering into fragments that inevitably generated further fragmenting collisions. Jupiter's inward migration thus most likely triggered a collisional cascade that eroded the planetesimal population, essentially grinding them back down to boulders, pebbles and sand.

Assaulted by collisional grinding and aerodynamic drag within the gassy confines of the inner protoplanetary disk, the fragmenting, eroding planetesimals bled off their energy and rapidly spiraled down closer to the sun in an avalanche of orbital decay. As they fell, they would have been easily captured in further resonances, ominously stacking up on the horizons of any primordial close-in super Earths.

This would have been very bad news for those planets, which would suddenly be hectored by parasitic swarms of debris feeding off their orbital energy. Continuously hindered by gas streaming through the disk, the swarms should have spiraled straight into the sun. But thanks to their resonances with the super Earths, the swarms were held in place, siphoning off orbital energy from the planets and bleeding it off as heat from aerodynamic drag. The net effect was that the swarms of eroded planetesimals pushed the planets into death spirals with ruthless efficiency, progressively lowering each world's orbit so that one by one they all fell into the sun. Our simulations suggest none of these hypothetical planets would have survived longer than hundreds of thousands of years after the collisional cascade began.

Thus, the Grand Tack of Jupiter and Saturn may have unleashed a bona fide Grand Attack on a population of primordial close-in planets in our solar system. As these erstwhile super Earths decayed onto the sun, they would have left behind a desolate unpopulated cavity in the solar nebula, extending out to an orbital period of perhaps 100 days. As a result, Jupiter's glancing swoop through the early solar system produced a relatively narrow ring of rocky debris, from which the terrestrial planets neatly coalesced hundreds of millions of years later. The concatenation of chance events required for this delicate choreography suggests that small, Earth-like rocky planets—and perhaps life itself—could be rare throughout the cosmos.

The Grand Tack of Jupiter and Saturn may have unleashed a bona fide Grand Attack on a population of primordial super Earths in our solar system.

A NICE MODEL

BY THE TIME JUPITER and Saturn plowed back outward from their foray into the inner system, the sun's surrounding disk of gas and dust was on the wane. The resonant pair of Jupiter and Saturn eventually encountered newly formed Uranus and Neptune, along with, perhaps, an additional, similarly sized body. Aided by the gravitational effects of the dissipating gas, the dynamic duo locked these smaller giants into resonances as well. Thus, just as most of the disk's gas disappeared, the solar system's inner architecture probably consisted of a ring of rocky debris in the neighborhood of Earth's current orbit. In its outer reaches, a compact and resonant chain of at least four giant planets resided in nearly circular orbits between Jupiter's current orbit and roughly the halfway point to the present orbit of Neptune. Beyond the outermost giant planet's orbit, the frozen, icy planetesimals of the outer disk stretched to the far edge of the solar system. Over hundreds of millions of years the terrestrial planets formed, and the once wild outer worlds settled down into what could have been enduring stability. But as chance would have it, this was not the final phase of our solar system's evolution.

The Grand Tack and coeval Grand Attack had arranged one last gasp of interplanetary violence in the solar system's history, a finishing touch that brings our sun's retinue of worlds close to the configurations we witness today. The last gasp is known as

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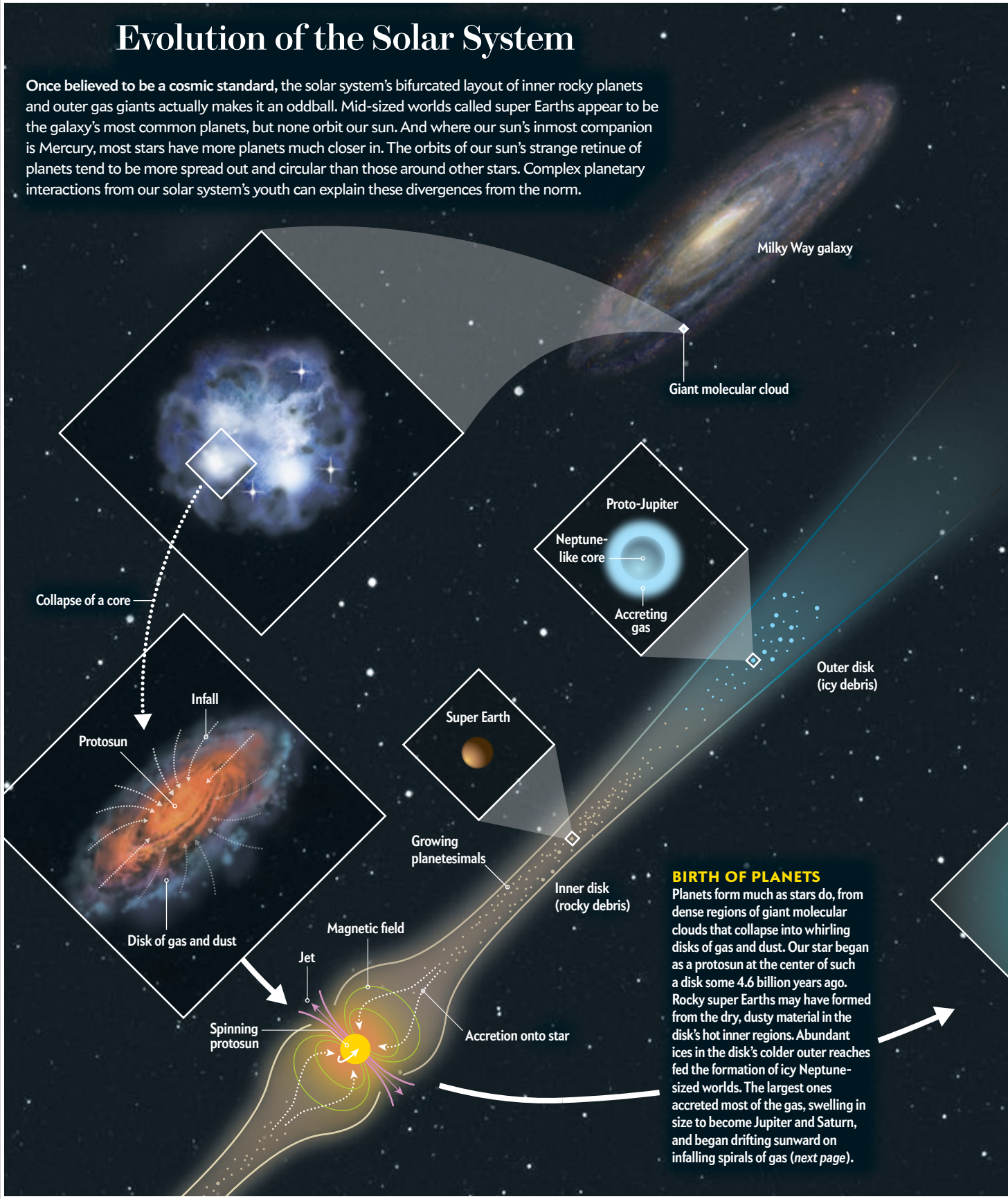
Evolution of the Solar System

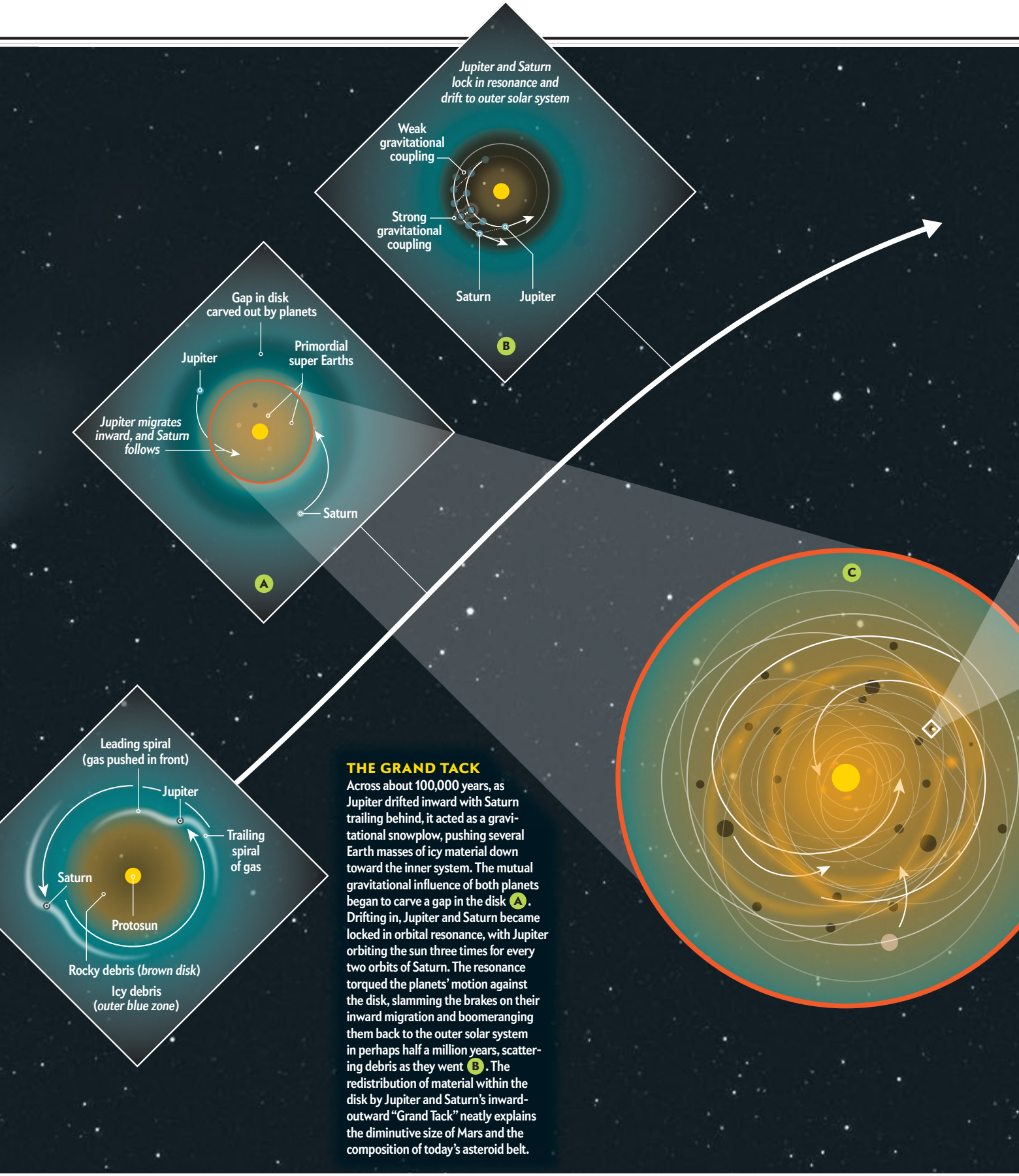
Once believed to be a cosmic standard, the solar system's bifurcated layout of inner rocky planets and outer gas giants actually makes it an oddball. Mid-sized worlds called super Earths appear to be the galaxy's most common planets, but none orbit our sun. And where our sun's inmost companion is Mercury, most stars have more planets much closer in. The orbits of our sun's strange retinue of planets tend to be more spread out and circular than those around other stars. Complex planetary interactions from our solar system's youth can explain these divergences from the norm.



BIRTH OF PLANETS

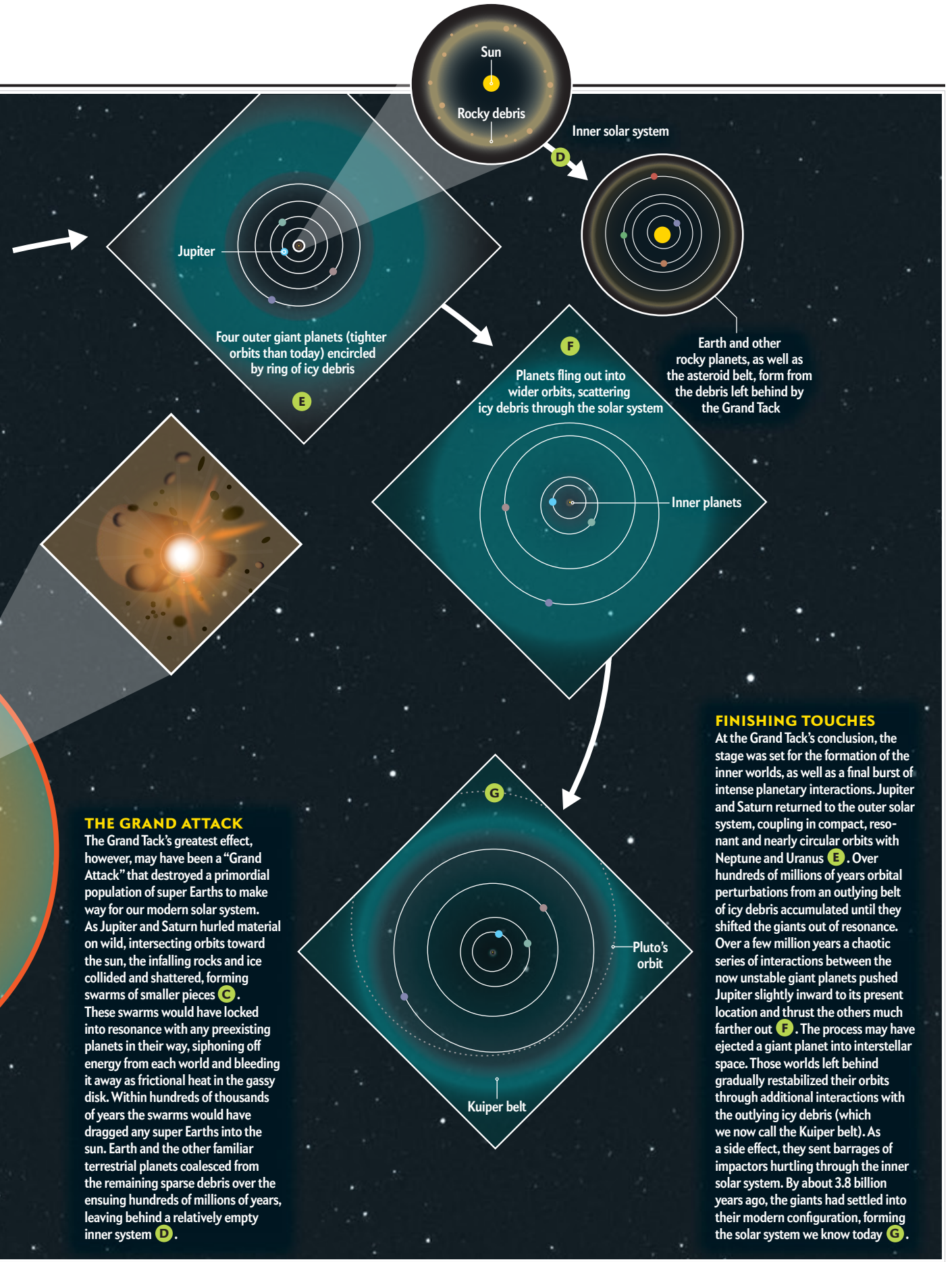
Planets form much as stars do, from dense regions of giant molecular clouds that collapse into whirling disks of gas and dust. Our star began as a protosun at the center of such a disk some 4.6 billion years ago. Rocky super Earths may have formed from the dry, dusty material in the disk's hot inner regions. Abundant ices in the disk's colder outer reaches fed the formation of icy Neptune-sized worlds. The largest ones accreted most of the gas, swelling in size to become Jupiter and Saturn, and began drifting sunward on infalling spirals of gas (*next page*).

Illustration by Jen Christiansen



THE GRAND TACK

Across about 100,000 years, as Jupiter drifted inward with Saturn trailing behind, it acted as a gravitational snowplow, pushing several Earth masses of icy material down toward the inner system. The mutual gravitational influence of both planets began to carve a gap in the disk (A). Drifting in, Jupiter and Saturn became locked in orbital resonance, with Jupiter orbiting the sun three times for every two orbits of Saturn. The resonance torqued the planets' motion against the disk, slamming the brakes on their inward migration and boomeranging them back to the outer solar system in perhaps half a million years, scattering debris as they went (B). The redistribution of material within the disk by Jupiter and Saturn's inward-outward "Grand Tack" neatly explains the diminutive size of Mars and the composition of today's asteroid belt.



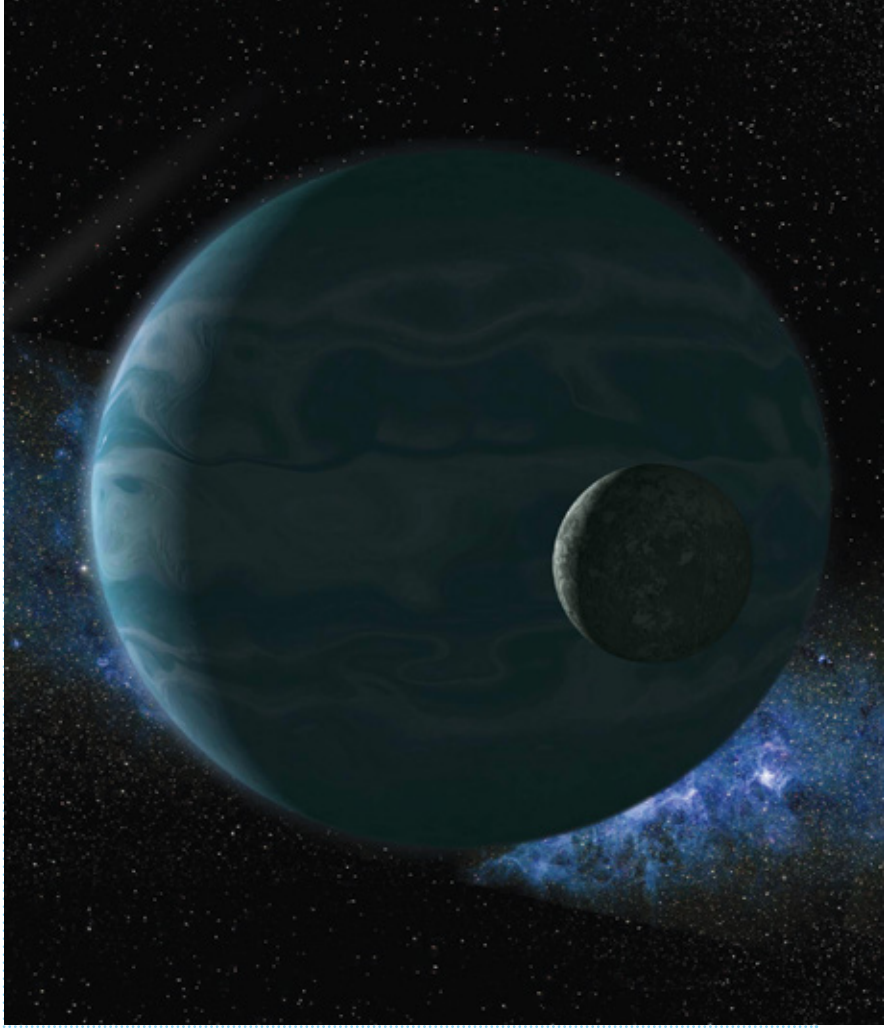
THE GRAND ATTACK

The Grand Tack's greatest effect, however, may have been a "Grand Attack" that destroyed a primordial population of super Earths to make way for our modern solar system. As Jupiter and Saturn hurled material on wild, intersecting orbits toward the sun, the infalling rocks and ice collided and shattered, forming swarms of smaller pieces C. These swarms would have locked into resonance with any preexisting planets in their way, siphoning off energy from each world and bleeding it away as frictional heat in the gassy disk. Within hundreds of thousands of years the swarms would have dragged any super Earths into the sun. Earth and the other familiar terrestrial planets coalesced from the remaining sparse debris over the ensuing hundreds of millions of years, leaving behind a relatively empty inner system D.

FINISHING TOUCHES

At the Grand Tack's conclusion, the stage was set for the formation of the inner worlds, as well as a final burst of intense planetary interactions. Jupiter and Saturn returned to the outer solar system, coupling in compact, resonant and nearly circular orbits with Neptune and Uranus E. Over hundreds of millions of years orbital perturbations from an outlying belt of icy debris accumulated until they shifted the giants out of resonance. Over a few million years a chaotic series of interactions between the now unstable giant planets pushed Jupiter slightly inward to its present location and thrust the others much farther out F. The process may have ejected a giant planet into interstellar space. Those worlds left behind gradually restabilized their orbits through additional interactions with the outlying icy debris (which we now call the Kuiper belt). As a side effect, they sent barrages of impactors hurtling through the inner solar system. By about 3.8 billion years ago, the giants had settled into their modern configuration, forming the solar system we know today G.

Planet Nine from Outer Space



Does the newly postulated "Planet Nine" fit in with the latest thinking about the origin of the solar system?

By Michael D. Lemonick

The idea that the solar system was violently reshuffled in the distant past may explain the existence of the Kuiper belt and the Oort cloud of icy bodies that surround us, the ancient bombardment of the inner planets by asteroids billions of years ago, and the seeming absence of so-called super Earths, which other solar systems have in abundance. But now planetary scientists have something new to wrestle with: a putative planet, with perhaps 10 times the mass of Earth, orbiting in the dark regions beyond Pluto. If it exists, the gravity of the world provisionally known as Planet Nine might be the reason why a handful of known Kuiper belt objects are following suspiciously similar paths around the sun.

But it might also be yet another clue to the wrenching changes the solar system went through early in its history. With an estimated minimum distance from the sun of 30.5 billion kilometers—five times farther than Pluto's average distance—it is unlikely that this massive world could have formed where it is now. There simply would not have been enough material to build it with. "If it's there," says Harold F. Levison, a planetary formation theorist at the Southwest Research Institute, "it most likely formed in the region of between about five and 20 [Earth-sun distances] and was scattered outward by [a gravitational interaction with] Jupiter or Saturn."

This point is uncontroversial. Jupiter, in particular, is so massive, says Scott Tremaine of the Institute for Advanced Study in Princeton, N.J., that "it doesn't care whether it's scattering a comet or a 10-Earth-mass planet." Once it got the boot, however, a planet would tend to keep going, eventually escaping into interstellar space. The odds that it would instead settle into orbit around the sun are extremely low. Statistically, Levison says, you would need to start with 50 or 100 to end up with one—which he considers unlikely.

If astronomers actually spot Planet Nine through a telescope, the question of likeliness becomes moot, of course. Still, the question of how something so improbable happened is something theorists will have to wrestle with. "My guess," Tremaine says, "is that the scattering process is more efficient than the standard model would lead us to believe"—that is, a higher percentage of outward-flung objects manages to stay within the solar system than everyone thinks.

One way this might happen, according to Ben Bromley of the University of Utah, is if the scattering of a super Earth took place very early in the life of the solar system, before the gas in the protoplanetary disk that formed into planets dissipated. If the scattering of a super Earth took place within that period, Bromley notes, "The planet could interact with the gas and settle out in the boondocks."

Or perhaps, says Nathan Kaib, a theorist at the Carnegie Institution for Science in Washington, D.C., Planet Nine, should it exist, did not come from our solar system. The sun formed not alone but in a cluster of perhaps thousands of stars, each (most likely) with its own planetary system. At least some of those systems would have undergone their own violent reshuffling, ejecting objects just as the sun presumably did. "These," Kaib says, "can be captured by our own sun."

The best explanation will depend on what Planet Nine's orbit turns out to be; its proponents have calculated only a range of possibilities. If it does exist, scientists should be able to figure out how it got to where it is. The answer to whether Planet Nine fits with current thinking about the early solar system, Tremaine says, "is a definite 'maybe.'"

Michael D. Lemonick is opinion editor at *Scientific American*.

SCIENTIFIC AMERICAN ONLINE Read more about Jupiter's Grand Attack at ScientificAmerican.com/may2016/grand-attack

Illustration by Ron Miller

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the Late Heavy Bombardment, a time between 4.1 billion and 3.8 billion years ago when the solar system temporarily transformed into a shooting gallery filled with barrages of impacting planetesimals. We see its scars today in huge craters pockmarking Earth's moon.

Working with several colleagues at the Côte d'Azur Observatory in Nice in 2005, one of us (Morbidelli) produced the so-called Nice model to explain how interactions between the giant planets could produce the Late Heavy Bombardment. Where the Grand Tack ends, the Nice model begins.

The closely packed giant planets were still resonant with one another and still felt the slight gravitational tugs of the outlying icy planetesimals. They were in fact poised on the knife-edge of instability. Accumulating over millions of orbits across hundreds of millions of years, each individually insignificant tug from the outer planetesimals subtly shifted the motions of the giants, slowly chipping away at the delicate balance of resonances that bound them together. The tipping point came when one of the giants fell out of resonance with another, unraveling the balance and kicking off a chaotic series of planet-planet perturbations that jolted Jupiter slightly inward while scattering the other giants outward. In a cosmically brief span of a few million years the outer solar system experienced a jarring transition from a closely packed, nearly circular state to an expansive, disordered configuration characterized by planets with wide, eccentric orbits. The interactions among the giant planets were so violent that one or more may have been scattered away, ejected beyond the boundary of interstellar space.

Had dynamical evolution stopped here, the outer solar system's architecture would have fit nicely into the trends we witness in giant exoplanets, many of which occupy eccentric orbits around their stars. Thankfully, however, the disk of icy planetesimals that ignited the disorder also helped to eradicate it through subsequent interactions with the eccentric orbits of the giant planets. One by one, most close-passing planetesimals were flung out by Jupiter and the other giant planets, gradually drawing orbital energy from the planets and circularizing their orbits once again. Whereas most planetesimals were ejected beyond the sun's gravitational reach, a small fraction remained in bound orbits, forming a disk of icy debris we now call the Kuiper belt.

A NINTH PLANET, A FINAL THEORY

PATIENT OBSERVATIONAL WORK with the largest telescopes is gradually revealing the full expanse of the Kuiper belt, slowly unveiling unexpected structure. In particular, astronomers have spied a peculiar pattern among the most far-flung objects of the Kuiper belt that exist at the outer limits of detectability. Despite having a range of distances from the sun, the orbits of these objects are highly clustered, as if they are all subject to a common, very large perturbation. Computer simulations performed by Batygin and Michael E. Brown of the California Institute of Technology have shown that this state of affairs is naturally produced by an as yet unobserved ninth planet, having a mass roughly 10 times that of Earth and in a highly eccentric orbit around the sun of approximately 20,000 years. Such a planet is unlikely to have formed so far out, but it can be quite readily understood as an exile ejected from closer in during the solar system's infancy [*see box on opposite page*].

If confirmed, the existence of a ninth planet around the sun would dramatically tighten the constraints on our understanding of our weird, hollowed-out solar system, placing new limits on the theories we could weave to explain all its anomalies. Even now astronomers are marshaling some of Earth's largest telescopes to ardently seek this putative world. Its discovery could mark the penultimate chapter in the long, complex tale of how we discovered our place in the universe, surmounted only by the yet to be written conclusion, when we at last find living worlds orbiting other stars.

Like strands of DNA, that on sequencing, reveal the story of humankind's ancient migrations across the surface of our small planet, astronomical clues have permitted our computer simulations to reconstruct the planets' majestic wanderlust during the solar system's multibillion-year lifetime. From its birth in roiling molecular clouds, to the formation of its first planets, to the world-shattering growing pains of the Grand (At)Tack and the Nice model, to the emergence of life and sentience around at least one sun in the vast Milky Way, the complete biography of our solar system will be one of the most significant accomplishments in modern science—and undoubtedly one of the greatest stories that ever can be told. SA

The interactions among the giant planets were so violent that one or more may have been ejected beyond the boundary of interstellar space.

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scientificamerican.com/magazine/sa

THE MADDENING SENSATION OF

itch

How it arises is only now becoming clear

By Stephani Sutherland

IN BRIEF

Acute itch plays a role in warning us to avoid insects and poisonous plants. Chronic forms of the sensation, however, may often appear mysteriously, without any apparent cause.

Familiar causes of itch, such as an insect bite or a similar insult to the skin, provoke immune cells to produce histamine, a chemical that can spur a paroxysm of scratching.

Major gains in recent years have revealed more about molecular processes that underlie itch, raising the possibility of developing new treatments for both acute and chronic cases.

Advances stem from the identification of a range of nonhistamine pruritogens (itch-inducing substances) and a better definition of the relation between itch and pain.

Illustration by Brian Stauffer

Stephani Sutherland is a neuroscientist and science writer based in southern California.

it

STARTED AS A TINY RASH ON NICOLE BURWELL'S CALF, APPEARING AT THE end of a trip to Las Vegas with her fiancé late in the summer of 2010. "I had this super, super itchy spot on my leg, but not like a mosquito bite. Not raised, not a bump. I couldn't get it to stop itching," she says. So Burwell, then 40, took the over-the-counter antihistamine Benadryl and slept the entire four-hour car ride home to Claremont, Calif. "It knocked me out," she says, but when she woke, the itch was still there. Over the next week the rash grew and with it the itch, so Burwell saw her doctor. "By then it had spread to both legs." For the next three years Burwell would battle an angry, weeping red rash that moved around her body, covering her arms and legs, hands, torso and back. But as ugly as the rash was, it did not bother Burwell nearly as much as the itch.

"I was consumed by it. I couldn't sit still; I couldn't pay attention to anything. It made me feel crazy," Burwell says. She developed a daily routine. After a day at work as a kitchen designer, she would return to her air-conditioned apartment, undress, take two Benadryls and mix herself a bourbon and Diet 7Up. "I would come home and cry because it itched so bad." Burwell kept ice packs on hand to help quiet the itch enough to fall asleep.

Burwell is not alone: an estimated one in five adults will experience itch lasting more than six weeks in their lifetime. Chronic itch can stem from any of a long list of maladies: skin diseases such as eczema or psoriasis, kidney failure, nerve damage caused by herpes or diabetes, mites burrowing in the skin, an allergic reaction to medication, even pregnancy. At its worst, itch can cause serious disability and drive people to suicide—a thought that certainly crossed Burwell's mind. Yet doctors for the most part still dismiss it as a mere nuisance. "If you don't have itch, it's not a problem, and it can be hard to relate to. We are just starting to understand that itch is really a huge problem for so many people," says Ethan Lerner, a dermatologist and itch researcher at Massachusetts General Hospital.

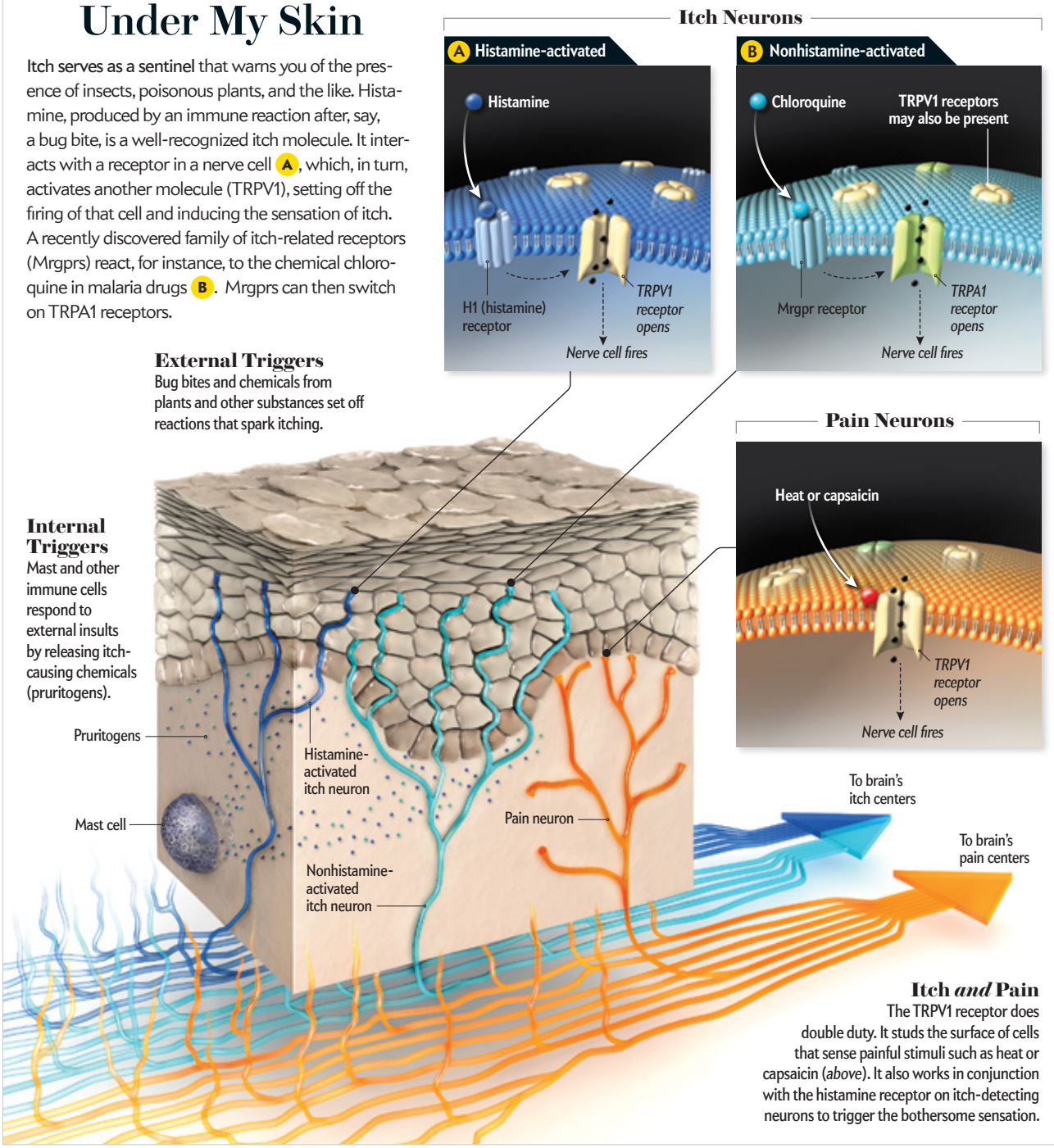
"Not all itch is equal," says Gil Yosipovitch, a researcher at Temple University. When acute, it serves an important purpose: as a sentry that protects us from the hazards of creepy-crawlies and poisonous plants [*see box on opposite page*]. But until recently, researchers had little grasp of how the vexing sensation arises from irritants in the skin. Chronic forms of itch such as Burwell's present a bigger mystery. But lately scientists have made major gains in understanding the malady, bringing them closer to developing treatments for chronic and acute itch. In particular, they have discovered new molecular receptors for pruritogens—itch-inducing substances—on nerve endings in the skin; these receptors detect the presence of the pruritogens. The new findings also reveal that part of the nervous system is specifically dedicated to itch, and it extends from the outer layer of the skin all the way to higher brain centers.

CLASSIC ITCH

THE BEST-KNOWN FORM of itch erupts when the body reacts to a simple mosquito bite. After the pest extracts its meal, it leaves behind chemicals and proteins that our immune system recognizes as foreign and so mounts a reaction at the bite site. Immune cells in the skin release cytokines, tiny chemical messengers that escalate the response. The first inkling of itch is felt on the skin—just enough to cause scratching. That, in turn, damages the protective outer layer of the epidermis. Immune cells then release a surge of histamine, a major itch-inducing chemical, along with other pruritogens. Histamine activates its receptors found on the fine endings of sensory nerves in the skin, triggering the familiar sensa-

Under My Skin

Itch serves as a sentinel that warns you of the presence of insects, poisonous plants, and the like. Histamine, produced by an immune reaction after, say, a bug bite, is a well-recognized itch molecule. It interacts with a receptor in a nerve cell (A), which, in turn, activates another molecule (TRPV1), setting off the firing of that cell and inducing the sensation of itch. A recently discovered family of itch-related receptors (Mrgprs) react, for instance, to the chemical chloroquine in malaria drugs (B). Mrgprs can then switch on TRPA1 receptors.



tion of itch. Or does it? Histamine is turning out to be less important to itch than researchers have long believed.

Until just a decade ago, histamine receptors remained the only known itch detectors, and so antihistamine medicines today are still the go-to treatment for itch, along with steroids to quell inflammation. But researchers have long suspected that chemicals other than histamine must trigger other kinds of itch—mainly because antihistamines do not aid many patients. Antihistamines help with some allergic reactions but not most chronic itches, Lerner says. "Doctors will escalate the dose, and it works only because it makes the person drowsy." Such was Burwell's experience: physician after physician prescribed steroids, which caused her to rapidly gain 20 pounds—and there was also a list of antihistamines that did nothing for the itch. "Only Benadryl helped—and only because it would calm me down enough to sleep," Burwell says. To find new itch receptors, scientists followed the trail of obscure substances known to trigger itch without involving histamine.

Illustration by Emily Cooper

The first discovery was cowhage, a plant used as an ingredient in itching powders sold in novelty shops. "When you put histamine in the skin, it causes a pure sensation of itch," Lerner says. "But if you talk to patients with eczema, they describe a pricking or burning sensation. That's the sensation that cowhage evokes." Back in the 1950s, the late Walter Shelley, a pioneer in itch research, speculated that cowhage's itch factor was a protein-cutting enzyme, a protease he named mucunain. In 2008 that hunch was finally confirmed when Lerner found that mucunain activates a receptor found in skin and nerve cells: protease-activated receptor 2 (PAR2). Certain proteases—including mucunain—can snip off a tiny piece of the PAR2 protein, which activates the receptor. That discovery led to a new appreciation that proteases and the peptide fragments they produce are key mediators of itch, at PAR2 and other receptors. Proteases are ubiquitous, including in insect saliva and bacterial secretions, perhaps explaining why bug bites and infections can be so itchy.

The second clue to finding new itch receptors came from chloroquine, a medicine meant to protect people from malaria. In an ironic twist, the drug prevents the disease but causes itching. The side effect, which is not alleviated by antihistamines, causes many at-risk Africans to refuse chloroquine, although it has made the drug a valuable tool for investigators to study itch. One of them was Xinzhong Dong, then working in the laboratory of David Anderson at the California Institute of Technology. In 2001 Dong discovered a family of receptors, activated by unknown chemicals, called Mrgprs (*M*as-*r*elated *G*-*p*rotein-coupled *r*eceptors). Some of the Mrgprs were found only in sensory neurons, suggesting they detected external stimuli, but what kind remained a mystery.

Dong applied chloroquine to cells containing Mrgprs to test whether the Mrgprs might qualify as undiscovered itch receptors. In research reported in 2009, Dong—now at Johns Hopkins University—and Anderson created transgenic mice that lacked one of the Mrgprs found in sensory cells, a receptor designated MrgprA3. "Normal mice showed a robust scratching response to chloroquine treatment," Dong says, but the transgenic mice lacking MrgprA3 did not. "Without MrgprA3, the animals just don't feel the itch. That was our breakthrough point," Dong says. Two other proteins in the Mrgpr family were also found to respond to pruritogens.

Thanks to the two quirky chemicals, researchers discovered some of the first new itch sensors since the histamine receptors were described in the latter half of the 20th century. "But the point was not to find the receptor for chloroquine or cowhage; the point really is to find out what activates these nonhistamine itch neurons in chronic itch conditions," says Diana Bautista, an itch researcher at the University of California, Berkeley. Researchers now want to identify those substances. "There are probably a small number of molecules in the skin that turn on Mrgprs, and finding them will lead to very good drug targets and therapies," Lerner says.

A LINK TO PAIN?

ANOTHER WAY INVESTIGATORS are trying to gain a fuller understanding of itch is by looking at the way the nervous system is wired to respond to it—and that inevitably leads to an examination of what causes pain. Since as early as the 1960s, scientists have understood that diverse pain-sensing neurons, which detect potentially harmful stimuli, are distinct from other sensory neurons. Some are specialized to detect heat, others cold, and still others mechanical pressure. But what about itch? Do pain-sensing neurons also sense itch, or are there specialized itch-sensing neurons—and if so, are there more than one kind?

"There is an intimate relation between itch and pain," Bautista says. As the pain of a healing wound subsides, it leaves an itch in its wake, as do some pain-relieving medications. And the pain of scratching can dissolve itch. That overlap in the senses led some researchers to lump pain and itch together. "There was an idea that a lesser stimulus—like an itchy wool sweater—would activate the same receptors and the same cells

MECHANISMS

Why Scratch?

You feel an itch, and there is no other option: you have to scratch. Ah, sweet relief. The itch subsides—at least momentarily. Why does scratching make us feel better? Relief comes from activity in the central nervous system. Scratching spurs nerve endings in the spinal cord to release the body's own painkilling molecules—endogenous opioids—which are now understood to dampen itch as well. From the spinal cord, neurons send signals to inhibit a brain region called the anterior cingulate cortex, which is strongly activated by itch; when this region quiets down, so does the feeling. "Itch and scratch are uniquely intertwined," says Gil Yosipovitch, a researcher at Temple University.

The sensation of scratching is not particularly pleasant, and yet when it relieves an itch, it feels intensely rewarding. Yosipovitch uncovered the reason in a 2013 study that imaged the brains of subjects while they scratched an acute itch and found that it activated the brain's reward system, which also lights up when, among other things, ingesting drugs of abuse.

In particular, regions linked to pleasure, craving and motivation switched on, including the striatum and the prefrontal cortex. Scratching activated the reward system more strongly in people who suffered from chronic itch than in healthy subjects, indicating that over time the reward of scratching can become amplified. That finding hinted at the addictive nature of scratching and why we are so powerless to resist when itch arises. Chronic itch sets up "a vicious cycle of itching and scratching, with no off switch," Yosipovitch says. The bottom line for doctors: "Don't tell patients not to scratch. It's so powerful, and they can't stop it."

Why does an itch compel us so strongly to rake the affected area? Consider the evolutionary purpose of scratching: itch sends a warning signal, and scratching dislodges interlopers and alerts the immune system. "Our ancestors lived in a very pruritogenic world," Yosipovitch says, one full of itchy plants and bugs that posed a real threat. That threat explains the contagious nature of itching. "When we see the signal of someone scratching, we start scratching, too," as a kind of preemptive strike, Yosipovitch says. —*S.S.*

SCIENTIFIC AMERICAN ONLINE Watch a video on contagious itch at ScientificAmerican.com/may2016/itch

that transmit pain," Bautista says. The idea was that mild activation evoked itch, whereas stronger stimuli produced pain.

And yet histamine—or cowhage or chloroquine—applied to the skin does not cause pain. Conversely, for the most part, painful stimuli produce only gradations of pain but not itch. And pain-sensing neurons go much deeper than the skin—the only place where itch is felt. In recent years the intensity theory faded away, and most researchers were of the mind that itch was transmitted by nerves and receptors dedicated to the sensation. Moreover, they postulated that there were multiple types of itch-sensing neurons, each detecting different itchy stimuli. "The real question that cowhage addressed was, Is there more than one kind of itch, like there is more than one kind of pain?" Lerner says. "And the answer is yes."

In 2003, however, German and Swedish researchers cast doubt on the existence of specialized itch-sensing nerves when they found that individual human nerve cells that fired in response to histamine were also activated by painful heat and capsaicin, the ingredient that gives chili peppers their spice. The dual responsiveness suggested that nerve cells supposedly devoted to sensing itch contained the receptor for capsaicin, a hallmark of pain-sensing neurons called transient receptor potential vanilloid type 1 (TRPV1). If itch neurons contained the pain-sensing TRPV1, how could they be specific for itch?

Allan Basbaum, a pain researcher at the University of California, San Francisco, found that despite TRPV1's reputation as a pain receptor, it was also required for histamine-evoked itch, demonstrating that TRP receptors were not limited to detecting painful stimuli. The histamine receptor appears to work in conjunction with TRPV1 to help neurons transmit an electrical nerve impulse known as an action potential. But other, nonhistamine itch agents complicated the picture because they did not work through TRPV1.

Meanwhile Bautista, who has spent her career studying TRP receptors, was looking for the molecules that transmit nonhistamine itch signals. Basbaum's finding that TRPV1 was involved in triggering histamine's itch gave Bautista a clue: perhaps other related TRP receptors were involved in other types of itch. She focused on another pain-sensing receptor, TRPA1, which detects inflammatory chemicals and mustard oil, and found it was required for chloroquine-mediated itch. Within an hour after presenting that finding at a meeting in 2009, Bautista received a call from Dong, and the two immediately decided to collaborate. Dong and Bautista went on to show that TRPA1 and MrgprA3 worked together to make neurons fire in response to chloroquine. "That finding strengthened the case for separate populations of neurons that mediate different types of itch," Bautista says. And it opened a new avenue for potential anti-itch treatments. "TRPA1 is such an attractive target because it is important for so many types of inflammatory conditions, including itch. If we could somehow inhibit TRPA1 [in people], that could be very useful therapeutically."

At this point, the myriad studies sufficed to demonstrate that pain-sensing receptors also participated in detecting itch. But the nagging question persisted of whether individual sensory cells specialized in transmitting itch or whether pain-sensing cells could somehow transmit both types of stimuli. Dong tackled that mystery in a 2013 study. His team created transgenic mice in which they selectively killed off the putative itch-specific neurons: the ones containing the newly described itch receptor, MrgprA3. With the loss of those cells, mice lost the ability to sense itch, whereas pain sensation remained intact.

But Dong still had to prove that the itch sensors were truly reserved for itch and did not sense pain. With an elegant use of mouse genetics, Dong created mice lacking TRPV1 from all neurons except the proposed itch neurons. When the researchers activated TRPV1 with capsaicin—a normally painful stimulus—the mice displayed only itch, not pain. That cemented the case for itch-specific neurons and showed that those cells use some of the same sensors as pain-sensing nerves. Why? "Nature just reused the molecules for both sensations," Dong says.

The link between itch and pain turns out to be far more complex than it was once thought to be.

All these advances have come from studies of sensory neurons that innervate the skin. In fact, the latest research indicates that skin cells themselves also participate in generating itch by releasing pruritogens that activate itch-sensing nerves. The complex circuitry of itch also extends to the spinal cord, where researchers have recently found neurons and signaling molecules dedicated solely to itch. And scientists are using brain imaging to better understand how neural activity produces the unique—and oh so irritating—sensation of itch.

As for Burwell, she was finally freed of her chronic itch in late 2013, when she saw a 10th doctor—a prominent dermatologist who sees patients with intractable, unexplained itch. He performed an extensive allergy patch test on her back, which showed that Burwell was allergic to a preservative found in body care and cleaning products. "It was in everything I used," she says. Once she got rid of them and started using products from an approved list, the rash—and the itch—disappeared.

Burwell's case illustrates how misunderstood itch is by medical professionals: a straightforward test revealed an easy solution but only after three years of agony. It also underscores the importance of finding underlying causes—and reveals why the molecular complexities of this simple sensation continue to yield new puzzles. SA

MORE TO EXPLORE

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scientificamerican.com/magazine/sa

CONSERVATIONISTS ARE LOOKING TO ECOTOURISM

HOT-AIR BALLOONS rise over the temples of Bagan in Myanmar.

ECOLOGY

SAVING EDEN

TO PRESERVE MYANMAR'S WILDERNESS, BUT CHALLENGES ABOUND

By Rachel Nuwer

ON A CLOUDLESS JANUARY AFTERNOON,

Rachel Nuwer is a freelance science writer based in New York City. Her reporting for this story was paid for with a grant from the Society of Environmental Journalists.

two tourists climb into bright-yellow kayaks and set out to explore Myanmar's Indawgyi Lake, one of the largest and most pristine bodies of freshwater in Southeast Asia. The lake's clear, still surface perfectly reflects the grassy wetlands fringing its shores and the forested mountains towering just beyond. The golden outline of Shwe Myitzu Pagoda—a pilgrimage site for local Buddhists, accessible only by boat during most of the year—shimmers on the horizon like a mirage. As in a holy place, speaking seems taboo here. Only the rhythmic slap-swoosh-drip of paddles breaks the kayakers' awestruck silence.

Such awe comes easily in Myanmar, the biggest country in mainland Southeast Asia. Decades of rule under a brutal military junta left vast swaths of its wilderness unexplored and undeveloped. Although smaller than the state of Texas, Myanmar contains eight distinct ecosystems, from mangrove-choked deltas to snow-peaked mountains. Much of its natural heritage is still spectacularly intact, especially compared with nearby Thailand, Malaysia, India and China. It has the most bird species of any nation in mainland Southeast Asia—more than 1,000—as well as 250 mammal species, seven of which live nowhere else in the world. Each mission into a fresh patch of jungle or coral reef there seems to yield species new to science, including 14 reptiles and amphibians, many freshwater fish, a bat, a primate and the world's smallest deer in the past few years alone.

POLITICAL AND ECONOMIC isolation left Myanmar's wildlife well preserved compared with that of neighboring countries.

Myanmar is changing quickly, however. In Yangon, new buildings pop up seemingly overnight, and tendrils of highway extend toward impossibly remote regions. As the military loosens its grip, foreign prospectors have taken note of Myanmar's ample timber, mineral and petroleum resources, which raise tantalizing business prospects for one of the poorest nations on earth.

In the face of these forces, the continued survival of Myanmar's extraordinary wildlife is by no means guaranteed. Ensuring that some of it withstands the country's transition into modernity requires convincing both policy makers and local communities that keeping it around is worthwhile, especially from an economic point of view. Evidence supports this case: a recent report commissioned by the European Union estimated that Myanmar's terrestrial and aquatic forest ecosystems provide $7.3 billion in benefits to the country every year, including vital habitat for fishes and agriculturally important insects.

Yet financial support for existing national parks makes up a mere 0.2 percent of the budget of Myanmar—boiling down to just $26,600 allocated for patrolling, research, community outreach and other operational expenditures for all the protected areas there, according to environmental economist Lucy Emerton of the Environment Management Group, a sustainability consultancy based in Sri Lanka. But even if Myanmar did want to invest more in protecting its biodiversity, she adds, the reality is that the government simply does not have the funds to do so.

Now conservationists think they might have a partial solution both for both motivating Myanmar to safeguard its wildlife and for providing the money to do so: ecotourism. When executed correctly, this nature-focused form of tourism operates in an environmentally sustainable and responsible way and educates locals and visitors about the importance of preserving wildlife. Although Myanmar already admits up to three million tourists a year, it has yet to take advantage of everything its many wild areas have to offer.

IN BRIEF

Having been long cut off from the rest of the world both politically and economically, Myanmar has an abundance of pristine wilderness.

Now that the military is relaxing its hold, the country is beginning to transition to modernity, raising questions about the fate of its wild places.

Conservationists are hoping to persuade locals and the government to preserve that biodiversity by developing ecotourism around it.

But a successful ecotourism program is tough to develop even under the best of circumstances, and Myanmar has many complicating factors.

PRECEDING PAGES: PETER STUCKINGS *Getty Images*

Map by Mapping Specialists

FISHER PADDLES across Indawgyi Lake in northern Myanmar. Plans to develop the site as an ecotourism destination are under way.

ALEX TREADWAY Getty Images

In theory, the promise of foreign visitors could help convince both locals and the government to protect valuable environments by putting a tangible price tag on the natural places they flock to see. But developing an effective ecotourism operation is a notoriously difficult task even under the best of circumstances, let alone in a politically unstable, severely impoverished and logistically challenged place like Myanmar. Will tourists make the trek? Will communities choose them over timber? Will the government pass up natural gas and petroleum drilling in favor of mangrove conservation? No one knows the answers to these questions, but one thing is certain: if measures are not taken to preserve Myanmar's wilderness—and fast—this Eden will soon be spoiled.

A UNIQUE OPPORTUNITY

FRANK MOMBERG is leading the charge on developing ecotourism in Myanmar. Momberg, a conservationist at the Cambridge, England–based nonprofit Fauna & Flora International, first ventured into the country—a "sort of last blank space on the map" in terms of biological exploration—in 2006. Almost all other conservationists had long since pulled out because of ongoing armed conflicts and international sanctions. Once there Momberg encountered a place that was like "a frozen historical picture," complete with ox-drawn carts and small organic farming communities. But most important, he found wildlife—lots of it.

That exceptional preservation is an outgrowth of Myanmar's long record of human-rights violations and repression. After gaining independence from the U.K. in 1948, Burma, as the country was then called, struggled as various factions jostled for power. In 1962 the Revolutionary Council of the Union of Burma seized control; crippling impoverishment followed, and the nation was cut off from much of the outside world.

Despite those grim social and political realities, Momberg, who was then based in Indonesia, increasingly found his thoughts returning to Myanmar after his initial visit. He began spending every vacation there and finding more wildlife on each trip, including amphibians, insects, plants and fishes, all newly recorded for Myanmar. The crowning discovery came during an expedition to the country's northwestern corner, when Momberg and several other conservationists discovered a new primate, the Myanmar snub-nosed monkey. He proposed that Fauna & Flora open an office in Yangon. But his employers balked. "They were excited to hear the stories from Myanmar," he recalls, "but they were not quite ready to engage."

In 2010 things began to change. The government shifted to a quasi-democratic model, releasing many political prisoners and loosening its grip on the economy and the press. Although some areas remain under rebel control today, significant cease-fires have been established. As a result, Momberg finally got his office in Yangon. Several other international conservation organizations followed suit. Likewise more foreign tourists began to arrive.

With Myanmar's political situation stabilizing and tourism on the rise, Momberg thinks the time is ripe to develop ecotourism there—before other, competing interests gain a foothold. "Burma is at an absolute historical, exciting moment," he says. "It's important to act quickly during this transition period because in the future there will be too much vested interest to save these places." Indeed, as ecologist William McShea of the Smithsonian Conservation Biology Institute observes, "Right now the only people paying for natural resources are those who are tak-

ing them away." The hope is that getting in on the ground floor will allow conservationists to carefully plan from the beginning, in terms of both preserving as much nature as possible and laying foundations for best-practices ecotourism.

In 2012 Momberg and his colleagues took a leap of faith and began searching for a site to serve as their first tentative venture into community-based ecotourism. In addition to the three tenets of such efforts—nature, sustainability and education—the community-based variety places special emphasis on empowering and benefiting local people, who typically manage the tourism themselves and form a cooperative to distribute the benefits. The conveniently located mangroves of Meinmahla Island, just southwest of Yangon, proved too crocodile-infested for the government's liking, whereas any thought of developing tourism around the newly discovered snub-nosed monkey was shelved indefinitely after insurgents seized control of roads leading to the forest. Indawgyi, however, seemed perfect. The lake hosts nearly 450 species of birds and is already listed as a wildlife sanctuary, meaning the habitat and species there enjoy some formal protection. That protection extends to the surrounding forests, home to elephants, endangered hog deer and vulnerable eastern hoolock gibbons. More important, local residents seemed receptive to the idea of opening up their communities to foreigners, as did the park staff. "If local people can benefit from tourism, then they'll protect what the tourists came to see: nature and the lake," says Htay Win, park warden at Indawgyi Lake Wildlife Sanctuary.

HIKERS trek between Kalaw and Inle Lake in central Myanmar.

JOEL CARILLET *Getty Images*

In 2014 an independent ecotourism consultant whom Momberg hired helped 35 local volunteers create Lovers of Indawgyi, the first community-based ecotourism group in Myanmar. Fauna & Flora donated kayaks and mountain bikes, which the group rents out to visitors for a few dollars a day. "The kayaks are good because they're quiet, unlike motor boats," observes Su Hla Phya, a Lovers of Indawgyi volunteer. Two small guesthouses and a few restaurants round out the tourist offerings. The facilities stand in stark contrast to those at Inle Lake, one of Myanmar's most visited attractions, where motorboat traffic, hotel crowding, deforestation and pollution have sent bird and fish populations into a tailspin.

In the near future, conservationists and the government hope to establish programs similar to Indawgyi's all over Myanmar, following the lead of flourishing ecotourism ventures in places such as Costa Rica, Namibia and Rwanda. The government recently issued a nationwide sustainable tourism development and regulation plan and an ecotourism strategy for 21 of the country's 45 protected areas. And whereas 6 percent of the land is currently protected, officials aim to increase that figure to 10 percent by 2030. "Myanmar is promising because they understand that their natural and cultural resources can be turned into assets to help improve economic activity," says Hannah Messerli, a senior private-sector development specialist in tourism at the World Bank. "They want to share their culture and nature, but at the same time, they want to protect and take care of it in the long term."

Still, if history is any guide, the odds of success are long. For every ecotourism triumph, there are multiple failures. Greenwashing plagues the industry, with many operations that claim to protect the environment actually doing more harm than good. James Sano of the World Wildlife Fund for Nature (referred to as the WWF) recollects a resort in Malaysia that, when it first opened, called itself an ecotourism destination on the basis of the thin strip of rain forest left in between its hotel and golf course; several ecolodges in Ambergris Caye in Belize were discovered dumping raw sewage into the environment. "Around the world, genuine ecotourism products are in the minority, for sure," says Ross Dowling, a tourism expert at Edith Cowan University in Joondalup, Australia. "A lot of conventional tourism operators simply slap 'eco' in front of their name because it's sexy and marketable."

Greed-fueled marketing schemes aside, even if operators' intentions are pure, aspirations often fall short of the mark for other reasons. For example, in 1990 the WWF began an ecotourism program at Dzanga Sangha, a stunning rain-forest reserve in the Central African Republic that is home to elephants and gorillas, among other creatures. But reaching the lodge required a 16-hour drive or else an expensive chartered flight. "It's not enough to have a really interesting place for people to visit, even if you develop adequate on-site facilities," says Alex Moad, assistant director for technical cooperation at the U.S. Forest Service International Programs. "Successful ecotourism also depends on a number of off-site factors, such as reliable transportation."

At Dzanga Sangha, transportation did gradually improve over the years, and from 2007 to 2011 the park regularly received up to 600 tourists each year, putting it on track to become self-sustaining by 2016. But when civil war erupted in 2013, the staff was forced to suspend all tourist activities. Now that peace has returned to the Central African Republic, the WWF is hopeful that Dzanga Sangha can rebuild its numbers. That regrowth will take time, though. In 2014 the park reopened but welcomed just 37 tourists.

SCIENTIFIC AMERICAN ONLINE See more images of Myanmar at ScientificAmerican.com/may2016/myanmar

A LONG WAY TO GO

IT IS TOO EARLY to tell how things will play out at Indawgyi, but thus far Momberg's vision has been partly realized. For starters, tourists do seem to want to visit the lake. Before Fauna & Flora got involved in 2013, Indawgyi saw just 20 or so foreign visitors a year. Now that advertisements appear online and in Lonely Planet guidebooks, numbers have risen to more than 300. Tourists spend an average of $45 during their stay at the lake, totaling around $19,000 pumped into the local economy in 2014 alone—a significant infusion for the community of about 300 households in the village of Lonton, the epicenter of the lake's ecotourism, where families earn an average of $1,080 a year. Profits from the rentals have paid for hospital treatments and school fees for the village's poorer members. And throughout this gradual process of developing and promoting Indawgyi as an ecotourism destination, local people have remained supportive of the efforts, even if most of them are not making money directly from the tourists—a crucial win.

Yet there is considerable room for improvement. For starters, Indawgyi's eco-offerings are hardly impeccable. The only options for disposing of inorganic waste are burning or burying it on-site instead of recycling it or sending it to a landfill. And sewage-treatment systems are nonexistent. Thus, instead of purely conserving the environment, ecotourists are also inadvertently degrading it—at least when it comes to producing waste. The forested hills surrounding the lake—a trekker's paradise—are also sporadically off-limits because of the presence of the insurgent Kachin Independence Army, a military group based in the north. And Lovers of Indawgyi members have not acquired expertise in nature guiding. "If you want to go bird-watching, who's going to ID those birds for you?" McShea says by way of example. "Many countries have worked on training up a group of core ornithologists, but [Myanmar] hasn't really done that yet."

Infrastructure poses another problem. The lake's closest airport is six hours away, along a brain-rattling road accessible only by expensive private vehicle. Most travelers instead choose the shoestring option, making the 24-hour trip overland from Mandalay by train and in the back of a pickup truck. Once they reach Indawgyi, Internet and cell service are nonexistent, and electricity in the two small guesthouses—the only places where tourists may legally stay—is available for just a couple of hours a day. Some tourists count these no-frills conditions as a plus, a welcome respite from the bustle of the plugged-in world. But for many others, they are probably a deal breaker. "At this stage in the game, [Myanmar] is a place for ecotourists who are hardy and don't mind toughing it out to reap the rewards of the country's natural history," says Chris Wemmer, an honorary fellow at the California Academy of Sciences and a scientist emeritus at the Smithsonian National Zoological Park. "The little old ladies in tennis shoes who like to watch birds are not going to put up with that."

Kyi Kyi Aye, who is a senior tourism adviser at the Myanmar Tourism Federation and co-author of the ecotourism strategy, insists that the problems stymieing development in Indawgyi and beyond will all be ironed out eventually. She points out that these things take time: "We want to make Myanmar a better place to live and to visit. But the country has just opened up. It's a gradual process."

The question is whether Myanmar can overcome those hurdles in time to save its wildlife. For Rwanda, whose mountain gorilla ecotourism counts as one of the most successful examples of such programs today, that process took two decades. The International Gorilla Conservation Program, founded by a coalition of nongovernmental organizations, began developing ecotourism in 1979. But the 1994 genocide and ongoing political tumult largely derailed those efforts until 1999, when stability returned. Getting the program up and running required an initial investment of around $2 million for training, infrastructure and marketing, but those funds have repaid themselves many times over, with gorillas generating close to $16 million in park entrance fees alone in 2014. Profits are shared across the country for development projects, and the government has created additional national parks to give tourists an incentive to spend even more time in Rwanda. "We're not conserving for the sake of gorillas only but also for economic benefits," says Michel Masozera, country director for the Wildlife Conservation Society's Rwanda program. "Politicians and local communities get that message."

In Myanmar, the basic challenges of getting a successful ecotourism operation up and running are complicated by deeper societal issues, including corruption and ongoing democratic freedom constraints, according to Adam Simpson, director of the Center for Peace and Security at the University of South Australia. Bureaucracy there is constrained by a decades-old political culture of authoritarian decision making by military leaders, Simpson says, and the political system is further burdened by crony capitalism. "The key issues that will limit the effectiveness of an ecotourism industry are also those that impinge on effective governance in Myanmar as a whole," he asserts. "Until these issues are addressed across the board, it's difficult to see ecotourism—although welcome in itself—having more than a marginal impact on environmental conservation."

Bathed in the rosy glow of an Indawgyi sunset, however, it is easy to be optimistic. As tourists read and sip tea on the porch, Ngwe Lwin, Fauna & Flora's northern Myanmar forest conservation program director, sits down after a long day of community meetings. "At the moment, we cannot say that tourism is benefiting conservation here, because [tourists are] bringing in only a little extra income," he admits. "But in 10 years I imagine that this area will be more peaceful, open and accessible. Perhaps each village will have a small community guesthouse, and tourists can travel the whole lake." The security that a flourishing ecotourism operation could bring might come at the expense of some of Myanmar's magical wildness. But that is a trade-off conservationists may be willing to make. As Lwin says: "Good and bad things always come together." SA

MORE TO EXPLORE

A New Species of Snub-Nosed Monkey, Genus *Rhinopithecus* Milne-Edwards, 1872 (Primates, Colobinae), from Northern Kachin State, Northeastern Myanmar. Thomas Geissman et al. in *American Journal of Primatology*, Vol. 73, No. 1, pages 96–107; January 2011.

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scientificamerican.com/magazine/sa

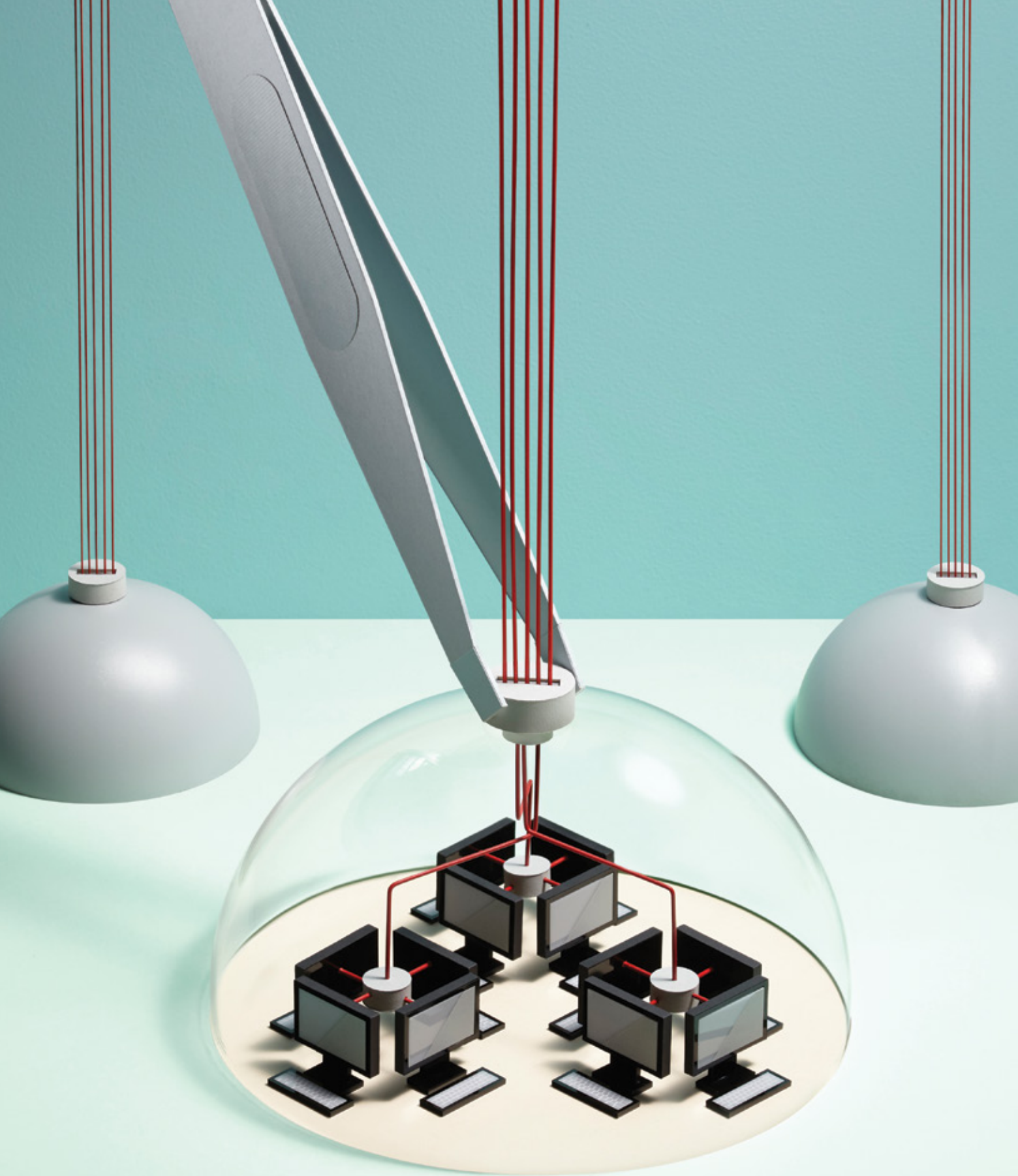
TECHNOLOGY

QUANTUM CONNECTIONS

Scientists are trying to make quantum computers a reality by connecting many small networks together into one large whole

By Christopher R. Monroe, Robert J. Schoelkopf and Mikhail D. Lukin

Illustration by Kyle Bean



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Robert J. Schoelkopf is a professor of physics at Yale University and director of the Yale Quantum Institute. He and his collaborators at Yale are leaders in the development of solid-state quantum bits (qubits) for quantum computing.

Mikhail D. Lukin is a professor of physics at Harvard University and a co-director of the M.I.T.-Harvard Center for Ultracold Atoms. He has made pioneering contributions to several areas of quantum computing, communication and metrology.

FOR THE PAST TWO DECADES SCIENTISTS HAVE BEEN ATTEMPTING TO HARNESS THE peculiarities of the microscopic quantum world to achieve leaps in information processing and communication ability. By exploiting several features of physics at the universe's smallest scales—that electrons are both particles and waves, that an object can be in many places at once and that two particles can maintain an eerie instantaneous connection even when separated by vast distances—quantum machines could make previously unthinkable computing, communication and measurement tasks trivial. To cite just one example, a quantum computer should be able to break "unbreakable" codes.

At the same time, quantum machines can be used for storing and communicating information such that privacy is guaranteed by the laws of physics. They can also be used to simulate processes in complex chemical and materials systems that would otherwise be intractable. And quantum systems could boost the precision of the world's most accurate timekeepers—atomic clocks—and serve as miniature precision sensors that measure the properties of chemical and biological systems at the atomic or molecular scale, with applications ranging from biology and materials science to medicine.

This potential is why technology behemoths such as Google and Intel, several start-up companies, and defense and other government agencies are betting big on the field. The academic community is also inspired: in 2015 alone, three major journals published more than 3,000 scientific papers mentioning "quantum computing" or "quantum information."

The problem is that scientists have not yet been able to build a large-scale quantum machine that realizes this promise. The challenge is that such a computer must, by definition, operate in the quantum realm, and yet when we try to build one large enough to be useful, its natural tendency is to start obeying the classical rules of the macroscopic realm.

Building a system that maintains quantum rules on a large scale and exercises the full power of quantum information processing will likely require a modular approach, where smaller, demonstrably quantum units are connected in a way that does not kill their quantum nature. Recent work has taken this so-called modular approach beyond the theoretical realm to successful tests on small scales and is paving the way for realizing the unique potential of quantum machines.

PROBABLY ZEROES AND POSSIBLY ONES

THE FIRST SUGGESTION that the quantum world could be exploited to build advanced computers came in the early 1980s from phys-

IN BRIEF

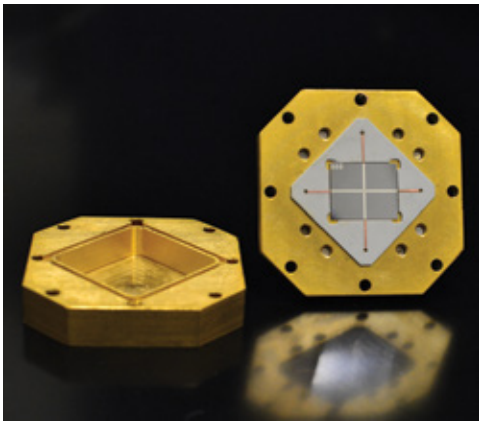
Scientists struggle to build quantum computers big enough to be useful because large collections of particles typically stop behaving quantum mechanically and start obeying classical laws. **The solution,** researchers are realizing, is to construct many small quantum computers and link them together through minimal connections that do not disturb their quantum properties—an approach called modular quantum computing. **Several modular methods** relying on different types of quantum bits, or qubits, have recently proved successful in small tests and could soon be scaled up into larger systems.

icists and mathematicians such as Richard Feynman of the California Institute of Technology and David Deutsch of the University of Oxford. The idea remained speculative for many years until 1994, when Peter Shor, then at AT&T Bell Laboratories, showed how a quantum computer could be used to quickly factor large numbers, igniting interest in the field. The first basic quantum computers arrived in the late 1990s and early 2000s, when researchers built simple systems consisting of several "bits" made of atoms, molecules or photons.

It is the special nature of quantum particles that can give quantum computing an advantage over its classical counterpart. Unlike classical computing, where the basic unit of information (the bit) takes a definite value of 1 or 0, the quantum unit of information, the qubit, can exist in two states at once, meaning it can represent 0 *and* 1 simultaneously. Or it can be probably 0 but possibly 1. Or equally likely to be 0 or 1. Or any other weighted combination of the two binary states. The qubit has this power because quantum particles can exist in two locations or physical states at once—a phenomenon known as superposition.

Beyond existing in two states simultaneously, qubits can be connected through a quantum property called entanglement: the ability of particles separated in space to retain a connection so that an action performed on one reverberates on the other. This property gives quantum computers a massive parallel processing ability. When a set of qubits is entangled, a simple operation on one can affect all the other qubit states. Even with just a few qubits, all those mutually dependent 0s, 1s and other superposition states create a hugely complex range of possible outcomes. Whereas a classical computer can handle only one possibility at a time, a quantum computer can effectively test all possible solutions to a problem simultaneously. Just a few hundred qubits can calculate a tableau of outcomes that exceeds the number of particles in the universe.

So far scientists have created small quantum-computing systems in many laboratories that use up to 10 qubits. But as we add qubits, it becomes ever more difficult to shield the system from the outside world—and any such interference dooms the very properties that make a quantum computer special. A quantum superposition of multiple states can exist only in isolation. Any attempt to prematurely observe or measure it will force a particle to collapse into a single state—to choose one possibility. At this point, quantum mechanics is out, and the qubits revert to the conventional bits of classical computers. In other words, the special abilities of quantum objects are typically seen only in very small systems and break down when those objects become fully connected to a larger whole—similar to the way an indie musical group might appeal most strongly to its fans when few people know of it. Large systems are usually too complex and insufficiently isolated to behave quantum mechanically—after all, we do not expect to find a baseball, or even a biological cell, in two places at the same time.



QUANTUM DEVICE: A circuit for measuring superconducting qubits is housed in a gold-plated box. These measurements can entangle qubits in separate clusters, or "modules," allowing modules to connect to form a unified quantum computer.

COURTESY OF MICHEL H. DEVORET *Yale University*

MODULAR QUANTUM SYSTEMS

THE CHALLENGE BECOMES scaling up without losing the necessary quantumness. A brute-force approach to creating a large quantum system by simply adding and wiring together qubits in one network will likely fail. This prediction is buttressed by the fate of machines developed by Canada-based company D-Wave Systems that have hundreds or thousands of individual qubits wired together. Although company officials maintain that these devices beat the calculation speeds of classical algorithms, we have found no published data that show evidence of large-scale entanglement or any speed advantage in these systems.

The modular technique, however, offers another path forward. This solution is akin to the strategy that commercial airlines exploit to manage complexity. Next time you fly, check the back of your in-flight magazine. The carrier's route map gives a rough sense of what a full-scale quantum computer might look like. Airlines do not directly connect every city with every other one, because the logistics and overhead would be prohibitive. Instead they use central hubs to create networks of indirect connections. Sacrificing direct connectivity allows them to grow and manage a much larger network of destinations.

Similarly, a modular quantum computer would not connect every qubit to every other one. Instead it would use a few qubits as hubs that would connect separate modules, akin to the way Atlanta serves as a hub connecting the southeastern U.S. to other regions.

Modular networks help to keep the number of interactions among qubits manageable while allowing each module to remain shielded from external interference. They compensate for sacrifices in direct connectivity by allowing thousands or even millions of qubits to collaborate indirectly. But unlike conventional modular systems such as multicore computer processors, which use the same type of wires between cores as those within cores, modular quantum systems may require two or more different types of linkage to achieve the necessary entanglement while maintaining isolation between the modules. Three leading modular quantum strategies, using different types of qubits, have emerged over the past decade. The three of us are independently developing these platforms, and we believe they will usher in larger quantum computers that will enable new kinds of information processing.

ATOMIC QUBITS

THE MOST NATURAL TYPE of qubit is a single atom whose electronic or nuclear energy levels (sometimes called spin states) store quantum information. Atomic qubits are fundamentally scalable

because multiple atoms of the same species are virtually identical and do not need to be engineered to match. Laser beams can cool the atoms until they are nearly at rest, chilling them by transferring momentum from the atom to scattered laser light. We do all this while suspending the atoms in free space in a vacuum chamber to prevent them from interacting with anything else.

Either neutral or charged atoms (ions) can serve as qubits. To confine neutral atomic qubits, we use focused laser beams or a crisscrossed pattern of laser beams called an optical lattice; dozens of research groups throughout the world are pursuing such methods. Although it is difficult to control and couple neutral atoms at the single-qubit level, there are many promising paths forward.

As an alternative, many groups use positively charged ions—atoms with an electron removed. Ions interact strongly with one

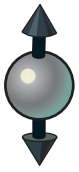
STRATEGIES

Three Ways to Build a Quantum Computer

Computers that capitalize on the bizarre laws of quantum mechanics could theoretically perform calculations that are impossible for classical computers. Yet the larger a quantum computer gets, the more difficult it becomes to preserve its quantum properties (*below*). Scientists think the solution is to build many small quantum computers and link them together into a larger whole—a strategy called modular quantum computing. The boxes at the right show three potential modular setups using three different types of quantum bits, or qubits.

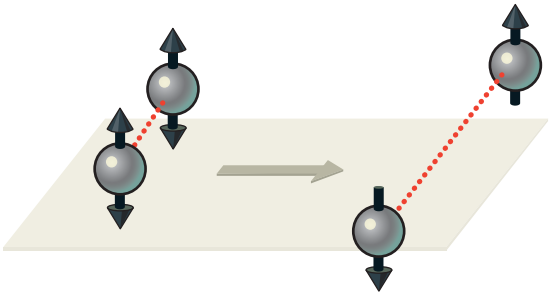
Quantum Property 1: Superposition

Atoms and subatomic particles can exist in multiple states and even multiple locations simultaneously—a state called superposition. Whereas a classical object, such as a marble, can spin in only one direction at a time, particles can be in two "spin states"—both spin up and spin down, for example—at once. By exploiting this property, quantum computers could test many possible solutions to a problem simultaneously.



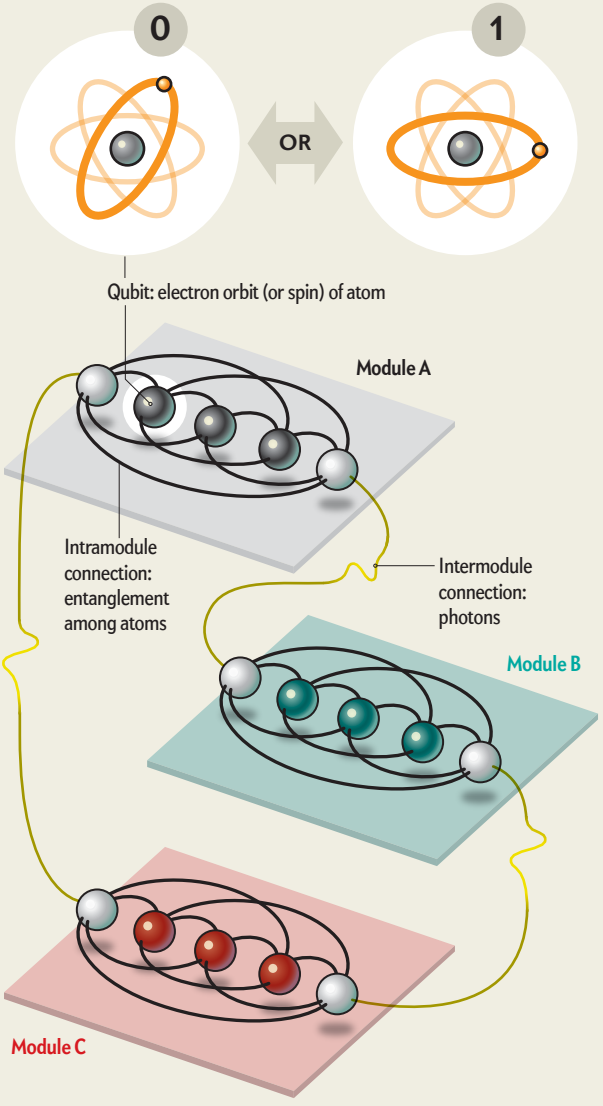
Quantum Property 2: Entanglement

Albert Einstein called it "spooky action at a distance": entanglement allows two particles to forge an instantaneous connection such that an action performed on one of them affects the other, even when they are separated in space. In the picture below, the entangled particles start out in a superposition of both up and down spin states. When an outside measurement forces the particles to "pick" a single state, the two will always pick coordinated states. Depending on the type of entanglement, if the first particle is in the spin-up state, the second will always be in the spin-down state. When multiple qubits are entangled, an operation performed on one will affect all the others instantaneously, allowing for unprecedented parallel processing.



Atomic Ion Qubits

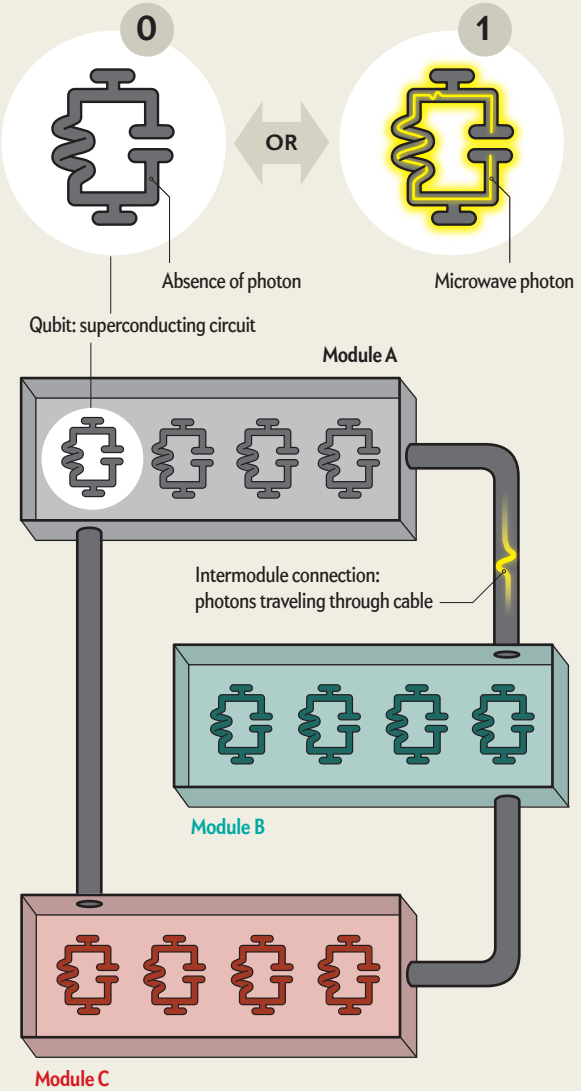
The simplest way to build a modular quantum computer is to use single atoms as qubits. Each atom can represent the binary code values of 0 or 1 (or a superposition of the two) via different electronic orbits (*top*). At the bottom is a schematic of three modules—mini quantum computers made of five atomic ions each—connected in a way that preserves each module's quantum properties. Within each module, all five ions are entangled with one another. The two end ions (*in white*) are special and can emit photons to communicate with other modules.



another through their electrical repulsion and can be confined with electromagnetic fields generated by nearby electrodes. We can laser-cool hundreds of trapped ions to form a stationary crystal of individual atoms that act like identical pendulums connected by springs. Additional control lasers can push the ions around in a way that can entangle their spin states through the vibrations of the ions, in a scheme first proposed in 1995 by Ignacio Cirac and Peter Zoller, both then at the University of Innsbruck in Austria. In the past couple of decades researchers have made astounding progress in the control and entanglement of individual trapped-ion qubits in this way. Lately groups led by one of us (Monroe), David J. Wineland of the National Institute of Standards and Technology, and Rainer Blatt of the University of Innsbruck have demonstrated high-quality entangle-

Superconducting Qubits

Another modular quantum-computing strategy uses "artificial atoms" made of superconducting circuits as qubits. These qubits are electrical circuits that can take on a value of 0 or 1 through the absence or presence of a microwave photon or an oscillating electric current running through the circuit. (When the qubit is in a state of superposition, the photon may be both "there" and "not there.") Within each module, qubits can be entangled directly with one another via trapped photons. These photons can also be sent through cables to link each module to the others.



Solid-State Spin Qubits

A third option is to make qubits out of defects in a solid-state material, such as a diamond lattice of carbon atoms. If one of the carbon atoms in the lattice is replaced by a nitrogen atom and a neighboring site is empty, the impurity is known as a nitrogen-vacancy (NV) center. The NV center and the surrounding carbon atom neighbors all become qubits, and their spin states represent 0s and 1s. Each cluster of impurities in the diamond lattice is an independent module, and modules can connect to other modules via entangled optical photons.

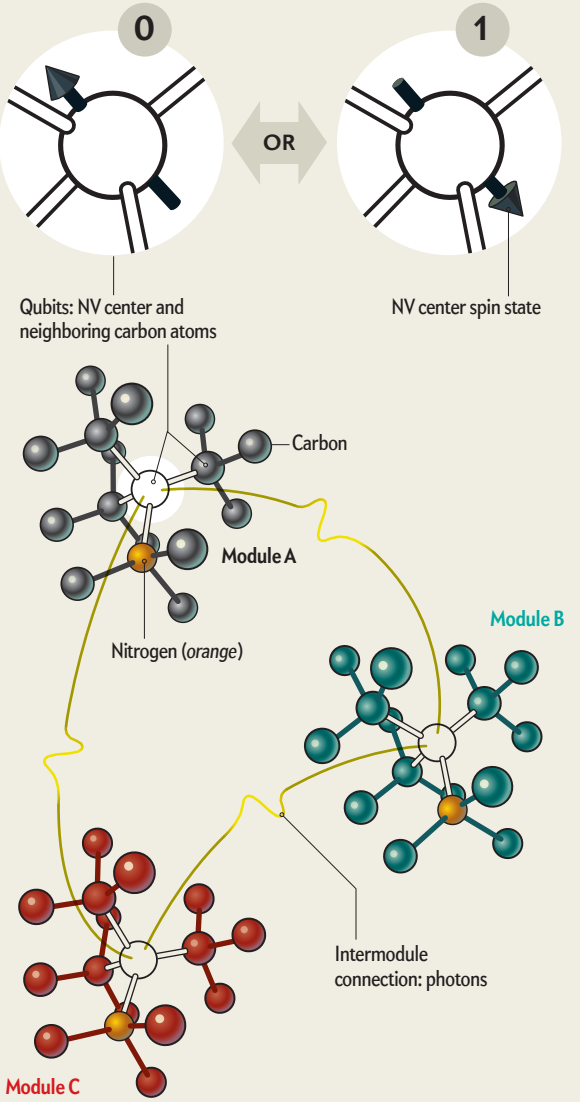
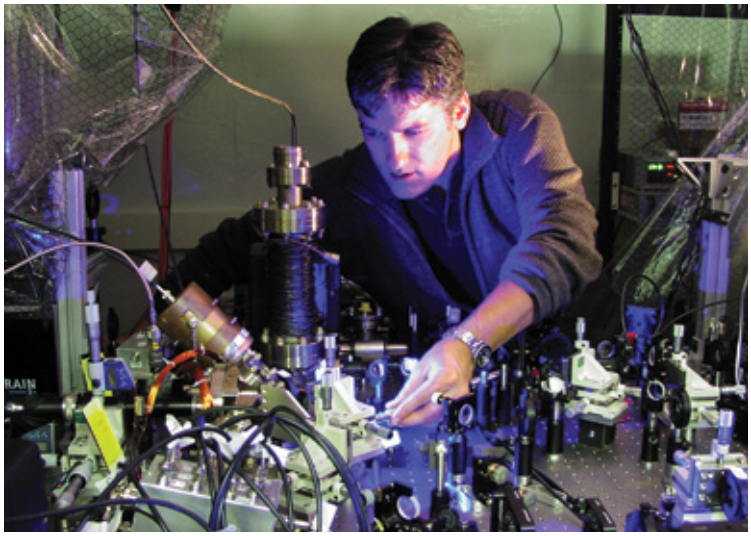


Illustration by Jen Christiansen

ment operations among up to 20 trapped-ion qubits.

Researchers have explored two ways to connect modules made of such entangled ion crystals. One is to physically move a few of the ion qubits through space, from one module to another, by passing them through a complex maze of electrodes (a method proposed in 2000 by Monroe, along with Wineland and David Kielpinski, then at NIST). The ions can be made to surf through space on an electrical field wave without disturbing their qubit state. When the ions touch down at the second module, laser pulses can induce them to form new entanglements. The two modules, each containing, say, 50 qubits, become part of a single set for computation, meaning that now 100 qubits are working together, albeit with a weak link. There is no theoretical limit to the number of modules that we can connect via this technique, which is called ion shuttling.

A difficulty with this method is controlling the complex ion traps, which consist of hundreds or thousands of precisely positioned electrodes that accomplish the shuttling. We must be able to manipulate all of the required electrode voltages to induce the ions to surf through the maze of electrodes. Notable efforts to fabricate ion-trap electrodes from silicon or other semiconductor materials in a scalable fashion are now coming from Sandia National Laboratories and Honeywell International.



LAB WORK: Author Christopher R. Monroe manipulates atomic ion qubits with lasers and confines them in a trap made of electromagnetic fields generated by electrodes.

The second method of connecting ion qubit modules together leaves the atoms in place. It relies on lasers to prompt ions to emit photons (particles of light) that are entangled with the ions. These photons can then transfer the entanglement between modules. This type of photonic quantum interface stems from ideas pioneered almost 20 years ago by researchers at the University of Innsbruck, Caltech and Harvard University and demonstrated 10 years ago by Monroe.

The photonic connection technique has the great advantage of allowing us to link qubit memories that may be far apart, and it can also be applied to other types of qubits, such as neutral atoms and superconducting and semiconductor qubits, as we will discuss. Moreover, we can scale up the photonic connection between modules through fiber-optic networks and switches that can allow us to reconfigure which qubits get entangled. The central hurdle for this strategy is that the qubit-photon link is typically inefficient because it requires capturing and guiding these photons. Many trials may be necessary to establish a successful connection. The best attempts so far have operated only at a rate of up to about 10 entangled links a second. Extensions of current technology, however, should be able to push this rate up by many orders of magnitude.

SUPERCONDUCTING QUBITS

ALTHOUGH ATOMS may be nature's qubits, controlling and scaling them to more complex systems poses several engineering problems. An alternative strategy is to devise "artificial atoms" using circuits made of superconducting material. These devices contain many atoms but can behave as simple, controllable qubits, where the presence or absence of a single microwave photon or the clockwise/counterclockwise direction of a circulating current inside the circuit corresponds to the "0" or "1" states. Such quantum circuits have distinct advantages. We can tailor their properties by design and mass-produce them with the fabrication techniques of conventional integrated circuits. And remarkably, when they operate at temperatures near absolute zero, they can persist in a superposition state for long enough to serve as a robust qubit. During the past 15 years the lifetimes of these systems have improved more than a millionfold.

In the past decade work on these superconducting quantum circuits has made rapid progress, demonstrating the various necessary features for a quantum computer. Researchers at many academic labs as well as industrial players such as Google and IBM can now manipulate and entangle several superconducting qubits. With techniques called circuit quantum electrodynamics, pioneered by one of us (Schoelkopf), together with his colleagues Michel H. Devoret and Steve Girvin, both at Yale University, we can also entangle multiple qubits over long ranges by using superconducting transmission lines.

Superconducting devices lend themselves naturally to a modular architecture. We can make connections among modules within a large cryogenic device via superconducting wires and measurement devices while reducing the cross talk and interference among modules by shielding them from one another. To generate the entanglement among modules, researchers at Yale, JILA at the University of Colorado Boulder, the University of California, Berkeley, and elsewhere have developed special superconducting devices for quantum measurement.

The modular approach with superconducting qubits has a number of appealing features. Instead of building and testing one gigantic circuit, we need only mass-produce and calibrate the more modest modules and then build complexity module by module. We can eliminate or skip over defective modules and rewire the connections among modules to create different architectures. Work is also under way to develop microwave-to-optical quantum transducers and then connect distant modules via optical fiber to create long-range quantum networks or a distributed quantum computer.

COURTESY OF KATHERINE MONROE

SCIENTIFIC AMERICAN ONLINE Watch a video on how quantum computers work at ScientificAmerican.com/may2016/quantum

SOLID-STATE SPIN QUBITS

FINALLY, A THIRD TYPE of qubit encodes information in spin states within solid-state materials. There are different models for this type of qubit, but a promising method, pursued by one of us (Lukin), as well as numerous other groups, uses defects in crystals to generate qubits. One such system is a diamond lattice of carbon atoms in which a single atom is replaced by nitrogen and a neighboring site is empty—an impurity known as a nitrogen-vacancy (NV) center. Electromagnetic pulses can control the electronic spin of this atomlike impurity. In a method pioneered by Lukin and his colleagues, the NV center reacts to the nuclear spins of its closest carbon neighbors, creating a cluster of neighboring qubits formed from the magnetic interactions among the particles. A nitrogen-vacancy impurity, though, has only so many close carbon neighbors, limiting the total number of qubits per module to fewer than a dozen.

Scaling up requires connecting multiple NV modules. If the qubits are in separate crystal lattices, we can link them by forcing each qubit to emit a photon and then measuring the photons. But if multiple NV impurities reside within a single diamond lattice, we can also try to connect them using quantum vibrations called phonons, which can transport quantum information between impurities.

Remarkably, although manipulating information encoded in these NV center qubits is challenging, we can often do it under ambient conditions at room temperature. Techniques to observe single NV centers, pioneered in the past decade by Jörg Wrachtrup of the University of Stuttgart in Germany and Fedor Jelezko, now at the University of Ulm in Germany, have allowed scientists to work with individual electronic spin qubits. A team led by David Awschalom of the University of Chicago has been able to manipulate these qubits on nanosecond timescales, comparable to the speed of modern classical processors.

Recently Ronald Hanson and his colleagues at Delft University of Technology in the Netherlands have entangled single-NV-impurity qubits separated by more than one kilometer using entangled photons, similar to the photonic method of connecting ions discussed earlier. Currently this process is not very efficient (in the Delft experiments, the entanglement links are established at a rate of only a few times per hour), but new techniques to greatly improve it using nanoscale optical devices have recently emerged at Harvard and the Massachusetts Institute of Technology. And because we already have the means to create several qubits around a single diamond-lattice defect and store them for longer than a second in ultrapure crystals such as those grown by scientists at Element Six, NV centers show great potential for a scalable modular quantum-computing architecture.

QUANTUM FUTURE

AS A RESULT of more than 20 years of research and development in this field, scientists have experimentally tested all these modular quantum-computing approaches on small scales. The task awaiting us is to expand these techniques to larger conglomerations of qubits and modules and to start using them for interesting applications. We believe this goal is now within sight.

The quantum future is both challenging and exciting. As quantum machines grow larger, it will become increasingly difficult to both control and verify that the overall system is indeed behaving quantum mechanically. Luckily, the modular architecture allows us to test and validate individual modules and the various connections among them independently, without disturbing the entire system. Scientists have recently taken important steps toward this goal.

And even modular quantum computers of relatively modest scale may enable unique applications. They naturally provide the backbone for a "quantum Internet" composed of small quantum processors that are connected via entangled optical photons. These can serve as repeater stations that extend the reach of secure quantum communication—currently limited to about 100 kilometers because of the photon loss in conventional telecom fibers—to continental distances.

Elements of modular quantum machines are already being incorporated into some of the world's most accurate timekeepers, and their role is expected to grow in a new generation of optical atomic clocks based on neutral atoms and atomic ions. Scientists have proposed a global quantum network of such clocks to create a real-time, single international timescale, or "world clock," that would operate with unprecedented stability and accuracy.

A miniature quantum network could also serve as a precision sensor of electromagnetic fields and temperatures in complex chemical and biological systems at the nanometer scale. For example, researchers have exploited electronic and nuclear spins associated with solid-state impurities to achieve magnetic resonance imaging with the resolution of a single atom. This technique could be used to directly image individual molecules, which would inform fundamental biological and materials science and deliver new tools for medical diagnostics and drug discovery.

The time has come to stop asking whether quantum computing is possible and to start focusing on its large-scale architecture and on what it will be able to do. The truth is that we do not know how quantum computers will change the world. But with the advent of modular quantum-computing networks, we should soon begin to find out. SA

Disclosure of commercial ties: *Christopher R. Monroe is a co-founder and co-inventor of intellectual property that is licensed to ionQ, a start-up company focused on the development of atomic quantum computers using the methods described in this article. Robert J. Schoelkopf is a co-founder, an equity holder and an inventor of intellectual property that is licensed to Quantum Circuits, a start-up that is developing superconducting circuits for quantum computation based on techniques discussed here. Mikhail D. Lukin is a co-founder, advisory board member and a co-inventor of intellectual property that is licensed to Quantum Diamond Technologies, a start-up focused on applications of quantum sensors for medical diagnostics using research described in this article.*

MORE TO EXPLORE

Scaling the Ion Trap Quantum Processor. C. Monroe and J. Kim in *Science,* Vol. 339, pages 1164–1169; March 8, 2013.

Superconducting Circuits for Quantum Information: An Outlook. M. H. Devoret and R. J. Schoelkopf in *Science,* Vol. 339, pages 1169–1174; March 8, 2013.

Atom-like Crystal Defects: From Quantum Computers to Biological Sensors. Lilian Childress et al. in *Physics Today,* Vol. 67, No. 10, pages 38–43; October 2014.

FROM OUR ARCHIVES

The Diamond Age of Spintronics. David D. Awschalom, Ryan Epstein and Ronald Hanson; October 2007.

Quantum Computing with Ions. Christopher R. Monroe and David J. Wineland; August 2008.

BIOMECHANICS

SWIMMERS UNDER PRESSURE

Jellyfish manipulate physics to become the most efficient animals moving in the sea

By Josh Fischman

Jellyfish never stop. Twenty-four hours a day, seven days a week, they move through the water in search of food such as shrimp and fish larvae, on journeys that can cover several kilometers a day. They are more efficient than any other swimmer, using less energy for their size than do graceful dolphins or cruising sharks. "Their cost of transport—the oxygen they use to move—is 48 percent lower than any other swimming animal," says Bradford J. Gemmell, a marine biologist at the University of South Florida. By studying moon jellies, the species *Aurelia aurita,* Gemmell and other researchers have recently found that jellyfish pull off this feat by creating zones of high and low pressure around their body that alternately suck and push them forward.

Scientists once believed that jellies traveled so easily because they were light, mostly water. But water has mass, and mass still has to be moved. So Gemmell, with engineer John Dabiri of Stanford University and their colleagues, took a close-up look. They put a jellyfish in a tank and dropped tiny glass beads into the water. By illuminating the beads with lasers, they could track their movements with a high-speed camera, essentially making the water velocity and pressure visible around the animal.

When the animal contracted its bell—the dome that forms much of the jellyfish body—it created lower pressure outside the bell and higher pressure within. Because objects move from high to low pressure, the moon jelly got pulled forward, the scientists noted in November 2015 in *Nature Communications*.

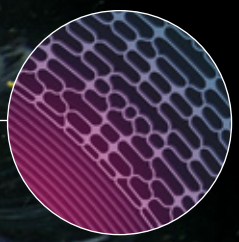
Then the researchers got a surprise. When the jelly relaxed the bell margin, letting it flare out, the high-pressure water below the animal rose up into the bell. "It gave the moon jelly a secondary bump forward, even while it relaxed," Gemmell says. To make these moves, the jelly needs to flex the bell margin up and down. Jellyfish have muscles, but most go around the bell like a stack of rubber bands. That arrangement is good mainly for squeezing. Recently, though, Richard Satterlie, a biologist at the University of North Carolina Wilmington, discovered other muscles at the margin that stick out at angles. Those fibers let the jelly bend its edge, moving water around it, and make for a very effective swimmer. SA

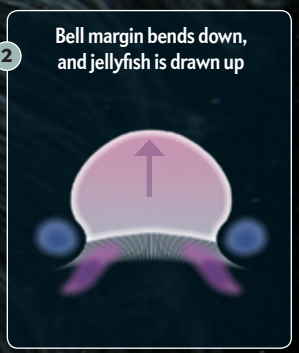
ALEXANDER SEMENOV

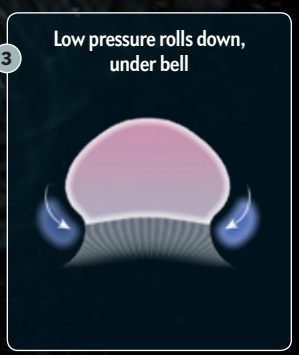
Josh Fischman is a senior editor at *Scientific American.*

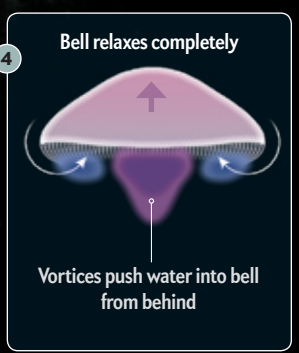
SCIENTIFIC AMERICAN ONLINE Watch engineer John Dabiri explain how jellyfish inspire submarine design at ScientificAmerican.com/may2016/jellyfish-physics

Muscle fibers generally circle the bell, but at the margin, they form a mesh, helping it bend.









The Jellyfish Swim Stroke

Jellyfish create zones of high and low pressure around themselves, then move from one to the other. By dropping tiny glass beads in a water tank with a jellyfish, a team of scientists was able to see that a vortex—a relatively low-pressure spinning doughnut of water—rolls down the jelly. Seen here as a cross-sectional slice, the vortex (*blue*) appears as two wheels of water 1. As the jelly contracts, it creates higher pressure within its bell, and the animal is pulled ahead to lower pressure 2. By flexing the edge of its bell, the jelly moves the vortex down and underneath 3. There the vortex pushes water up as it spins, giving the jelly an extra shove 4.

Illustrations by Eleanor Lutz

LANGUAGE WARS

Where did the most successful family of languages in history originate? New evidence from DNA and evolutionary biology has only heightened the scientific disagreements

By Michael Balter

IN BRIEF

Nearly half the world's population speaks one of the languages derived from a single ancient tongue, dubbed Proto-Indo-European, or PIE.

Linguists have long argued that PIE first spread from the vast steppes of Central Asia to Europe some 6,000 to 5,000 years ago.

An alternative hypothesis posits that PIE spread some 8,000 years ago from what is now Turkey, after the introduction of agriculture into those regions.

The latest evidence from evolutionary biology and ancient DNA samples, rather than settling the issue, is adding to the controversy.

Illustration by Mark Allen Miller

Michael Balter is a freelance journalist, whose articles have appeared in *Audubon, National Geographic* and *Science,* among other publications. His book *The Goddess and the Bull* (Free Press, 2005) explores the excavation of one of the world's earliest and largest villages, Çatalhöyük in Turkey.

"WHAT'S IN A NAME?" ASKED JULIET OF ROMEO. "THAT WHICH WE CALL A rose by any other name would smell as sweet." A real-life Juliet probably would have spoken to Romeo in an obscure medieval Italian dialect rather than Shakespeare's English. Nevertheless, her word for the sweet-smelling flower would have shared the same linguistic root (*rosa,* in modern Italian) as the English version does and indeed as many other languages spoken throughout Europe do—*Rose,* capitalized in German fashion, or the lowercase French *rose*. Croatian? An aromatic *ruža*. To the nearly 60,000 Scots who still speak the ancient Scottish Gaelic, this symbol of passionate love is a *ròs*.

Why do such geographically diverse languages use similar words for the same flower? All these tongues, along with more than 400 others, belong to the same family of languages—the incredibly far-flung Indo-European language family—and have a common origin. Indo-European languages, which include Greek, Latin, English, Sanskrit, and many languages spoken in Iran and on the Indian subcontinent, are the most dominant linguistic group in the history of humanity. They account for about 7 percent of the world's estimated 6,500 languages but are nonetheless spoken by three billion people—nearly half the world's population. Understanding how, why and when they spread so readily is key to understanding the social, cultural and demographic changes that created today's diverse populations in Europe and much of Asia. As Paul Heggarty, a linguist at the Max Planck Institute for the Science of Human History in Jena, Germany, puts it: "We have to explain why Indo-European was so outrageously, overpoweringly successful."

Because words and languages do not fossilize, the task of tracking their movements across time and space was left for more than a century to traditional linguists and a small number of archaeologists. Recently, however, the search for Indo-European origins has gone high tech, as biologists and experts in ancient DNA have gotten into the act. Armed with new theoretical and statistical approaches, these investigators have begun to transform linguistics from a paper-and-pencil exercise into a field that uses powerful computers and methods borrowed from evolutionary biology to trace language origins.

You might think that this attempt to modernize linguistics would bring researchers closer to an understanding of where and when the Indo-European languages arose. But in many ways, the opposite has happened, and the question is in even greater dispute. Everyone agrees on one key point: the Indo-European languages descend from a common ancestor, a mother tongue called Proto-Indo-European, or PIE. But as to why this particular language produced so many linguistic offspring or where it originated, there is no accord.

Researchers have fallen into two warring camps. One camp, which includes the majority of traditional linguists, argues that Central Asian nomads, who invented the wheel and domesticated the horse, spread the mother tongue throughout Europe and Asia beginning about 6,000 years ago. The other camp, led by British archaeologist Colin Renfrew, credits early farmers from more than 500 miles to the south in what is now Turkey with disseminating the language at some point after they began spreading their agricultural know-how 8,500 years ago.

Over the years first one idea then another has had the upper hand. Evolutionary biologists published a series of studies in 2003 that concluded that the Indo-European family tree originated in the Middle East at least 8,000 years ago, based on the idea that the evolution of words can mimic the evolution of living organisms; their results are consistent with the farmer hypothesis. In the past year or two some linguists, archaeologists and geneticists struck back, using rival computational analyses and samples of DNA from ancient skeletons to support the nomad hypothesis. And so the pendulum continues to swing.

THE HORSE, OF COURSE

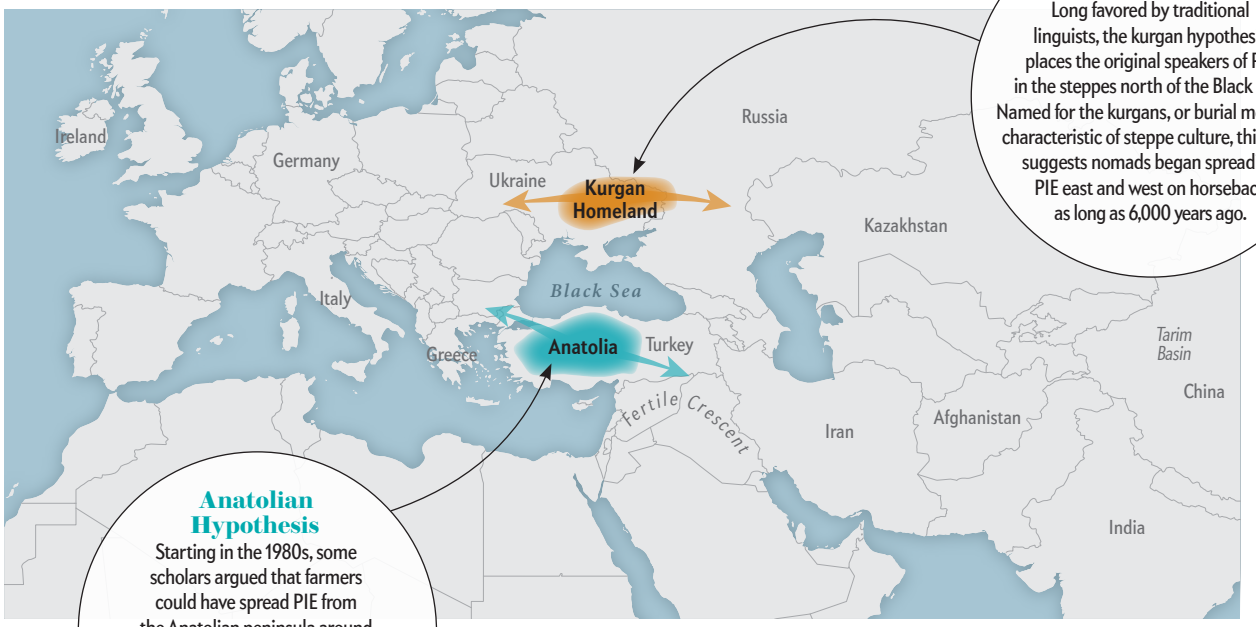
SCHOLARS DID NOT have to wait for high-speed computers to recognize connections among the Indo-European languages. That realization dawned as early as the 1700s, after Europeans had begun to travel far afield. Some of the parallels among widely distributed tongues are now seen as dead giveaways. Thus, the Sanskrit and Latin words for "fire," *agní-* and *ignis,* clearly indicate their Indo-European family ties.

By the 19th century, linguists were sure there must be a common ancestor for all Indo-European languages. "There was a sense of shock that the classical languages of European civilization sprang from the same source as Sanskrit, an exotic language spoken in India, on the other side of the world," says David Anthony, an archaeologist at Hartwick College and a fierce advocate of PIE's nomadic origin.

So linguists set about reconstructing this ancestral tongue.

Two Homeland Possibilities

Nearly half the world's population speaks at least one of more than 400 languages, which descend from a mother tongue known as Proto-Indo-European, or PIE. Scholars have reconstructed many of PIE's words, but they are still fighting over where the ancient language, whose influence reaches as far west as Ireland and as far east as China, originated.

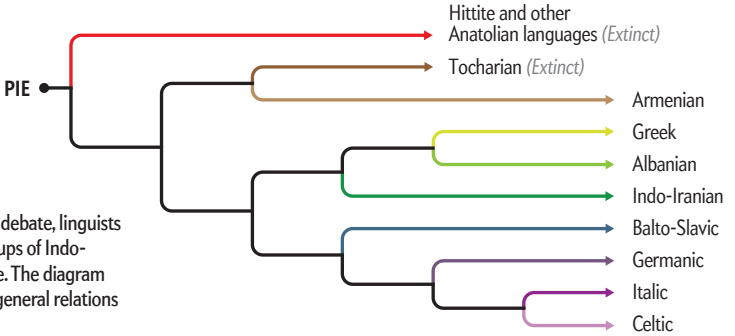


Kurgan Hypothesis

Long favored by traditional linguists, the kurgan hypothesis places the original speakers of PIE in the steppes north of the Black Sea. Named for the kurgans, or burial mounds, characteristic of steppe culture, this idea suggests nomads began spreading PIE east and west on horseback as long as 6,000 years ago.

Anatolian Hypothesis

Starting in the 1980s, some scholars argued that farmers could have spread PIE from the Anatolian peninsula around 8,000 years ago. Some archaeological evidence and calculations based on the rate at which languages evolve support the idea but are not conclusive.



Proto-Indo-European's Family Tree

Although the timing and point of origin of PIE are up for debate, linguists generally agree on the broad outline of how various groups of Indo-European languages descended from the mother tongue. The diagram at the right is highly stylized and is meant to show only general relations among language groups, not actual dates of divergence.

Sometimes this was not too difficult, especially if the original word had not changed unrecognizably. For example, linguists could take the English word "birch," the German *Birke,* the Sanskrit *bhūrjá* and other Indo-European words for this slender tree and, by applying basic linguistic rules of language change, extrapolate backward to figure out that the PIE root was something like **bherh$_1$ǵ-* (the asterisk indicates that this is a reconstructed word for which there is no direct evidence). Other reconstructions are not as obvious. Thus, the PIE word for "horse"—*áśva-* in Sanskrit, *híppos* in Greek, *equus* in Latin and *ech* in Old Irish—was determined to be **h$_1$éḱwo* (the subscript 1 refers to a sound made in the back of the mouth).

But when some linguists tried to identify the peoples behind the language, things became trickier. These scholars began linking certain cultures with PIE, an approach called linguistic paleontology. They noticed that PIE contained many terms for domesticated animals, such as horses, sheep and cattle, and began postulating a pastoral Indo-European "homeland."

That approach eventually led to trouble. In the early 20th century German prehistorian Gustaf Kossinna proposed that a group of Central European settlers, who created intricately engraved pottery called Corded Ware starting 5,000 years ago, were in fact the first Indo-Europeans. Kossinna argued that they later spread out of what is today Germany, carrying their language with them. That idea was music to the ears of the Nazis, who resurrected the term "Aryan" (a 19th-century term for

SOURCE: "MAPPING THE ORIGINS AND EXPANSION OF THE INDO-EUROPEAN LANGUAGE FAMILY," BY REMCO BOUCKAERT ET AL., IN *SCIENCE*, VOL. 337; AUGUST 24, 2012

Map by Mapping Specialists, Graphic by Tiffany Farrant-Gonzalez

Indo-Europeans), along with its connotations of racial superiority.

The Nazi endorsement gave Indo-European studies a bad name for many years. Many researchers give credit to Marija Gimbutas, an archaeologist who died in 1994, for making the subject respectable again, starting in the 1950s. Gimbutas situated the origins of PIE in the so-called Pontic steppes north of the Black Sea. For her, the prime mover of PIE was the Copper Age Kurgan culture, which can first be identified in the archaeological record about 6,000 years ago. After a millennium of roaming the barren steppes—in which the nomads learned how to domesticate the horse—Gimbutas argued, they charged forth into Eastern and Central Europe, imposing their patriarchal culture as well as the strongly enunciated vowels and consonants of their native Indo-European language. More specifically, Gimbutas identified the Yamnaya people, who lived in the Pontic steppes between about 5,600 and 4,300 years ago, as the original PIE speakers.

Other researchers also found evidence to support such a view. In 1989 David Anthony began working in Russia, Ukraine and Kazakhstan, focusing on horse teeth that had been earlier excavated by Soviet archaeologists. Anthony and his colleagues confirmed previous suggestions that there was bit wear on teeth dated as early as 6,000 years ago, pushing back the earliest evidence for horse domestication—and horse riding—by about 2,000 years. Their studies also provided evidence to link several technological developments—including the use of wheeled vehicles such as chariots—to the Yamnaya people. These finds supported the idea that the steppe pastoralists had the necessary transportation and technology to fan out rapidly from their homeland and spread their language in all directions.

REVOLUTIONARY FARMERS

THE STEPPE HYPOTHESIS, also known as the kurgan hypothesis, after the kurgans, or burial mounds, in which the pastoralists buried their chiefs, was rarely questioned until the 1980s. Then Renfrew put forth a radically different idea, called the Anatolian hypothesis. (*Anatolia,* from the Greek for "sunrise," refers to present-day Turkey.) Renfrew, the dean of British prehistorians, who now sits in the House of Lords, had spent years digging in Greece and was struck by how much the artifacts he unearthed, especially the carved female figurines, resembled those from earlier archaeological sites in Turkey and the Middle East.

Archaeologists already knew that farming spread from the Middle East to Greece first. Renfrew wondered if there might be a continuity of language in addition to culture. Thus, the first PIE speakers, he posited in lectures and a book, might be the farmers who moved from Anatolia to Europe 8,500 years ago, bringing their words along with their agricultural practices.

Traditional linguists, who had spent decades working painstakingly with paper and pencil to reconstruct PIE by tracing modern Indo-European words back to their original roots, were outraged. Most dismissed the Anatolian hypothesis, sometimes with bitter invective. One University of Oxford professor called the idea "rubbish," and another skeptic declared that "a naive reader would be grossly misled by the simplistic solutions that the author offers."

Renfrew and his supporters fought back, arguing that the steppe hypothesis cannot explain the broad expansion of PIE from wherever it began across both Europe and Asia. Researchers know that PIE-derived languages were spoken as far west as Ireland and as far east as the Tarim Basin, in what is now northwestern China, and down into India. A key question is how PIE would have gotten from the steppes to East Asia if the kurgan hypothesis were right. Did it spread to the north around the Black and Caspian seas, as in the steppe hypothesis? Renfrew sees no archaeological evidence for this route. Or did PIE take a southerly and earlier path to the east from Anatolia? He thinks it more likely that PIE spread south around the Black Sea from Turkey and then along early trade routes through Iran and Afghanistan.

Thus, Renfrew believes, only an Anatolian origin can account for PIE's simultaneous spread to the east and west because the peninsula offers the best historical evidence of movement between the European and Asian continents. And the only sociotechnological driver powerful enough to propel the language so far in opposite directions, he adds, was the advent of agriculture, which appeared in the Fertile Crescent—just south and east of modern Turkey—roughly 11,000 years ago. This transition of human society from hunter-gatherers into settled farming communities marked the so-called Neolithic Revolution and was "the only big thing that happened on a Europe-wide basis," Renfrew says. "If you wanted a simple theory for the coming of the Indo-European languages, the Neolithic was the best thing to hang it on."

Emblematic of the linguists' objections to Renfrew's Anatolian hypothesis is the origins of the word "wheel." The reconstructed PIE root is **kʷékʷlo-,* which became *cakrá-* in Sanskrit, *kúklos* in Greek and *kukäl* in Tocharian A, an extinct Indo-European language of the Tarim Basin. The earliest evidence for wheeled vehicles—depictions on tablets from ancient Mesopotamia (modern-day Iraq)—dates to about 5,500 years ago. The actual remains of wagons and carts show up in kurgans beginning about 5,000 years ago.

Many linguists have argued that the PIE root for "wheel" could not have arisen until the object was invented, and so PIE cannot be much earlier than 5,500 years—or about 5,000 years after the invention of agriculture. "That doesn't mean the PIE speakers invented wheels," Anthony says, "but it does mean that they adopted their own words for the various parts of wheeled vehicles."

But Renfrew and others counter that the word **kʷékʷlo-* derives from a much earlier root meaning "to turn" or "to roll" and only later was adapted as a name for the wheel. "There was a whole language about rotation before the wheel was invented," Renfrew says.

Andrew Garrett, a linguist at the University of California, Berkeley, and proponent of the steppe hypothesis, agrees that the PIE word for "wheel" has an earlier derivation, the root **kʷel(h)-,* which probably meant "turn" or "roll." He says that the word **kʷékʷlo-* was formed by duplicating that root, putting the **kʷe-* part into the word twice. "It would be as if I saw a wheel for the first time," adds Garrett's graduate student, Will Chang, "and I called it a ro-roller." That might seem a point for Renfrew's position, but Garrett argues that while such duplications were common in PIE when forming verbs, they were "extremely rare" when forming nouns, which suggests to him and other linguists that **kʷékʷlo-* must have developed as a word close to the time wheels were invented.

CONTESTED EVIDENCE

RENFREW'S ANATOLIAN HYPOTHESIS was facing an uphill battle when, in 2003, a bombshell landed in the middle of the debate from an

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entirely unexpected direction—the field of evolutionary biology. Russell D. Gray, a biologist who had made his early reputation studying bird cognition, and Quentin D. Atkinson, then his graduate student at the University of Auckland in New Zealand, used state-of-the-art methods from computational biology to date the origins of PIE. Gray and Atkinson adapted an earlier linguistic technique called glottochronology, which compared the proportion of cognates—words with shared roots—in different languages to determine how long ago they diverged. Glottochronology had long been out of favor because it required linguists to assume that words change their form steadily over time—something they knew was not true. Gray and Atkinson employed a new and improved version of glottochronology, along with other statistical techniques used to determine the evolutionary trees of living organisms. Their database included cognates from 87 Indo-European languages, including Hittite, an extinct language that had been spoken in Anatolia.

The results were a slam-dunk for the Anatolian hypothesis. No matter how the pair crunched the numbers, the divergence of Indo-European languages from PIE came out no later than about 8,000 years ago—or nearly 3,000 years before the apparent invention of the wheel. Despite howls of objection from some linguists that words do not change the way that living organisms and genes do, the paper was highly influential and gave a big boost to the Anatolian hypothesis. Gray, who is now co-director of the Max Planck Institute for the Science of Human History (where Heggarty works), says that he and Atkinson were simply bringing linguistics into the 21st century.

Moreover, although Gray and Atkinson found that the initial spread of PIE tracked the spread of farming, they also detected a second divergence 6,500 years ago, which led to the Romance, Celtic and Balto-Slavic languages. The Anatolian and steppe hypotheses "need not be mutually exclusive," they concluded.

Indeed, subsequent analyses favored the Anatolian hypothesis so strongly that some younger linguists began to call for older linguists to drop their objections. "Traditional linguistic objections to the Anatolian hypothesis are now wearing a little thin," Heggarty wrote in a June 2014 commentary in *Antiquity*.

Calls for advocates of the steppe hypothesis to surrender, however, may have been premature. Beginning in 2013, Garrett and Chang launched their own analysis, using Gray's methodology. But the Berkeley researchers made an assumption that Gray's team did not: They "constrained" certain languages to be ancestral to their descendants, based on what they insist is solid historical evidence. Thus, they assumed, for example, that Classical Latin was directly ancestral to Romance languages such as Spanish, French and Italian. Gray and Atkinson, in contrast, allowed for the possibility that some as yet unidentified form of popular Latin spoken in the streets of Roman cities was the true ancestor of the Romance languages.

Garrett and Chang's results, published last year in *Language,* were also a slam-dunk—but for the steppe hypothesis, not the Anatolian hypothesis. Despite this apparent new life for the steppe hypothesis, Heggarty argues that Garrett's team is wrong to assume that some ancient languages are directly ancestral to others. Even small differences in Classical versus "Vulgar" Latin could throw off Garrett's estimates, Heggarty argues.

Garrett remains unconvinced. "For many of these languages we know quite a bit about the speech communities and the history of the languages," he says. "Best understood are Greek and Latin. It isn't likely that there are other varieties of Greek and Latin floating around that we don't know about."

Gray, for his part, calls the *Language* paper that used his own methods against the Anatolian hypothesis "a lovely piece of work" that really engages with the methods "rather than just saying [that Atkinson and I] are wrong." Yet since turnabout is fair play, Gray's team has now started recrunching Garrett's data, but letting the data decide whether some languages are ancestral to others rather than assuming it. Although this work is preliminary and still unpublished, Gray and his colleagues are finding that the numbers again come up trumps for the Anatolian hypothesis.

NEW CLUES FROM DNA

IF THE WORDS THEMSELVES cannot tell us who is right, perhaps more evidence from outside the field of linguistics could help tip the balance. The latest genetic studies, at least, seem to favor the steppe hypothesis. Anthony and an international team of ancient DNA experts sequenced samples of genetic material from 69 Europeans who lived between 8,000 and 3,000 years ago, including nine skeletons from Yamnaya sites in today's Russia, and compared the DNA samples with those from four skeletons of the later Corded Ware culture of Central Europe.

Amazingly, the Corded Ware people, whose culture spread across Europe as far as Scandinavia, could trace three quarters of their ancestry to the Yamnaya people, and this Yamnaya genetic signature is still found in most Europeans today. So the Yamnaya, along with their genes and possibly their language, did indeed sweep out of the steppes in massive numbers, probably about 4,500 years ago. These results are a "smoking gun" that such massive migrations did take place out of the steppelands, says Pontus Skoglund, an ancient DNA expert at Harvard Medical School who was not involved in the paper but works in the laboratory of one of its authors. They "level the playing field" between the two hypotheses, he adds.

Unless, of course, this migration was a "secondary" wave that carried later Indo-European languages with it but not the original mother tongue, Proto-Indo-European. Such an interpretation, the pro-Anatolian researchers counter, would fit with the conclusions of Gray's 2003 study that pointed to the possibility of a later migration out of the steppes.

Will we ever know who is right? New evidence from ancient DNA for the spread of steppe peoples eastward into Siberia around 4,700 years ago could potentially overcome one of Renfrew's key objections to the steppe hypothesis, but it offers no proof about which languages went with them. One thing is sure: researchers will continue to debate the issue in whatever language their ancestors bequeathed them. SA

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FARMER Rhoda Mang'yana has vastly increased the yield of maize crops on her land in Malawi by planting trees whose fallen leaves and roots rebuild the soil.

A CURE FOR AFRICA'S SOIL

By growing trees, shrubs and other perennial plants among crops in the field, African farmers can revitalize some badly depleted soils while raising food yields

By John P. Reganold and Jerry D. Glover

Mariko Majoni in Malawi has dramatically changed how he farms. Like many small-scale African farmers, he could not afford fertilizers, and over the years his maize yields plummeted. When he learned about "fertilizer trees" that capture nitrogen from the atmosphere, he planted seedlings between his rows of maize. Six years later he was harvesting 10 times as much food, enough for his family and a surplus to sell. At first his neighbors thought he had gone mad. Now many of them have adopted the same practice.

Across much of sub-Saharan Africa, temperatures are warm, and days are long and sunny. Crops should grow well there, but as with Majoni, farmers are struggling mightily, even when they use chemical fertilizers. Yields of maize, a staple cereal, average around one metric ton per hectare—barely one tenth of maize yields that farmers in the U.S. Midwest enjoy. The reason is simple: A large proportion of soil in the lands south of the Sahara Desert is depleted. It

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Jerry D. Glover is the senior sustainable agricultural systems adviser at the U.S. Agency for International Development in Washington, D.C. The views expressed in this article are not necessarily those of USAID.

PLANT BREEDER Albert Chamango shows how peanuts and taller pigeon peas can flourish together while also enriching the soil.

lacks the organic matter and nutrients needed by plants. Applying extra chemical fertilizer alone is not always enough to raise yields significantly and in some cases can actually harm the soil further. Soil degradation continues at alarming rates, causing already low yields in some regions to stagnate or fall still lower.

The situation is troubling because about 220 million of the world's 800 million undernourished people live in the sub-Saharan region. And recent studies indicate that the population of roughly one billion people will double by 2050 and will be hard hit by climate change. Without a significant upgrade of the soil, hunger is sure to increase. Restoring soils, scientists agree, is the number-one priority to raising agricultural productivity.

In principle, the solution is straightforward. The soils need to be rebuilt with decomposed plant and animal material. This organic matter adds nitrogen and carbon, helps to retain water and nourishes microbes that keep the earth productive. In practice, though, challenges abound. A majority of African farmers cannot create or afford to buy enough crop residue, compost or animal manure to rebuild their land. And restoration has to occur while the land continues to be farmed; families cannot stop planting while croplands are repaired. Farmers also face the daunting task of increasing yields while avoiding overuse of water and chemicals and earning enough money to maintain the financial and social stability of their families and communities.

The approach Majoni adopted belongs to a set of strategies known as perenniation, which could make a huge difference in Africa. The methods rely on raising trees, shrubs or perennial grasses right among or alongside food crops to renew soils, thereby boosting crop yields and improving the long-term sustainability of food production. The perennial plants supply carbon and nitrogen to the ground, help to retain water, reduce erosion, fight off pests and raise crops' uptake of chemical fertilizers. The techniques work well with modern management practices, including no-till agriculture and organic farming, and with modern crop cultivars that have been bred for better drought tolerance and disease and pest resistance. The perennials can also provide farmers with feed for livestock and wood for fuel.

Three perenniation methods illustrate how farmers can sustainably increase the yields of important staples such as maize and sorghum and so enrich soils. Although other approaches exist, these three have succeeded in sub-Saharan Africa and have great potential to be more widely adopted there. They can help increase cereal grain yields from one to three metric tons per hectare over several years. And lessons learned could benefit other areas of the world with nutrient-poor tropical and subtropical soils, including countries in South Asia and South America.

TREES AND PEAS

THE PERENNIATION STRATEGY most widely employed by African farmers, including Majoni, is known as evergreen agriculture. Farmers establish certain kinds of trees in the fields of annual crops. Their nitrogen-rich leaves drop and fertilize the soil surface, and the activity of their deep roots adds nitrogen and carbon to the soil. Often farmers use *Faidherbia albida,* an acacia-like species native to the continent. It grows primarily in the months between the harvest and planting of crops, so it does not compete with them for water, nutrients or sunlight. In regions where crops are harvested by hand, farmers may plant the trees randomly, but they can also space the trees evenly and far enough apart that tractors and combines can navigate through. In recent decades more than 100,000 farmers in Zambia have integrated these leguminous fertilizer trees into their maize fields. In Niger and Mali, farmers have protected naturally growing tree seedlings on more than five million hectares of millet and sorghum fields, creating seminatural parklands. Several other tree species are working well, too.

The trees, some reaching 30 meters high, also draw up other nutrients such as phosphorus and potassium because their roots mine much deeper soil layers than those used by the crops. As with nitrogen, these nutrients are made available to the crops through decomposing leaf litter and root activity. In addition, the trees protect the crops from hot, dry winds and thereby reduce the amount of water evaporating from the ground. These

IN BRIEF

Soils in many regions across sub-Saharan Africa are so depleted that simply adding fertilizer will not improve them and may even make them worse. **Growing perennial plants** such as trees, shrubs and legumes among food crops can rebuild soils and reduce pests while the crops grow, ultimately raising yields. **More than a million** African farmers have used the three leading "perenniation" techniques, but millions more need technical or financial help to exploit them.

PAGE 66 AND THIS PAGE JIM RICHARDSON

SCIENTIFIC AMERICAN ONLINE To learn how perennial crops could replace those that are planted annually, go to ScientificAmerican.com/may2016/reganold

benefits can double grain yields and help to triple them when combined with modern crop varieties and fertilizers.

More than 30,000 farmers in East Africa have adopted a second type of perenniation called the push-pull system. They plant specific perennial plants among the maize fields, as well as around the edges. The plants suppress insect pests and weeds but can also mitigate erosion, produce animal feed and lessen the need for fertilizers. For example, farmers in East Africa use push-pull systems to manage both stem-borer larvae that chew into maize stems and African witchweed, which steals nutrients from maize roots. Farmers plant desmodium (*Desmodium uncinatum*), a perennial legume usually cultivated to feed livestock, in between rows of maize. It produces a smell that repels, or "pushes out," the stem-borer moths that want to lay their eggs. And a chemical from its roots suppresses witchweed.

To further reduce pest damage, farmers may grow perennial Napier grass (*Pennisetum purpureum*), also a valuable livestock feed, around the edges of the maize field to "pull in" the stem borers. The grass provides an attractive place for the stem borers that are repelled by the desmodium to lay their eggs, yet it produces a sticky resin that traps the hatched larvae.

Push-pull systems can more than double maize yields when both stem borers and witchweed are problems and increase yields by 25 to 30 percent when only stem borers are an issue. The livestock feed and increased soil nitrogen are added benefits.

Malawian and U.S. scientists developed the third approach—the "doubled-up" legume system—adopted on more than 8,000 farms in Malawi. In its simplest form, a farmer plants a low, fast-growing legume such as peanut or soybean and adds pigeon pea, another legume that grows taller but much slower and is deeper-rooted. The peanuts or soybeans mature in a few months, just when the pigeon pea is surpassing them in height and would block the sun. After the peanuts or soybeans are harvested, their leaves fall and enrich the soil. The pigeon pea matures in another month or two and is harvested, and its leaves drop, continuing the enrichment. Because the two crops grow at different rates and tap different depths of the soil, they generally do not compete for nutrients or water. This system boosts the amount of protein-rich plants a farmer can harvest in a year and enhances soils while requiring less labor than two separate crops would. And it broadens the farm family's diet.

Pigeon peas regrow after being harvested. Thus, in the second season farmers can plant maize among the regrowing pigeon peas and subsequently harvest the maize and a second crop of the peas. Across two seasons this system produces three harvests of legumes and one harvest of maize, providing 50 percent more protein than the traditional maize-legume rotations.

OPTIMIZING CROPS TO LOCAL CONDITIONS

FOR MORE THAN A MILLION African farmers who have integrated perennials into their routines, the rewards have been great. They have rebuilt soils while sustainably increasing food production and dramatically improving their livelihoods. But millions more farmers in sub-Saharan Africa do not even know the techniques exist, or they need technical or financial help to exploit them. Good practices, however, are less straightforward than applying fertilizer or pesticide. Farmers must learn how to grow perennial and annual crops together, manage longer crop rotations and devise marketing strategies for a diversified harvest. Also, many farmers do not own the land they work or lack firm leases, which can dissuade them from investing in longer-term solutions.

To help, the international community should expand its investments in perenniation development, supporting efforts to scale up the successful techniques and backing research into others that farmers and scientists have not tested widely. Some efforts are well under way. The World Agroforestry Center, an international research institute that has led the development of evergreen agriculture, is in the final year of a four-year project called Trees for Food Security, in partnership with the governments of Ethiopia, Rwanda, Burundi and Uganda. The Program for Sustainable Intensification, run by the U.S. Agency for International Development, is supporting all three of the techniques we have described in regions of sub-Saharan Africa.

Scientists at the International Crops Research Institute for the Semi-Arid Tropics, the University of Malawi and Michigan State University are helping farmers in East Africa further improve doubled-up legume systems. They are developing more types of pigeon peas suitable for different climate conditions and farmer needs. Other experts have managed to create perennial versions of traditional annual crops such as sorghum, wheat and rice, and they are now trying to raise the yields and other desirable characteristics of these novel plants. Washington State University, Michigan State and the Land Institute in Salina, Kan., are breeding perennial grains that could thrive in diverse farmlands.

These efforts are good starts. But researchers are not yet certain which perenniation techniques would work best in various environments, in sub-Saharan Africa and beyond. An in-depth analysis is needed. To do that, scientists at Rutgers University and a Chinese company's department of agriculture and bioenergy have proposed a global network of 27 to 45 research stations, including in Africa. The stations would study the suitability of a range of trees, shrubs and other perennials for local climate, environmental and cultural conditions. The scientists estimate that $540 million to $1.8 billion could endow the network with sustainable programs. The losses of nitrogen, phosphorus and potassium from cultivated fields in sub-Saharan Africa alone have been estimated at $4 billion annually. Considering that perenniation can significantly stem those losses, tap into new sources deeper in the soil and, when legumes are involved, reduce nitrogen fertilizer use, the investment seems worthwhile.

Africa's farmers face a host of difficulties, yet many have successfully used perenniation in challenging environments. Expanding perenniation will help more of them feed their families and neighbors and create incomes for themselves and workers, raising their communities' standards of living. SA

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RECOMMENDED

By Clara Moskowitz

MORE TO EXPLORE
TO READ AN INTERVIEW WITH AUTHOR NEAL BASCOMB, VISIT
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DEV PATEL (*right*) and Jeremy Irons in *The Man Who Knew Infinity.*

The Man Who Knew Infinity

IFC Films, 2015. In theaters April 29

For the brilliant mathematician Srinivasa Ramanujan, every positive integer was a personal friend, according to his colleague John Edensor Littlewood. Starring Dev Patel as Ramanujan, this biopic portrays the brief life of the visionary mathematician, who achieved incredible breakthroughs in such fields as number theory, infinite series and mathematical analysis—including devising a landmark formula to calculate how many different ways one could sum up each positive integer. The film follows Ramanujan from his origins as an autodidact and shipping clerk in what was then Madras, India, to England, where he traveled to study and work with University of Cambridge mathematician Godfrey Harold ("G. H.") Hardy (played by Jeremy Irons). Despite their differences in background, culture and education, the two men formed a profound bond grounded in their love for numbers, sometimes to the exclusion of other people. The movie offers a touching look at their relationship and the revolutionary discoveries they achieved in their short collaboration.

Rise of the Rocket Girls: The Women Who Propelled Us, from Missiles to the Moon to Mars

by Nathalia Holt. Little, Brown, 2016 ($27)

"Before Apple, before IBM, and before our modern definition of a central processing unit partnered with memory, a computer referred simply to a person who computes," writes scientist and author Holt in this chronicle of the human "computers" who helped to launch America's space program. Most computers were women, and the story starts with a team at the fledgling Jet Propulsion Laboratory in the 1940s, before it became a NASA center. Using pencils, paper and slide rules, they performed the mathematical calculations necessary to develop jet planes and rockets. Many of the computers kept working through the 1960s and later; some became engineers. Holt investigates the fascinating lives and important contributions of these women, who defied the sexist stereotypes of their times to play pivotal roles in sending the first rockets beyond Earth.

Eruption: The Untold Story of Mount St. Helens

by Steve Olson.
W. W. Norton, 2016 ($27.95)

The death map grabs your attention. Spread over two pages in this chronicle of modern America's most infamous volcano, it lists the names and locations of 57 people killed by the eruption of Mount St. Helens in 1980. Hikers, a geologist and the most well-known victim, a stubborn man named Harry Truman, who refused to leave his lodge despite the two months of earthquakes that led up to the explosion, are pinned to their last known spots. To explain what people were doing in the danger zone, journalist Olson reconstructs what Earth scientists knew—and underestimated—about the volcano. The bulk of Olson's book, though, is about the land and people in this part of Washington State, a place of change during the preceding century, where roads and towns and the timber business, and even a zeal for conservation, brought people ever closer to the mountain, lured into harm's way. *—Josh Fischman*

The Winter Fortress: The Epic Mission to Sabotage Hitler's Atomic Bomb

by Neal Bascomb.
Houghton Mifflin Harcourt, 2016 ($28)

During World War II, the German effort to develop a nuclear bomb hinged on a rare substance called heavy water. Like the A-bomb the U.S. was pursuing at the same time, the Nazi design relied on nuclear fission: as an atomic nucleus breaks apart, it releases neutrons that shatter other nuclei, resulting in the liberation of more neutrons in a chain reaction that ultimately runs out of control and detonates. Whereas the U.S. used graphite to slow neutrons enough to allow the chain reaction to proceed, the Nazi bomb needed heavy water. To thwart the plan, the Allies launched a high-stakes commando raid to destroy a Norwegian power plant that was Germany's sole source of heavy water. Writer Bascomb brings this overlooked tale of wartime nuclear sabotage to life while taking care to explain the science behind the story. *—Jennifer Hackett*

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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

Doomsday Catch

Why Malthus makes for bad science policy

By Michael Shermer

If by fiat I had to identify the most consequential ideas in the history of science, good and bad, in the top 10 would be the 1798 treatise *An Essay on the Principle of Population,* by English political economist Thomas Robert Malthus. On the positive side of the ledger, it inspired Charles Darwin and Alfred Russel Wallace to work out the mechanics of natural selection based on Malthus's observation that populations tend to increase geometrically (2, 4, 8, 16 …), whereas food reserves grow arithmetically (2, 3, 4, 5 …), leading to competition for scarce resources and differential reproductive success, the driver of evolution.

On the negative side of the ledger are the policies derived from the belief in the inevitability of a Malthusian collapse. "The power of population is so superior to the power of the earth to produce subsistence for man, that premature death must in some shape or other visit the human race," Malthus gloomily predicted. His scenario influenced policy makers to embrace social Darwinism and eugenics, resulting in draconian measures to restrict particular populations' family size, including forced sterilizations.

In his book *The Evolution of Everything* (Harper, 2015), evolutionary biologist and journalist Matt Ridley sums up the policy succinctly: "Better to be cruel to be kind." The belief that "those in power knew best what was good for the vulnerable and weak" led directly to legal actions based on questionable Malthusian science. For example, the English Poor Law implemented by Queen Elizabeth I in 1601 to provide food to the poor was severely curtailed by the Poor Law Amendment Act of 1834, based on Malthusian reasoning that helping the poor only encourages them to have more children and thereby exacerbate poverty. The British government had a similar Malthusian attitude during the Irish potato famine of the 1840s, Ridley notes, reasoning that famine, in the words of Assistant Secretary to the Treasury Charles Trevelyan, was an "effective mechanism for reducing surplus population." A few decades later Francis Galton advocated marriage between the fittest individuals ("What nature does blindly, slowly, and ruthlessly man may do providently, quickly and kindly"), followed by a number of prominent socialists such as Sidney and Beatrice Webb, George Bernard Shaw, Havelock Ellis and H. G. Wells, who openly championed eugenics as a tool of social engineering.

We think of eugenics and forced sterilization as a right-wing Nazi program implemented in 1930s Germany. Yet as Princeton University economist Thomas Leonard documents in his book *Illiberal Reformers* (Princeton University Press, 2016) and former *New York Times* editor Adam Cohen reminds us in his book *Imbeciles* (Penguin, 2016), eugenics fever swept America in the early 20th century, culminating in the 1927 Supreme Court case *Buck v. Bell,* in which the justices legalized sterilization of "undesirable" citizens. The court included prominent progressives Louis Brandeis and Oliver Wendell Holmes, Jr., the latter of whom famously ruled, "Three generations of imbeciles are enough." The result: sterilization of some 70,000 Americans.

Science writer Ronald Bailey tracks neo-Malthusians in his book *The End of Doom* (St. Martin's Press, 2015), starting with Paul Ehrlich's 1968 best seller *The Population Bomb,* which proclaimed that "the battle to feed all of humanity is over." Many doomsayers followed. Worldwatch Institute founder Lester Brown, for example, declared in 1995, "Humanity's greatest challenge may soon be just making it to the next harvest." In a 2009 *Scientific American* article he affirmed his rhetorical question, "Could food shortages bring down civilization?" In a 2013 conference at the University of Vermont, Ehrlich assessed our chances of avoiding civilizational collapse at only 10 percent.

The problem with Malthusians, Bailey writes, is that they "cannot let go of the simple but clearly wrong idea that human beings are no different than a herd of deer when it comes to reproduction." Humans are thinking animals. We find solutions—think Norman Borlaug and the green revolution. The result is the opposite of what Malthus predicted: the wealthiest nations with the greatest food security have the lowest fertility rates, whereas the most food-insecure countries have the highest fertility rates.

The solution to overpopulation is not to force people to have fewer children. China's one-child policy showed the futility of that experiment. It is to raise the poorest nations out of poverty through democratic governance, free trade, access to birth control, and the education and economic empowerment of women. SA

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Illustration by Izhar Cohen

Steve Mirsky has been writing the Anti Gravity column since a typical tectonic plate was about 35 inches from its current location. He also hosts the *Scientific American* podcast Science Talk.

Big Hummer

Our gorilla cousins sing as they supper

By Steve Mirsky

Where, an old joke asks, does a 400-pound gorilla sleep? Anywhere it wants to, the superannuated gag answers. In keeping with that line of reasoning, a 400-pound gorilla should similarly hum anytime it wants to. The scientifically verified answer, however, is that the gorilla in question actually hums when he's eating—if the gorilla in question is a socially prominent male, anyway, according to a study recently published in the journal *PLOS ONE*. The humming sounds more like rumbling Dolby Audio in a theater showing a *Fast & Furious* movie than what you and I might come up with when we're doing the dishes. But it's definitely a hum coming out of that huge, hairy head.

The same study found that some gorillas may even sing when they're chewing on a favorite piece of vegetation. (And you thought it was impolite to even *talk* with your mouth full.) Gorilla singing doesn't approach the mellifluous stylings of, say, the Monkees, but it's vaguely musical, and the logical thing to call this sound that clearly isn't humming would be singing. Just as humans who perform "Aba Daba Honeymoon," with the immortal line "Baba daba daba daba daba daba dab, said the monkey to the chimp," are certainly singing, even if the work is "the nadir of all American expression," according to Thomas Pynchon.

That gorillas produce such noises was not a total shock. "We know from studies on chimpanzees and bonobos that great apes produce certain vocalizations while they're feeding, so-called food associated calls," said one of the authors of the new study, Eva Luef of the Max Planck Institute for Ornithology in Germany, in an interview for *Scientific American*'s Science Talk podcast. "And our study wanted to investigate whether gorillas do the same."

So Luef and her colleagues trooped off to the Republic of the Congo to spend some time with two different populations of western lowlands gorillas, which have the easy-to-remember Linnaean subspecies designation of *Gorilla g. gorilla*. (See if you can guess what the "g" stands for.)

Primatologist Dian Fossey, who died in Rwanda in 1985, noted that gorillas hum and sang. She categorized such sounds as "belch vocalizations," which often seemed to signal contentment—can you believe some people still don't accept that gorillas and humans have a common ancestor?

The current research, however, is the first to really track the vocalizations and connect them to specific behaviors. "And we found that it was [males—blackback adolescents and silverback adults—that] were the most frequent callers," Luef revealed. "This is not surprising as adult males are usually the most frequent callers, concerning any gorilla vocalization. And then we found that the food calls were produced when they were feeding on certain foods. So aquatic vegetation or seeds elicited a lot of food calls. And … they never called when they were eating insects like termites or ants." Because feasting on *Formicidae* or ingesting *Isoptera* is nothing to sing about. Even among gorillas.

So what's with all the Sturm und Sang? "We believe that the food calls have a social function in gorillas," Luef said. "They may signal to [other gorilla] listeners that an individual is busy eating at the moment. Silverback males have a special role in gorilla society…. They are most often the ones making group decisions. So when the silverback sits and eats, the others eat as well. And [when] he gets up and starts to … travel in the forest…, the others follow him. So it makes sense for the silverback to signal to his group mates that he's still eating and then signal that he has finished eating when he stops calling." In other words, humming and singing may be the dominant male's Do Not Disturb sign. And his eventual silence could be gorilla for "Ladies and almostmen, may I have your attention?"

In fact, Luef and her colleagues plan to do more in-depth analysis of gorilla vocalizations to see if they can learn anything about how we came to yap. They want to study "how the gorillas compose their food songs," she said, "and whether they possess a certain repertoire of song notes, which they combine into their little food songs. That would be more similar to human language because [we have] a certain repertoire of sounds we can make, and we combine them into words and different languages. So if gorillas could do the same with their songs, that would just be amazing." Aba daba indeed. SA

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Illustration by Matt Collins

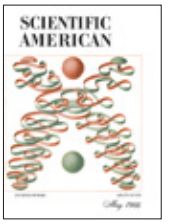
1966 Josephson Effect

"Four years ago Brian D. Josephson, a young graduate student in physics at the University of Cambridge, made a startling prediction. On the basis of a purely theoretical analysis of the phenomenon of superconductivity (the abrupt disappearance of electrical resistance in certain substances at temperatures near absolute zero), Josephson came to the conclusion that in principle a 'supercurrent' consisting of correlated pairs of electrons could be made to flow across an insulating gap between two superconducting bodies, provided that the gap was small enough. He further suggested that this 'tunneling' of electron pairs through an insulator could take two forms, which have come to be known as the Josephson effects. Both forms have been observed in recent experiments."

Josephson shared the 1973 Nobel Prize in Physics for his work.

Indicting Detroit

"Book review: *Unsafe at Any Speed: The Designed-In Dangers of the American Automobile,* by Ralph Nader. Grossman Publishers ($5.95). For decades we have followed the policy that greater automobile safety was to be achieved primarily by campaigns of driving legislation, law enforcement, technical education and moral exhortation. This view has had, and for many it still has, the force of an ideological commitment. Nader's book can be described as an analysis and a critique of this ideology. It is an adversary work that points an accusing finger at the automobile manufacturers, charging them with indifference, callousness and arrogance in the face of genuine possibilities of safer automobile design. In his conclusion Nader advocates publicly defined and Federally enforced standards of safety in design and manufacture, supported by continuous research. —David Hawkins"



1966

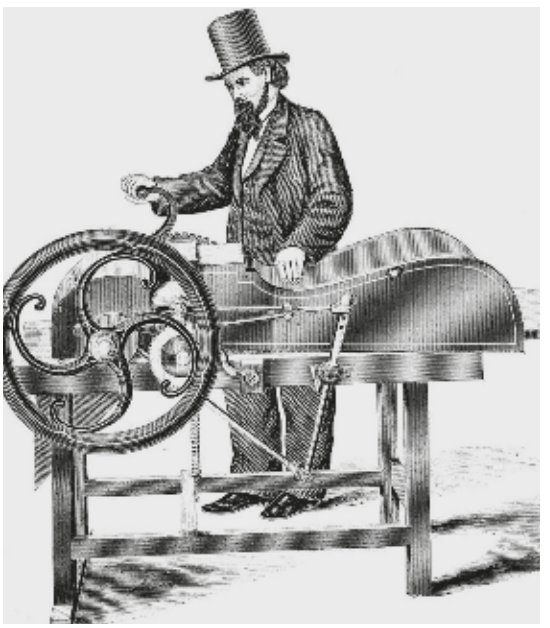
1916

1866

1916 News from the War

"After almost five months of siege the British forces under General Townshend at Kut el Amara, in Mesopotamia, have been compelled to surrender. This force, which originally constituted the flying column which attempted to take Baghdad, was reduced at the time of surrender to something less than 10,000 men. Shrinking to this almost negligible number of men was brought about by losses incurred during the advance on Baghdad, the retirement from the battle of Ctesiphon and the subsequent investment of Kut. General Townshend's surrender was primarily caused by lack of food, ammunition, and the dearth of equipment to meet sanitary needs."

The defenders lost Kut despite being the first in the history of warfare to be resupplied by aircraft.



MACHINE FOR FARMERS: A fodder cutter. The proud inventor probably donned his "Sunday best" for this 1866 engraving.

1866 Technology for Farming

"A regular and steady demand exists for good agricultural implements. Farmers are always looking out for those which are really durable and advantageous to them, and they seem willing, to judge from the quantities of all varieties sold, to give them a fair trial. In this engraving [*see illustration*] we have shown a new fodder cutter (for cutting up animal feed) recently introduced in the West [in this case, Richmond, Ind.]. It is substantially made and capable of being repaired by any ordinary mechanic or blacksmith, should an accident happen to it."

A slide show of more great ideas from 1866 is at www.ScientificAmerican.com/may2016/inventions

Bad Air

"The steamship *Virginia* arrived at this port recently with a large number of passengers on the sick list. She was immediately put in quarantine, the sick cared for and isolated from the city until cured. Investigations made by the proper officers show that none of the passengers came from ports infected with cholera, and that it was not until some eight days after the departure of the *Virginia* from Liverpool, that disease broke out on board. It appears that the ventilation was so defective that the passengers suffered greatly, and being enfeebled by bad air and insufficient food, were especially liable to attack. It seems passing strange that with all the modern appliances for obtaining fresh air and creating a thorough circulation in apartments, that so little attention is paid to it. The loss to the owners by the detention of their vessel amounts to a large sum, and if not for humanity then for the pocket's sake, a little more interest in the welfare of the steerage passengers would pay."

SCIENTIFIC AMERICAN, VOL. XIV, NO. 19; MAY 5, 1866

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TO LEARN HOW LIGHTNING CAN PRODUCE X-RAYS, GO TO
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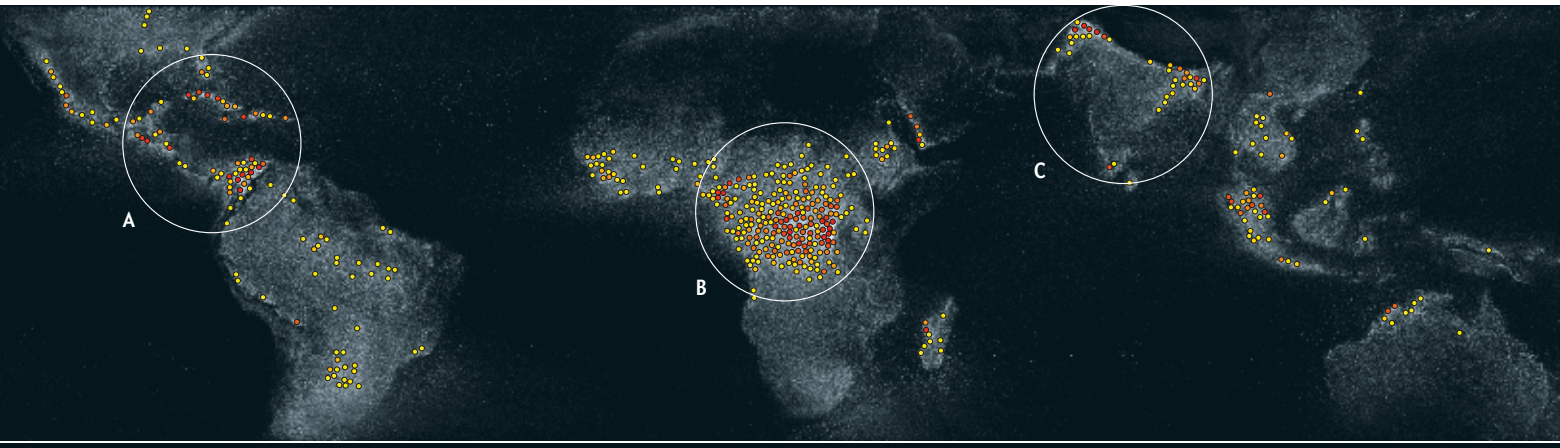


White dots show flashes per year, which define the land and ocean features visible; no other map data were used. Lightning diminishes toward higher latitudes.

Flashes per square kilometer per year: 0 233

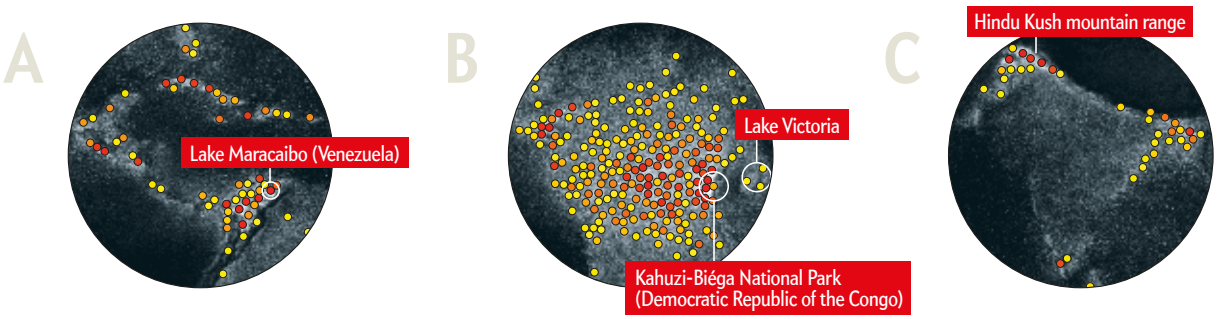
Top 500 strike locations: #500 (51 flashes) #1 (233 flashes)

Lightning Hotspots

Central Africa is the epicenter, but a South American lake ranks number one

Lightning flashes above Lake Maracaibo in Venezuela more than anywhere else on earth and does so for a stunning 297 days of the year. Second place goes to Kahuzi-Biéga National Park in the Democratic Republic of the Congo. A new study of satellite data spanning 16 years shows that cloud-to-ground lightning and intracloud lightning occur most frequently over complex terrain—notably the foothills of rugged mountain regions, especially if a big, warm lake lies nearby (*insets below*). Ironically, the leading U.S. spot is not rugged, but a flat corner of the Everglades near Orangetree, Fla. Africa is home to the most hotspots—283 of the top 500—followed by Asia (with 87), South America, North America and Australia (*colored dots on main map*). Above land, thunderstorms are most prevalent during the afternoon; fewer form over the oceans, but they tend to flare up at night.

—Mark Fischetti



Americas

Lake Maracaibo (*above*) ranks first worldwide for lightning. Hot, humid air rises from the warm lake and Gulf of Venezuela there, mixing with ocean breezes, as well as winds channeled in by the converging Andes Mountains. The cauldron often erupts into thunderstorms very late at night. Six of the other top 10 spots in South America lie in Andes valleys or foothills.

Central Africa

Eight of Africa's 10 most active locations are in the Democratic Republic of the Congo, in part because heavy moisture from rain forests there mixes with strong vertical air currents, creating "an explosive convection" scenario, according to researchers. Lake Victoria, which is adjacent to the Mitumba Mountains and is divided among three countries, is one hotbed for nighttime storms.

Indian Subcontinent

In monsoon regions, lightning peaks in spring, before the drenching rains hit, and returns for a second peak from August to October, as the rains fade. Flashes occur most frequently along the western hills of the Himalayas, where moist, rising winds from the sea meet dry air descending from the Afghan and Tibetan plateaus.

SOURCE: "WHERE ARE THE LIGHTNING HOTSPOTS ON EARTH?" BY RACHEL I. ALBRECHT ET AL., IN *BULLETIN OF THE AMERICAN METEOROLOGICAL SOCIETY* (IN PRESS)

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1 EPA-estimated 53-mile EV range based on 106 MPGe combined city/highway (electric); 367-mile extended range based on 42 MPG combined city/highway (gas). Actual range varies with conditions.